Application of Fatigue Theories to Seismic Compression Estimation and the Evaluation of Liquefaction Potential

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ABSTRACT

Earthquake-induced liquefaction of saturated soils and seismic compression of unsaturated soils are major sources of hazard to infrastructure, as attested by the wholesale condemnation of neighborhoods surrounding Christchurch, New Zealand. The hazard continues to grow as cities expand into liquefaction- and seismic compression-susceptible areas hence accurate evaluation of both hazards is essential.

The liquefaction evaluation procedure presented herein is based on dissipated energy and an SPT liquefaction/no-liquefaction case history database. It is as easy to implement as existing stress-based simplified procedures. Moreover, by using the dissipated energy of the entire loading time history to represent the demand, the proposed procedure melds the existing stress-based and strain-based liquefaction procedures into a new, robust method that is capable of evaluating liquefaction susceptibility from both earthquake and non-earthquake sources of ground motion.

New relationships for stress reduction coefficient ($r_d$) and number of equivalent cycles ($n_{eq}$) are also presented herein. The $r_d$ relationship has less bias and uncertainty than other common stress reduction coefficient relationships, and both the $n_{eq}$ and $r_d$ relationships are proposed for use in active tectonic and stable continental regimes. The $n_{eq}$ relationship proposed herein is based on an alternative application of the Palmgren-Miner damage hypothesis, shifting from the existing high-cycle, low-damage fatigue framework to a low-cycle framework more applicable to liquefaction analyses.

Seismic compression is the accrual of volumetric strains caused by cyclic loading, and presented herein is a “non-simplified” model to estimate seismic compression. The proposed model is based on a modified version of the Richart-Newmark non-linear cumulative damage hypothesis, and was calibrated from the results of drained cyclic simple shear tests. The proposed
model can estimate seismic compression from any arbitrary strain time history. It is more accurate than other “non-simplified” seismic compression estimation models over a greater range of volumetric strains and can be used to compute number-of-equivalent shear strain cycles for use in “simplified” seismic compression models, in a manner consistent with seismic compression phenomenon.

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Chapter 1

Introduction

Loose, granular soils have a tendency to contract when cyclically loaded (e.g. as in an earthquake). In saturated soils, this tendency can lead to the generation of excess pore water pressure and the consequent loss of shear strength. This process is called cyclic softening and, if the process continues, the soil may liquefy. In unsaturated soils, this same tendency to contract leads to seismic compression, a decrease in soil volume. Various methodologies have been proposed to evaluate the potential for liquefaction and seismic compression, many of which are loosely based on fatigue theories. The objective of the research presented herein is the more rigorous and consistent application of specific fatigue theories to these important geotechnical earthquake engineering phenomena. In particular: 1. The development of a method to estimate seismic compression using a modified version of the non-linear Richart-Newmark (Richart and Newmark 1948) cumulative damage hypothesis, and 2. The development of a dissipated-energy-based liquefaction evaluation procedure based on a low-cycle fatigue application of the Palmgren-Miner (Palmgren 1924; Miner 1945) hypothesis. This chapter introduces the research presented in this dissertation and details the objectives of this research. Throughout this chapter and dissertation, the terms “simplified” and “non-simplified” are used to describe seismic compression and liquefaction evaluation procedures. In this context, a “non-simplified” procedure requires a site response analysis to compute the induced stresses/strains in the soil profile where a “simplified” procedure does not require these site-specific analyses.
1.1 Soil Liquefaction

Liquefaction occurs when the soil skeleton of a loose, saturated sand contracts (e.g., as a result of earthquake shaking), with the self-weight of the soil particles and the overburden load being transferred to the pore water. As the overburden load is transferred to the pore water, the pore water pressure increases and the shear strength of the soil is temporarily reduced. Possible consequences of this loss of strength include bearing capacity failures of foundations, slope failures, and settlements; the safety of buildings, bridges, dams, and many other structures is often affected.

The damaging effects of liquefaction were realized during the 1964 Niigata, Japan earthquake. During this event, liquefaction caused apartment buildings to tilt dangerously on their sides, underground tanks to rise to the surface, and costly damage to other buildings and infrastructure (Seed and Idriss 1967). More recently, at the Port-au-Prince, Haiti seaport, liquefaction-damaged piers (via lateral-spreading) hampered the delivery of relief supplies (Rathje et al. 2010; see Figure 1.1). In most large earthquakes, liquefaction inflicts heavy economic damages (see Figure 1.2) and potentially threatens lives.

The current state-of-practice for assessing the potential for liquefaction is to use in-situ index test data (e.g. SPT blow counts, CPT logs, shear wave velocity profiles) and expected earthquake loading in conjunction with the stress-based simplified procedure. The stress-based simplified procedure was proposed by Whitman (1971) and Seed and Idriss (1971), and subsequently modified by many others (e.g. Youd et al. 2001). At its core, it is based on the Palmgren-Miner (Palmgren 1924; Miner 1945) cumulative damage hypothesis, a well-used fatigue theory in earthquake engineering.

While the stress-based simplified procedure is useful in liquefaction potential evaluations, it has several limitations. For example, in implementing the procedure in a non-simplified form (i.e. computing the induced stresses using a site response analysis) only the estimation of the induced amplitude of the load is refined, not the duration of the load. Also, applicability of the procedure for evaluating motions other than active shallow crustal earthquakes (e.g. subduction zone or stable continental earthquakes), non-tectonic earthquake motions (e.g. induced seismicity), or non-earthquake motions (e.g. blasting) is questionable.
The energy-based liquefaction evaluation procedure presented herein imple-
ments an established low-cycle metal fatigue theory (an alternative imple-
mentation of the Palmgren-Miner hypothesis; Green and Terri 2005) that is
easily calibrated for a range of soils, stress conditions, and earthquake ground
motions. The damage metric for the theory is dissipated energy, the cumula-
tive area bound by stress-strain hysteresis curves, and dissipated energy has
been shown to be a good indicator of excess pore pressure and the result-
ing liquefaction (Nemat-Nasser and Shokooh 1979) irrespective of the shape
of the loading history (Liang et al. 1995). By using this well-established
low-cycle fatigue theory with dissipated energy as the damage metric, the
energy-based liquefaction evaluation procedure proposed herein can be ap-
plied in tectonic settings that are under-represented in the current liquefac-
tion case history database or for applications dealing with non-earthquake
cyclic loading, such as the design of ground improvement programs.

1.2 Seismic Compression

Seismic compression is the accrual of volumetric strain that occurs when a
loose, unsaturated sand is cyclically loaded (e.g. from earthquake shaking).
Compared to liquefaction, damages due to seismic compression are relatively
small. This is because shear strengths are never completely lost in the soil,
and seismic compressions occur only in the relatively shallow depths above
the water table. However, Stewart et al. (2001) documented hundreds of
cases of permanent vertical and horizontal ground displacements in struc-
tural fills. They suggested that many of the these displacements were caused
by seismic compression, and concluded that seismic compression poses a sig-
nificant risk to engineered structural fills in particular.

Currently, several methods are available to estimate the magnitude of seismic
compression (e.g. Tokimatsu and Seed 1987; Duku 2008). These are mainly
“simplified” methods that rely on a number-of-equivalent-cycles correlation
to represent duration. In many cases, the number of equivalent cycles is com-
puted inconsistently with the underlying mechanics of seismic compression.
Proposed herein is a “non-simplified” method that was developed using the
Richart-Newmark (1948) cumulative damage hypothesis in conjunction with
the results of cyclic direct simple shear tests performed at Virginia Tech. The
proposed method can predict seismic compression for any arbitrary cyclic
loading.

1.3 Objectives

As stated previously, the overall objectives of the research presented herein are: 1. the development of a seismic compression estimation method based the Richart-Newmark (R-N; Richart and Newmark 1948) cumulative damage hypothesis, and 2. the development of an energy-based liquefaction evaluation procedure based on low-cycle fatigue principles.

In order to achieve the first objective, over 450 cyclic simple shear laboratory tests have been performed on dry sand specimens at various relative densities and overburden pressures. From the results of sinusoidal tests, the proposed R-N-based model was calibrated. From other cyclic simple shear test performed with variable-amplitude sinusoidal and earthquake loading functions, the calibrated model was validated.

For the second objective, equivalent-linear site response analysis were conducted using 50 soil profiles and 228 pairs of earthquake motions (representing two different tectonic regimes). From the resulting site responses, a number of equivalent cycles correlation was developed based on low-cycle fatigue and dissipated energy. A stress reduction coefficient correlation was also developed from the site response analyses. With the number of equivalent cycles correlation, the stress reduction coefficient correlation, and a liquefaction/no-liquefaction case history database, the energy-based liquefaction evaluation procedure was developed. Finally, the results of constant-volume cyclic simple shear tests support the form of the liquefaction evaluation procedure.

1.4 Organization

This dissertation is organized as a collection of four manuscripts with three introductory chapters and one closing chapter. Chapter 2 gives a brief literature review. A large portion of the chapter gives a historical overview of seismic compression research and outlines procedures that are currently in use for the evaluation of seismic compression. Another large portion of the chapter provides a historical overview of energy-based liquefaction evaluation
procedures. Lesser sections of the chapter provide background information for the subsequent chapters and discuss topics such as field and laboratory soil testing, the stress-based simplified procedure, and equivalent-linear site response analyses.

Chapter 3 is the first of four manuscripts that have been or will soon be submitted for publication. It presents the aforementioned method to estimate seismic compression using the Richart-Newmark (Richart and Newmark 1948) cumulative damage hypothesis. It also contains a discussion on fatigue hypotheses including the Richart-Newmark and Palmgren-Miner (1924; 1945) hypotheses. The results of the method presented therein are compared with those of the Byrne (1991) and Palmgren-Miner methods, and the newly proposed method provides the best overall results of the three methods.

Chapter 4 contains the second manuscript. It presents a new number of equivalent cycles ($n_{eq}$) correlation which is a function of the peak ground acceleration and earthquake magnitude. The proposed $n_{eq}$ correlation is based on the Palmgren-Miner cumulative damage hypothesis, like many other $n_{eq}$ correlations in geotechnical earthquake engineering. However, instead of assuming high-cycle fatigue conditions (many cycles, little damage in each cycle), the proposed correlation assumes low-cycle fatigue conditions (few cycles to failure; significant damage in each cycle) and uses dissipated energy as the damage metric. Correlations are presented for both shallow-crustal tectonic regimes (e.g. the western United States) and stable continental regimes (e.g. the central-eastern United States).

Chapter 5 is a technical note that introduces a new stress reduction coefficient ($r_d$) relationship. The stress reduction coefficient allows for the computation of the seismically induced stresses at depth in a soil profile without the need to perform numerical site response analyses. As such, $r_d$ is an integral part of the simplified liquefaction evaluation procedure. The stress reduction coefficient relationship proposed therein yields values having less bias and uncertainty than those of other commonly-used $r_d$ relationships. Also, relationships are presented for both shallow-crustal tectonic regimes (e.g. the western United States) and stable continental regimes (e.g. the central-eastern United States).

Chapter 6 presents a simplified liquefaction evaluation procedure based on dissipated energy and the $n_{eq}$ correlation described in Chapter 4. The pro-
The proposed procedure is a function of peak ground acceleration, SPT blow count, earthquake magnitude and fines content. It is presented in a manner that will be familiar to current users of the stress-based simplified procedure. For the liquefaction case history database from which it was derived, the proposed procedure is as successful at predicting liquefaction/no-liquefaction as other stress-based simplified procedures. Additionally, because the proposed liquefaction evaluation procedure is based on dissipated energy, it can more easily be applied to sites outside the tectonic regime from which it was derived or used to evaluate liquefaction potential for non-earthquake loadings.

A summary of the significance of the research findings and conclusions are given in Chapter 7. Additional research details are given in the numerous appendices.

## 1.5 Significance

Earthquakes present a serious risk to life and property for large portions of the world’s population. A significant part of this risk can be attributed to the possible effects of liquefaction and seismic compression. The research presented herein brings powerful fatigue theories to bear on the evaluations of liquefaction potential and seismic compression. By providing more accurate and versatile evaluation methods, limited resources can be applied in the best possible manner to reduce this risk.

Both the seismic compression and the liquefaction evaluation procedures proposed herein can be used in a “non-simplified” manner. Barriers to the application of numerical site response analyses (such as the equivalent-linear procedure) have been reduced in recent years. Cost-effective methods for site characterization for dynamic analyses are becoming more prevalent as are protocols for selecting input motions and performing site response analyses (e.g. Kottke and Rathje 2008; Bradley 2012; Stewart and Kwok 2008). As these site response analyses become more common, the usefulness of procedures that can compatibly perform both “simplified” and “non-simplified” evaluations grows. Although not developed as part of this research, the modified R-N model developed for seismic compression estimation can be used to develop a “simplified” procedure with a consistent damage metric (i.e. volumetric strain).
In addition to providing better earthquake-induced liquefaction and seismic compression evaluations, the procedures proposed herein can be used with any cyclic loading for which stress and strain time histories can be obtained: from machine foundation design to remedial ground densification.

1.6 References


1.7 Figures

Figure 1.1: Liquefaction during the 2010 $M_w 7.0$ earthquake caused damage at the Port-au-Prince seaport, hampering relief efforts. (gCaptain 2010) [Fair Use]
Figure 1.2: Liquefaction during the Christchurch earthquake sequence led to the condemnation of entire neighborhoods (NZDF 2011). [Fair Use]
Chapter 2

Literature Review

2.1 Introduction

This chapter presents an overview of and background information on the concepts central to the subsequent manuscripts. Some of the topics are introduced in detail in the manuscripts themselves; this chapter contains the subjects that are not covered in sufficient detail in other chapters. This chapter is organized as follows: first, a brief introduction on laboratory and in-situ soil testing is given followed by a detailed review of historic seismic compression research and evaluation methods. The equivalent-linear site response analysis is then presented. Next, a brief introduction to stress-based liquefaction evaluation methods is presented. Finally, a historic overview of energy-based liquefaction evaluation procedures is given.

2.2 Soil Testing

The testing of soils in order to characterizing their engineering behavior is generally divided into two categories: in-situ testing and laboratory testing. In-situ testing provides information about the current state of a soil deposit and, under some conditions, provides information on engineering parameters of soils. Laboratory testing is used to characterize the behavior of the soil under various loading conditions. This information is required to make competent design decisions and allow for modeling and predictions. Geotech-
nical earthquake engineers are mainly concerned with the composition of
the soil (e.g. grain size distribution and plasticity), the in-situ density, the
strain-dependent stiffness and damping of the soil, and ultimately the cyclic
strength of the soil. This section provides an overview of the soil testing that
are relevant to characterizing the seismic compression and liquefaction be-
havior of soils. Laboratory testing will be discussed first, followed by in-situ
testing.

2.2.1 Laboratory Testing

Laboratory tests are performed on soil samples obtained from field investi-
gations and can be generally placed in one of two categories: index testing
and characterization of the stress-strain behavior of the soil. Index testing
provides information on the inherent properties of the aggregate soil par-
ticles, irrespective of the packing of the particles. For example, common
index tests determine grain size distribution, Atterberg limits (liquid limit
and plastic limit), minimum and maximum void ratios (void ratio is defined
as the volume of voids over the volume of solids), particle angularity, and
particle composition. Since index tests measure inherent properties of the
aggregate soil, they can be performed on disturbed soil samples.

Characterization of stress-strain behavior involves the evaluation of the
stress-strain behavior of a soil under a given loading condition and drainage
condition. Geotechnical earthquake engineers are interested in the cyclic
strength of soils under undrained conditions for liquefaction analysis and
under drained conditions for seismic compression analysis. The soils most
susceptible to liquefaction and seismic compression are sands, silts, and
gravels. The cyclic strength of these soils is evaluated by applying a dynamic
loading to the soil specimen until failure occurs. In most cases, this loading
is sinusoidal, but several other load shapes are also used in practice and
research.

The fabric of the soil can have a profound effect on the results of these
strength tests (Ladd 1974; Seed et al. 1975; Mulilis et al. 1977), so undis-
turbed soil samples give the most reliable results. However, undisturbed
sampling of liquefaction- and seismic compression-susceptible soils is, in most
cases, prohibitively expensive and, under some circumstances, not possible.
Where undisturbed samples are unavailable, soil test specimens must be re-
constituted from disturbed soil samples. For liquefaction evaluations, soil specimens are commonly reconstituted by dry or wet tamping (soil is placed into a mold then tamped to density; Ladd 1978), dry or wet pluviation (soil is pored into the mold; Vaid and Negussey 1984; Vaid et al. 1999), or, for soils with fines, slurry deposition (Kuerbis and Vaid 1988). Sample preparation should aim to mimic natural soil deposition and soil fabric.

In laboratory testing, the relative density is often used as a measure of the soil density. It is defined as:

\[
D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100\% \tag{2.1}
\]

where \(e\), \(e_{max}\), and \(e_{min}\) are the void ratio, the maximum void ratio, and the minimum void ratio, respectively. \(e_{max}\) and \(e_{min}\) are determined using standardized index tests.

A number of different laboratory tests are used to evaluate the cyclic strength of a soil. These tests vary in the ways that static and dynamic stresses are applied to a specimen and each have their own strengths and weaknesses. In this section, cyclic triaxial, cyclic simple shear, and cyclic hollow cylinder torsional shear tests will be briefly detailed. Finally, a few common cyclic failure criteria are enumerated.

### Cyclic Triaxial

Triaxial tests have a long history in geotechnical engineering (Holtz et al. 2010). Triaxial soil specimens are cylindrically-shaped with a height roughly twice that of the diameter (ASTM 2013, Standard D5311). The specimens are enclosed in a rubber membrane (see Figure 2.1), and confining stress (outside the membrane) and pore pressure (inside the membrane) can be controlled independently. Cyclic triaxial tests are predominantly used for liquefaction evaluations (not for seismic compression), and for reliable results, the specimen must be saturated with no sizeable air voids present. This is often obtained via back-pressure saturation. In back pressure saturation, the samples are first flushed with CO\(_2\) and both the confining stress and pore pressure are increased until the air voids are sufficiently small to have little effect. While the back pressure saturation occurs, a positive effective confining stress (confining stress minus pore pressure) is
maintained. After the specimen is saturated, it is allowed to consolidate under a target effective confining stress.

Once consolidation has completed, a cyclic axial stress is applied at the top of the specimen until failure occurs (failure criteria are discussed in a subsequent section). Drainage from the specimen is not allowed to occur during the cyclic loading phase (i.e. the pore water pressure is allowed to rise), and the pore water pressure is recorded throughout the cyclic phase of the test. For more information, see Appendix H.

**Cyclic Simple Shear**

In a simple shear test, a stout cylindrical specimen is enclosed by rings or a reinforced membrane (see Figure 2.2). The diameter of the specimen should be at least 2.5 times greater than the height (ASTM 2007). A few variants of the cyclic simple shear (CSS) test are possible. For an ordinary CSS test for liquefaction, a saturated sample is prepared and a confining stress is applied via a normal confining stress. Consolidation is allowed to occur; drainage lines are left open while consolidation continues. After consolidation, drainage lines are closed and the normal confining stress is held constant while a cyclic shear load is applied to the top or the bottom of the specimen, depending on the configuration of the testing apparatus. Cyclic loading continues until failure occurs, and pore water pressures are recorded throughout the cyclic phase of the test.

Another variant of the CSS is the constant-volume (C-V) cyclic simple shear test (Finn and Vaid 1977). A C-V CSS test can be performed on a wet or dry specimen. Like an ordinary CSS test, a normal consolidation stress is applied to consolidate the specimen with drainage lines open. After consolidation, however, the normal displacement is held constant while the cyclic shear loading is applied and drainage lines are left open. Instead of measuring the pore water pressure, the normal stress is recorded and allowed to change during the cyclic phase of the test. The test is based on the premise that the decrease in the normal stress during loading is equal to the increase in pore water pressure for an ordinary CSS test (Finn and Vaid 1977; Finn et al. 1979; Dyvik et al. 1987).

One benefit of performing constant-volume cyclic simple shear tests is that the specimen does not need to be saturated and no enclosing cell is needed.
This allows for specimens to be prepared and tested in much less time compared to the ordinary CSS and triaxial tests. For more information on specific test procedures used during this research, see Appendix G.

The induced shear stresses and strains of cyclic simple shear tests are more representative of earthquake-induced stresses and shear strains (Kramer 1996) than those of cyclic triaxial tests because the CSS apparatus can directly apply shear stresses to the horizontal planes of a specimen. However, due to the confining rings or reinforced membranes of conventional (and C-V) CSS tests, the normal confining stresses applied to the sides of the specimen are not controlled; only the normal vertical stresses that are applied to the top and the bottom of the specimen can be controlled.

**Hollow Cylinder Torsional Shear**

Hollow cylinder torsional shear tests are performed on specimens that are shaped like a hollow cylinder, open at the top and the bottom. The inside and outside of the hollow specimen are membrane covered, allowing for any combination of normal confining stresses to the top and sides of the specimen. During cyclic loading shear stresses are imposed on horizontal planes of the specimen via a torque applied at the top (Holtz et al. 2010). Like cyclic triaxial tests, most hollow cylinder tests are performed on saturated specimens and drainage is closed during the cyclic loading phase of the test. These tests are sometimes simply called ‘torsional shear tests.’ These are the least common of the three laboratory tests discussed in section.

**Failure Criteria in Liquefaction Testing**

Several different failure criteria are used in laboratory testing to define the onset of liquefaction. These liquefaction criteria can be categorized as follows (Wu et al. 2004):

1. Pore Water Pressure-Based: Initial liquefaction is considered to have occurred when the pore water stress is equal to the confining stress. This can also be stated as when the residual excess pore water pressure is equal to the initial effective confining stress or when the residual excess pore water pressure ratio \( r_u \) is equal to 1.
2. Strength-Based Criteria: Liquefaction is considered to have occurred when a significant amount of strength is lost. The threshold value of strength will vary depending on application and judgment.

3. Strain-Based Criteria: Liquefaction is considered to have occurred when a certain amplitude of strain or deformation has occurred. This criteria is similar to the strength-based criteria because strain increases as strength decreases. As with the strength-based criteria, the threshold strain value varies between researchers with some using 3% single-amplitude and others using up to 20% double-amplitude strain as the liquefaction initiation criteria.

For the cyclic simple shear tests discussed in Chapter 6 of this work, a strain-based criteria of 3.75% single-amplitude strain was used (Vaid and Sivathayalan 1996; Sivathayalan and Ha 2011). The failure criteria are not necessary for drained seismic compression tests because catastrophic loss of strength does not occur during cyclic loading. Instead, volumetric strains are the damage metric and are recorded throughout the cyclic phase. Seismic compression tests are halted when designated volumetric strains have occurred.

### 2.2.2 In Situ Testing

Because undisturbed soil specimens are difficult and costly to obtain, in-situ soil tests have an important role in evaluating liquefaction and seismic compression susceptibility. In-situ tests provide information such as soil type stratigraphy, in-situ density, and depth to the water table. From these details an engineer can identify liquefaction- and seismic compression-susceptible soil layers in the profile. Many in-situ tests have been proposed and used over the years. This section will detail two common in-situ tests: the standard penetration test and the cone penetrometer test.

#### Standard Penetration Test

The standard penetration test, or SPT, is a test commonly used for standard geotechnical site investigations and liquefaction potential evaluation. It is standardized by ASTM standard 1586 (2011). To perform the test, a borehole must first be drilled from the ground surface to the depth of interest. Next,
a ‘split-spoon’ (or ‘split barrel’) sampler is lowered to the bottom of the borehole by means of driving rods. The split-spoon sampler has an outer diameter of 5.1 cm (2 inches) and inner diameter of 3.5 cm (1.375 inches). The sampler is driven into the bottom of the borehole by dropping a 0.623 kN (140 pound) weight a distance of 76.2 cm (30 inches). It is driven a total of 45.7 cm (18 inches) into the bottom of the borehole, and the number of ‘blows’ required to drive the sampler the last 30.5 cm (12 inches) is the measured SPT blow count $N_m$.

The earliest stress-based simplified procedures (e.g. Whitman 1971) used SPT blow count as a proxy for soil density, and it remains a common in-situ test for liquefaction evaluations. Besides being ubiquitous, the SPT also returns a disturbed soil sample which is useful for soil type identification and index testing. Because the test is common, many correlations exist for the SPT blow count and most engineers are familiar with it. However, the site profiling from SPT testing is discrete (or non-continuous); thin layers may be missed entirely because testing is generally performed at depth increments of 0.076, 0.1524, or 3.048 m (2.5, 5 or 10 ft).

**Cone Penetrometer Test**

The cone penetrometer test (CPT) has become common in recent years and rivals the SPT in popularity for geotechnical site investigations in some regions of the United States. It is performed by pushing a cone-tipped rod into the soil at a constant rate of 20 mm/s (ASTM 2012). The cone has an apex angle of 60 degrees and a cross-sectional area of 10 cm$^2$. As the cone progresses through the profile, the tip resistance ($q_c$) and sleeve resistance ($f_s$) are measured in units of stress. The sleeve is located directly behind the cone. The tip resistance and sleeve resistance can be correlated to soil type, and for soils that are determined to be liquefiable, the tip resistance can be used in many stress-based liquefaction evaluation procedures.

The CPT has some benefits over the SPT: it provides a nearly continuous profile and is better at revealing thin soil layers. Also, the CPT is more repeatable and less prone to operator error (Robertson and Cabal 2007). However, it does not return a soil sample, is still less common than the SPT, and is often not able to be used to characterize profiles having gravel layers or dense soil layers.
2.3 Seismic Compression

Research in the area of seismic compression of unsaturated sands began in earnest in the late 1960s and early 1970s. Early studies (Whitman 1969; Silver and Seed 1971; Youd 1972) established the relationship between the amplitude of the horizontal shear strain and the amount of seismic compression. Other studies recognized the effect of two dimensional motions (Pyke et al. 1975) and that fine-grained soils are less susceptible (Chu and Vucetic 1992) to large-magnitude volume changes. Several methods have been proposed to estimate the magnitude of seismic compression (Seed and Silver 1972; Tokimatsu and Seed 1987; Byrne 1991; Pradel 1998; Stewart and Whang 2003). Most of these procedures are “simplified” procedures that rely on number-of-equivalent-cycles correlations.

More recently, a great quantity of laboratory testing (Whang 2001; Hsu and Vucetic 2004; Stewart et al. 2004; Duku et al. 2006, 2008) has been performed to better understand soil compositional factors that affect the magnitude and accumulation of seismic compression and to improve the existing procedures (Duku et al. 2008; Yi 2010). In this section, a brief historical review of seismic compression research is given in chronological order.

2.3.1 Whitman and Ortigosa (1969)

Whitman and Ortigosa (1969) imposed vertical accelerations of various magnitudes on sand samples using a shaking table. They found that vertical accelerations alone did not cause appreciable settlement for accelerations less than about 1 $g$. Assuming it unlikely that vertical accelerations would exceed 1 $g$ in an earthquake, they concluded that the effects of vertical accelerations could be neglected.

2.3.2 Silver and Seed (1971)

Silver and Seed (1971) performed strain-controlled cyclic simple shear tests using an NGI-type device. The tests were performed on dry crystal silica (#20) sand at target relative densities of 45, 60, and 80%. The cyclic shear strain amplitudes imposed on the samples ranged from 0.01 to 0.5%. From their test data they derived what would be known as a “volumetric strain
material model” (Stewart et al. 2004) for No. 20 crystal silica sand. They found that vertical strain increases with increasing shear strain amplitude, increasing number of strain cycles, and decreasing relative density of the sand. Vertical strain rate falls off exponentially as the number of cycles increases; most straining occurs in the first few cycles. Additionally, their tests showed that overburden stress had little effect on the total vertical strain. However, they discovered that the cyclic shear strain needed to produce a vertical strain in the sample (hereafter known as the threshold shear strain) increases with increasing overburden stress.

### 2.3.3 Youd (1972)

Youd (1972) performed strain-controlled tests on saturated and air-dried Ottawa sand with an NGI-type cyclic simple shear apparatus. The relative densities of the test specimens ranged from 70-80%. Youd’s experiments confirmed Silver and Seed’s (1971) results that vertical strain is a function of cyclic shear strain amplitude and that overburden stress does not affect vertical strain above a certain amplitude of cyclic shear strain. Additionally, Youd showed that there is not a significant difference in the behavior of dry sands and saturated sands under drained cyclic shear strain. Finally, Youd confirmed that no vertical strain occurs below a limiting or threshold shear strain.

### 2.3.4 Seed and Silver (1972)

Seed and Silver (1972) reported on a few sites that experienced seismic compression during the 1971 San Fernando earthquake, and proposed a semi-empirical method to estimate seismic compression. The method first requires a response analysis of the soil profile to estimate earthquake-induced shear strains. Next, representative samples from the profile are collected and subjected to the estimated vertical effective stress and an equivalent number of shear strain cycles (determined from the design earthquake magnitude). The vertical strain measured from testing each sample is integrated over the corresponding layer of the soil profile, yielding the total settlement. Seed and Silver (1972) validated their method by predicting settlements for shake table tests on dry sand. For these tests, their prediction error was less than
50%. They also provided a field case history where they predicted 6.35 cm (2.5 inches) of settlement for a profile similar to that of a site that had experienced settlements of 10 to 15 cm (4 to 6 inches). The method assumes vertically propagating shear waves in the soil profile.

2.3.5 Pyke et al. (1975)

Pyke et al. (1975) introduced the Jensen Filtration Plant case history in which a compacted fill settled up to 10 cm (4 inches). Pyke et al. (1975) used the procedure outlined by Seed and Silver (1972) but calculated a settlement of about one-third of the recorded settlement. They hypothesized that the uni-directional nature of the simple shear apparatus did not accurately reflect the multi-directional nature of earthquake motions. To study the issue, Pyke et al. performed stress-controlled tests using dry Monterey No. 0 sand on a combined pair of shaking tables whose motions were perpendicular.

Tests reported in Pyke et al. (1975) were performed with one-, two-, and three-directional random motions. The authors concluded that settlements from simultaneous perpendicular horizontal motions are nearly the same as the sum of the settlements of the motions acting separately. As a result, Pyke et al. (1975) recommended that computed settlements based on uni-directional tests should be doubled to more accurately represent field conditions. Additionally, contrary to the conclusions of Whitman and Ortigosa (1969), Pyke et al. concluded that vertical accelerations acting with horizontal accelerations may “cause a marked increase in settlements.”

2.3.6 Tokimatsu and Seed (1987)

Tokimatsu and Seed (1987) provided an updated method to compute seismic compression; their seismic compression method is a simplified version of Seed and Silver’s (1972) method. Where Seed and Silver require a site response analysis to be performed on the soil profile in order to estimate shear strains, Tokimatsu and Seed employ an equation similar to the equation for CSR (see Eqn. 2.3) in the simplified liquefaction evaluation procedure. Relationships between shear strain and volumetric strain are then used to calculate settlements (see Figure 2.3). Tokimatsu and Seed recommend multiplying calculated settlements by a factor of 2 per Pyke et al.’s (1975) suggestion.
This has been the customary practice since then. Tokimatsu and Seed (1987) represents a breakthrough for simple seismic compression estimations. However, it is a graphical procedure and was intended for clean sand only.

2.3.7 Byrne (1991)

Byrne (1991) proposed an alternative version of Martin et al.’s (1975) incremental shear-volume strain coupling equation for seismic compression or pore-water pressure increases. Byrne’s equation can be used to estimate volumetric strains in a “non-simplified” manner. A “non-simplified” procedure in this context requires site response analyses and the resultant strain time history to estimate incremental and total volume changes. As such, it does not rely on a number of equivalent cycles correlation, but requires a numerical site response analysis to be performed. Byrne’s model will be discussed in more depth in Chapter 3.

2.3.8 Chu and Vucetic (1992)

Chu and Vucetic (1992) performed strain-controlled cyclic simple shear tests (Marshall Silver-type device with NGI-type membranes) on brown, low plasticity clay ($CL, PI = 10.5$) at various moisture contents. Similar to the behavior of sands, they discovered that volumetric strains occur according to the amplitude of cyclic shear strain and the applied number of strain cycles. At small strains, like those considered in an earthquake, settlements are virtually independent of water content. Compared to sands, the threshold shear strain of the clay samples was an order of magnitude greater.

2.3.9 Pradel (1998)

In order to make Tokimatsu and Seed’s (1987) procedure less tedious, Pradel (1998) developed equations that follow Tokimatsu and Seed’s charts, enabling the procedure to be easily implemented in a spreadsheet or with other programming. Pradel’s method shows good agreement with Tokimatsu and Seed’s (1987) and Seed and Silver’s (1972) methods for two case histories. However, the procedure is still only intended for use with clean sands and offers only a quick, rough estimate of seismic compression.
2.3.10  Stewart et al. (2001)

Stewart et al. (2001) document cases of permanent vertical and horizontal ground displacements in structural fills caused by the 1994 Northridge earthquake. While several different modes of failure may have occurred, Stewart et al. conclude that many of the displacements were caused by seismic compression in the compacted fills. Stewart et al. (2001) hoped to bring attention to the fact that seismic compression is a serious risk in engineered fills and cuts.

2.3.11  Whang (2001)

In an effort to better understand how compositional factors affect seismic compression, Whang (2001) performed bi-directional, strain-controlled cyclic simple shear tests on four different sands and seven different fill soils. The fill soils contained plastic and/or non-plastic fines.

In general, clean sands were found to undergo more volumetric strain than soils with fines. The clean sands with broad gradations and coarse particles showed about half the volumetric strain of sands with fine grain-particles and narrow gradations. Soils with non-plastic fines performed similarly to clean sands: seismic compression increased with decreasing relative density and was not affected by degree of saturation. The greatest volumetric strains in soils with plastic fines occurred at low compaction energy and low saturation. Whang hypothesized that this was caused by inter-clod void spaces that exist in pre-sheared plastic soils. Greater compaction energy and water content appeared to breakdown the proposed clod structure, thus limiting the seismic compression of the soil. Whang also proposed revisions to Tokimatsu and Seed’s (1987) procedure. These suggestions are treated in Stewart and Whang (2003).

2.3.12  Stewart et al. (2002)

Stewart et al. (2002) performed a comprehensive case study on two occurrences of seismic compression from the 1994 Northridge earthquake. Both cases of settlement occurred on compacted fills; one experienced settlements of up to 18 cm, and the other site experienced settlements of less than 6
The researchers endeavored to explain the recorded settlements using an updated version of Seed and Silver’s (1972) procedure and to quantify the sensitivity of their results. To that end, they collected and tested many samples, performed a detailed site investigation, analyzed recorded ground motions, and performed site response analyses using 1-D and 2-D methods.

From the results of strain-controlled cyclic simple shear testing, Stewart et al. (2002) produced new material models for soils with varying amounts of fines and saturation levels. They found that soils with significant amounts of non-plastic fines behave in a similar manner as clean sands (e.g. as relative compaction increases, seismic compression decreases), but undergo less seismic compression. Similarly, for soils with significant amounts of low-plasticity fines \( (P_I \approx 15) \), as relative compaction or saturation increases, the seismic compression decreases. At low saturation, volumetric strains are similar to those for clean sands at the same relative compaction, but at high saturation, the volumetric strains are one fifth to one half that of clean sands. These findings are in line with Whang’s (2001) inter-clod void hypothesis.

Another important finding of Stewart et al. (2002) is that shear strains in the soil profile near slopes may be much greater than those obtained from a traditional 1-D analysis; a 2-D site response analysis usually provides better results.

### 2.3.13 Stewart and Whang (2003)

Striving to improve upon Tokimatsu and Seed (1987) and Pradel (1998), Stewart and Whang (2003) suggested four improvements:

1. The stress reduction factor \( (r_d) \) given by Tokimatsu and Seed is originally from Seed and Idriss (1971). Recent studies by Seed et al. (2001) show this factor to be generally high; new factors are suggested that incorporate the shear wave velocity in the top 12 meters of the soil.
2. Like many methods, Tokimatsu and Seed’s procedure is based on 15 uniform strain cycles. Fifteen cycles is the assumed number of cycles from a magnitude 7.5 earthquake. For a magnitude different than a 7.5, Tokimatsu and Seed present a chart with correction factors for the volumetric strain. In Stewart and Whang’s method, Liu et al.’s (2001) regression equation is used to estimate the number of cycles. In
this equation, the number of equivalent cycles is a function of earthquake magnitude, source-to-site distance, and site conditions. With the equivalent number of cycles from Liu et al.'s equation, a correction factor can be obtained from a material model.

3. Modulus reduction curves (shear modulus degradation curves) give the shear modulus as a function of shear strain and are an important part of Tokimatsu and Seed’s method. Newer curves from Darendeli and Stokoe (2001) are offered to replace the older curves. Darendeli and Stokoe’s curves are a function not only of shear strain, but also of plasticity index and effective overburden stress. Additionally, other shear modulus degradation curves have been published and may be more applicable.

4. An essential part of Tokimatsu and Seed’s procedure is the volumetric strain material model from Silver and Seed (1971) for No. 20 crystal silica sand. Stewart and Whang (2003) suggest using a material model that incorporates the type of sand, the fines content, and the saturation level.

Stewart and Whang’s (2003) suggestions aim to give better results from the same framework. With these suggestions, Tokimatsu and Seed’s basic procedure is augmented to better estimate settlements in soils with fines and with varying levels of saturation.

2.3.14 Hsu and Vucetic (2004)

Hsu and Vucetic (2004) performed multistage, NGI-type direct simple shear tests on seven different soils. The plasticity index ($P_I$) of the soils ranged from 0 to 34, and the saturation of the samples varied. Their results support earlier findings that no volumetric strain and virtually no change in the soil fabric occurs when the applied cyclic shear strain is less than the threshold shear strain, $\gamma_{tv}$. When the applied cyclic shear strains are above the threshold strain, permanent changes to the soil fabric occur, resulting in a volumetric strain. These authors found that the value of the threshold shear strain can be correlated with the plasticity index of the soil.
2.3.15 Whang et al. (2004)

Focusing on the performance of compacted fills, Whang et al. (2004) continued in the direction of Whang (2001) by performing strain-controlled cyclic simple shear tests on four different fill soils. All soils contained a significant amount of fines; some of the fines were non-plastic and others were of moderate plasticity. Many tests were performed on the soils at varying levels of saturation and relative compaction.

Altogether, Whang et al.’s (2004) results reiterate those of Whang (2001). In general, soils with fines experienced less settlement than clean sands. The effect of saturation was important for soils of medium-plasticity fines (greater volumetric strains occurred at lower saturations), but negligible for soils with non-plastic fines. The occurrence of clod formation in plastic soils enhanced the susceptibility of seismic compression. For construction of new fills, Whang et al. suggest minimizing clod formation by compacting plastic soils to greater than 90% modified proctor relative compaction (RC) and at wetter than optimum water contents.

2.3.16 Stewart et al. (2004)

Expanding on the work of Whang (2001) and Whang et al. (2004), Stewart et al. (2004) performed strain-controlled cyclic simple shear tests on 14 different clean sands, 8 silty sands, and one moderately plastic ($PI = 27$) clay. Results of testing did not show that the volumetric strain of clean sands is affected by the compositional factors of particle size ($D_{50}$), angularity, and gradation ($C_U = D_{60}/D_{10}$). For silty sands, increasing fines content resulted in greater seismic compression for a given relative compaction. This result is seemingly at odds with the conclusions of Whang et al. (2004). However, since Stewart et al. used non-plastic fines, they concluded that the addition of non-plastic fines to clean sand at the same relative compaction increases seismic compressions, but plastic fines tend to decrease seismic compression. The degree of saturation was found to make a significant difference in the amount of seismic compression in soils with fines. At 30% saturation, seismic compressions were lowest, with volumetric strains increasing as the saturation increased or decreased. It was hypothesized that matric suction in the soil increases the stiffness of the specimen, decreases the amount of compression, and is greatest at a saturation of 30%. The degree of saturation showed
little effect for clean sands. As mentioned, Stewart et al. (2004) tested one plastic clay ($FC = 77\%$ and $PI = 27$). Volumetric strains in the plastic clay were approximately one-half of those experienced by low plasticity clays ($PI = 15$). Otherwise, the clay performed similarly to low plasticity clays ($PI = 15$, see Whang (2001) and Whang et al. (2004)). Several new material models were produced that correlate volumetric strain to relative compaction, fines content, saturation, and plasticity index. Conveniently, the new material models are defined by variables in a standard equation, allowing easy use in spreadsheet functions.

2.3.17 Sawada et al. (2006)

Sawada et al. (2006) performed stress-controlled cyclic triaxial tests on Ohgishima sand at 50, 75, and 100 percent saturation. The sands contained a significant proportion of non-plastic fines ($FC = 21.8\%$), and were subjected, in the triaxial test, to irregular motions obtained from actual earthquake motions. Their results showed that for maximum shear strains less than 10%, total volumetric strains increased with decreasing saturation. At face value, this result runs counter to those of Stewart et al. (2004). However, the differences between settlements in the case of Sawada et al. were minimal, and Stewart et al. (2004) used soil mixtures that were 50% fines. Similar to other tests on clean sands, the final volumetric strain for soils with non-plastic fines was best indicated by the maximum shear strain, reiterating results from earlier investigations.

2.3.18 Duku et al. (2006)

Duku et al. (2006) studied the effect of aging on seismic compression using one non-plastic and three plastic unsaturated soils. An overburden stress was applied to the samples for different amounts of time (two minutes or two hours) before the samples were subjected to strain-controlled cyclic simple shear testing. For the non-plastic soil, aging made no significant difference in the amount of seismic compression that occurred. The plastic soil samples that experienced the two hours of applied overburden stress before testing demonstrated 50-70% less volumetric strain than the samples that experienced only two minutes. This finding may explain why few, if any, cases of
seismic compression have been recorded in plastic soils.

2.3.19 Duku et al. (2008)

Using strain-controlled cyclic simple shear tests, Duku et al. (2008) examined the effects of compositional and environmental factors on the seismic compression of sixteen clean sands. As expected, of all compositional and environmental factors, relative density had the greatest effect on the seismic compression of the sands. Other compositional factors (mineralogy, soil fabric, gradation, void ratio “breadth” \( e - e_{\text{min}} \), and particle angularity) showed little influence on the seismic compression susceptibility of the sands. Among the environmental factors, the degree of saturation and age did not influence the seismic compression of the sand. Contrary to the results of Silver and Seed (1971) and Youd (1972), Duku et al. (2008) found that overburden stress can have a significant effect with seismic compression decreasing as overburden increases. Additionally, the stress history of the sands was found to be an influencing environmental factor. It was found that sands with greater OCR experience less volumetric strain. However, Duku et al. concluded that the effects of stress history can be neglected during seismic compression analysis of clean sand fills because most fills become normally consolidated with depth. Besides examining the effects of compositional and environmental factors, Duku et al. (2008) produced several new material models to add to those produced by Stewart et al. (2004).

2.3.20 Yi (2010)

Based on the methods of Tokimatsu and Seed (1987) and Pradel (1998), Yi (2010) developed a shear wave velocity-based procedure to estimate seismic compression. Using a new relationship between relative density and shear wave velocity, Yi’s method estimates volumetric strain from Tokimatsu and Seed (1987)-derived plots (see Figure 2.3).
2.4 Equivalent-Linear Site Response Analysis

The 1D equivalent-linear site response analysis first introduced by Schnabel et al. (1972) is a well-known and widely-used method to estimate the amplification (or de-amplification) of seismic waves as they propagate through a soil profile. In the years since it was first introduced, it has been shown to give a good approximation of real-world conditions. It assumes the vertical propagation of shear waves from a uniform half-space through the horizontal layers of a soil profile (Idriss and Sun 1992). These calculations are performed in the frequency domain. In order to model the non-linear response of soil, an iterative procedure is used.

For each layer in a soil profile, the equivalent-linear procedure begins by defining shear modulus reduction and damping curves for a range of expected shear strains. Figure 2.4 shows examples of these shear modulus reduction and damping curves for a range of overburden stresses. For the first iteration of the algorithm, the response of the soil profile is calculated using the initial conditions of shear modulus and damping. Generally these initial conditions are those corresponding to very small strains. From the shear strain time history response of each layer, a representative shear strain, \( \gamma_{\text{eff}} \), is chosen from the strain time history of each layer (typically, \( \gamma_{\text{eff}} = 0.65 \cdot \gamma_{\text{max}} \)). This representative strain is used to pick values of shear modulus and damping using the aforementioned curves, and the process iterates until modulus and damping values reasonably agree between iterations.

Historically, the ratio of effective shear strain to maximum shear strain \( (\gamma_{\text{eff}}/\gamma_{\text{max}}) \) has taken a range of values in equivalent-linear site response analyses. For example, the SHAKE91 manual (Idriss and Sun 1992) defines the ratio of effective to maximum shear strain as:

\[
\frac{\gamma_{\text{eff}}}{\gamma_{\text{max}}} = \frac{M - 1}{10}
\]  

(2.2)

where \( M \) is the magnitude of the earthquake. However, the computed site response has been shown to not be particularly sensitive to this value (within a certain range), so it is generally taken as 0.65 (Kramer 1996).

Several software packages to perform equivalent-linear site response have
been developed over the years. SHAKE91, ShakeVT, SHAKE2000, and ProShake are all closely based on the original SHAKE code (Schnabel et al. 1972b). More recently, other equivalent-linear site response software have been developed, namely: DEEPSOIL (Hashash et al. 2010), Strata (Rathje and Kottke 2010), and ShakeVT2 (Lasley et al. 2014). For more information on the equivalent-linear procedure, in general, and the code written for this research, in particular, see Appendices I and J.

2.5 Stress-Based Simplified Liquefaction Evaluation Methods

The “simplified” liquefaction evaluation procedure was proposed separately by Whitman (1971) and Seed and Idriss (1971). This simplified procedure did not require site-specific response analysis, nor an earthquake time history to determine induced shear stresses (i.e. demand), hence the name “simplified” procedure. The core of the simplified procedure is the cyclic stress ratio (CSR):

\[
CSR = \frac{\tau_{\text{avg}}}{\sigma'_{v0}} = 0.65 \frac{a_{\text{max}}}{g} \frac{\sigma_v}{\sigma'_{v0}} r_d
\]

where \(\tau_{\text{avg}}\) is the average amplitude of the seismically-induced shear stress, \(\sigma'_{v0}\) is the initial effective overburden stress, 0.65 is an arbitrary ratio of average shear stress to maximum shear stress \((\tau_{\text{avg}}/\tau_{\text{max}})\) of the earthquake motion, \(a_{\text{max}}\) is the peak ground acceleration at the surface of the profile, \(g\) is the acceleration due to gravity, \(\sigma_v\) is the total overburden stress, and \(r_d\) is the stress reduction factor to account for the non-rigid response of the soil column. By plotting \(CSR\) versus SPT blow count (or the results of any other in-situ test for soil state) for each liquefaction and non-liquefaction site in a case history database, a capacity (i.e. limit state) curve to divide liquefaction and non-liquefaction sites can be formed (see Figure 2.5). This curve defines the cyclic resistance ratio \((CRR)\).

The cyclic resistance ratio is the cyclic stress ratio at which liquefaction occurs in a specific number of cycles (generally 15 cycles for a \(M_w\,7.5\) earthquake) and is a function of the soil density. Traditionally, a factor of safety
against liquefaction is calculated as the ratio of cyclic resistance ratio and cyclic stress ratio (Eqn. 2.3).

\[
FS = \frac{CRR}{CSR}
\]  

(2.4)

Over the years, the procedure has undergone a number of improvements and additions (e.g. Yould et al. 2001). The most notable of these changes are the additions of magnitude scaling factor (MSF), overburden correction factor (Kσ), and the correction for static shear stresses (Kα). The magnitude scaling factor corrects for the durations of earthquakes with magnitudes other than 7.5. The Kσ and Kα correction factors were needed because the cyclic stress ratio required to cause liquefaction changes with effective overburden stress and in the presence of an initial static shear stress (i.e. non-level ground conditions). Thus, the factor of safety now includes these corrections:

\[
FS = \frac{CRR}{CSR} \cdot MSF \cdot K_\sigma \cdot K_\alpha
\]  

(2.5)

where CRR is the smallest cyclic stress ratio at which liquefaction occurs for a Mw 7.5 earthquake and under one atmosphere of initial effective overburden stress. The cyclic resistance ratio is commonly correlated to SPT blow count corrected for fines content, but CRR curves that are correlated to CPT tip resistance or shear wave velocity are also common.

Following on the work of others (e.g. Liao et al. 1988; Youd and Noble 1997; Toprak et al. 1999), Cetin et al. (2004) developed a probabilistic, stress-based liquefaction evaluation procedure using SPT case histories. The probabilistic procedure allows for the incorporation of uncertainties (in both input parameters and the location of the CRR curve) into the analysis. Cetin et al. (2004) expanded the case history database and corrected or removed erroneous cases. Additionally, they developed a new stress reduction coefficient and incorporated fines content, effect of overburden stress, and duration weighting factors into the formulation of the CRR curve using Bayesian updating.

Idriss and Boulanger (2008) presented deterministic, stress-based simplified liquefaction evaluation procedures for the SPT and CPT. Their procedures retain the same general form of the Youd et al. (2001) procedure and provide updated relationships for rd, MSF, Kσ, and the overburden correction factor.
for SPT blow count, $C_N$. Building on that foundation and a reevaluation of the SPT case history database (Boulanger et al. 2012), Boulanger and Idriss (2012) presented a probabilistic update to the 2008 deterministic SPT procedure.

The energy-based liquefaction evaluation procedure presented herein uses the SPT case history database revised by Boulanger et al. (2012) and some of the probabilistic methods of Cetin et al. (2004) and Boulanger and Idriss (2012) (see Chapter 6).

2.6 Energy-Based Liquefaction Evaluation Methods

Dissipated energy per unit volume of soil is the cumulative area bound by stress-strain hysteresis loops. Figure 2.6 shows the stress-strain hysteresis loops from a stress-controlled cyclic simple shear test. Nemat-Nasser and Shokooh (1979) were the first to suggest the use of dissipated energy to estimate pore water pressure increases in saturated, undrained sands. They recognized that densification of drained sands or liquefaction in undrained sands involves the rearrangement of sand particles which, in turn, requires an expenditure of energy. Using dissipated energy, they accurately predicted pore pressure increases for the results of cyclic laboratory tests on undrained sands.

Following the pioneering work of Nemat-Nasser and Shokooh (1979), dissipated energy has been implemented as the damage metric in a number of liquefaction evaluation methods. Several of these methods are detailed below. They are primarily organized here by the manner in which the capacity (i.e. limit state) curve was developed. Presented first are the methods whose capacity curves are obtained from field case histories with in-situ measurements of soil properties. Next, procedures that define the capacity curves using the results of laboratory tests are presented. Not all of the liquefaction evaluation methods included in this section are based on dissipated energy; several are based on other measures of energy. They all aim to account for the damaging effects of the entire earthquake motion.
2.6.1 Field-Based Capacity Curves

The earliest liquefaction evaluation procedures used the Gutenberg-Richter (1956) relationship and some attenuation relationship to obtain the energy at the site of interest. Other procedures use site-response analyses or number of equivalent cycles correlations to estimate the energy. In all procedures described in this section, energy is determined for each case history in a database, and the capacity curve is estimated directly from this data without relying on laboratory results. For forward analysis of these procedures, the demand is obtained in the same way as the energy was determined for regression of the capacity curve. While there may be a discrepancy between the actual and estimated dissipated energies, the estimated demand energy of these procedures is consistent with the capacity curve energy. The most recent stress-based simplified procedures are developed in the same way; laboratory results have an effect on the development of the stress-based capacity curves (e.g. the overburden stress correction factor), but are not directly used for capacity curve regression.

Davis and Berrill (1982)

Beginning with Davis and Berrill (1982) several energy-based liquefaction methods have used the Gutenberg-Richter (1956) energy relationship to estimate the dissipated energy leading to liquefaction. The Gutenberg-Richter relationship is:

\[ E_0 = 10^{1.5M+1.8} \]  

where \( E_0 \) is the total radiated energy (kJ) from a magnitude \( M \) earthquake. Davis and Berrill (1982) begin with the Gutenberg-Richter total radiated energy at the source and apply a geometric spreading attenuation to obtain the corresponding energy at the site. The portion of this reduced energy arriving at the site is dissipated as a function of the effective overburden stress and SPT blow count. Thus, the dissipated energy at the site and layer of interest is a function of magnitude, site-to-source distance, SPT blow count, and effective overburden stress. Using 57 liquefaction/no-liquefaction case histories, Davis and Berrill (1982) proposed a capacity curve that is a function of the corrected SPT blow count and uses the dissipated energy described
above as the damage metric. They were quick to point out some issues with their proposed approach, for example: 1. the model doesn’t take into account directivity effects or other non-uniform energy radiation patterns; 2. site-to-source distances, in many cases, are difficult to establish with accuracy; 3. their SPT case history database was sparse and only contained results for fine sands. A more significant issue that Davis and Berrill (1982) did not mention is the application of a global measure of energy to a single layer of soil which is a crude approximation.

**Berrill and Davis (1985)**

Berrill and Davis (1985) aimed to improve upon the previous work. They retained the Gutenberg-Richter (1956) relationship but allowed for material attenuation as well as geometric spreading. In addition, they used a new dissipated energy-excess pore pressure model with a non-linear relationship (the Davis and Berrill 1982 method uses a linear relationship). Using 90 liquefaction/no-liquefaction case histories and the improved demand term, Berrill and Davis (1985) again obtained a capacity curve that is a function of corrected SPT blow count.

**Law et al. (1990)**

Following the general outline of Davis and Berrill (1982), Law et al. (1990) defined an energy-based demand term using the Gutenberg-Richter relationship that is a function of magnitude and distance and a capacity term that is a function of corrected SPT blow count. They fit their capacity curve using the results of 136 liquefaction/no-liquefaction case histories and provided separate curves for sand and silty sand. The form of their demand term allows for regime-specific attenuation by changing the value of $B$:

$$T = \frac{10^{1.5M}}{R^B}$$

where $T$ is the demand term, $M$ is the magnitude of the earthquake, $R$ is the site-to-source distance, and $B$ is the energy-attenuation parameter which they specify to be $4.3 \pm 0.5$ for the ‘highly-fractured rock’ of the western United States and Canada.
Trifunac (1995)

Based on the 90 case histories from Berrill and Davis (1985), Trifunac (1995) proposed five capacity curves that are a function of corrected SPT blow count and various other parameters. The first of these capacity curves uses the Gutenberg-Richter energy relationship and is simply a modification of the Davis and Berrill (1982) capacity curve. The second one of these obtains the demand energy term from the Fourier amplitude spectrum of the earthquake motion (via a regression model for the amplitude spectrum). The third Trifunac (1995) capacity curve estimates the demand energy at the site using the peak velocity and the duration, the fourth uses the Fourier amplitude of velocity at a period of 0.39 seconds, and the final uses the peak velocity, duration, and the Lamé constant \( \mu \). In all five cases, the demand energy was calculated for each case history and the capacity curve was defined as a function of SPT blow count.

Kayen and Mitchell (1997)

Kayen and Mitchell (1997) developed a procedure based on Arias intensity. Arias intensity is defined as (Arias 1970):

\[
I_a = \frac{2\pi}{g} \left[ \int a_x^2(t)dt + \int a_y^2(t)dt \right] \tag{2.8}
\]

where \( a_x \) and \( a_y \) are horizontal and orthogonal components of an acceleration recording, and \( g \) is the acceleration due to gravity in the same units of acceleration. Kayen and Mitchell (1997) calculated the Arias intensity for several liquefaction/no-liquefaction case histories that had nearby ground motion recordings. After correcting the Arias intensity for depth in the profile and the SPT blow count for fines content, Kayen and Mitchell (1997) fit a capacity curve to the case history data. They also fit a curve for CPT tip resistance. For forward analyses, the Arias intensity demand can be calculated using recorded motions from similar magnitude-distance scenarios or estimated using a regressed relationship by Kayen (1993, unpublished PhD dissertation) which is a function of magnitude and site-to-source distance. Thus, the Kayen and Mitchell (1997) procedure either depends on site-specific earthquake time histories or an energy attenuation relationship.
Green (2001) proposed a liquefaction evaluation procedure based on an SPT liquefaction/no-liquefaction case history database. The dissipated energy for each case history was estimated using the hysteretic definition of damping ratio, shear modulus reduction and damping curves, and the number of equivalent cycles concept. In Green’s procedure, the normalized energy demand ($NED$) is estimated for a given earthquake scenario using inputs similar to those of the stress-based procedure:

$$NED = \frac{2\pi D_\gamma}{\sigma_m^0 G_\gamma} \cdot \left[ 0.65 \frac{a_{max}}{g} \sigma_v r_d \right]^2 \cdot n_{eq} \quad (2.9)$$

where the squared quantity, $0.65 \cdot a_{max}/g \cdot \sigma_v \cdot r_d$, yields an approximation of the average shear stress, $\tau_{avg}$, in the same way as the stress-based simplified procedures (Eqn. 2.3). The variable $n_{eq}$ is the number of equivalent cycles (the basis for the stress-based MSF). The values of $D_\gamma$ and $G_\gamma$ are obtained from shear modulus reduction and damping curves and correspond to the shear strain developed by $\tau_{avg}$. Since this general form is used in the procedure proposed herein, the method of obtaining $D_\gamma$ and $G_\gamma$ will be explained in Chapter 6. Green’s (2001) normalized energy capacity term, $NEC$, is defined as:

$$NEC = 1.195 \cdot 10^{-4} \exp(0.185 \cdot N_{1,60cs}) \quad (2.10)$$

where $N_{1,60cs}$ is the SPT blow count corrected for overburden stress, energy, and fines content, among other things. Both $NED$ and $NEC$ are terms of dissipated energy normalized by the mean initial effective confining stress.

Green (2001) also showed that the dissipated energy from laboratory testing cannot be directly related to the dissipated energy from equivalent-linear site response analyses. The reason is that equivalent-linear site response analyses assume a constant value of shear modulus and damping for the entire loading time history, neglecting the additional dissipated energy that results from the softening of the soil at high excess pore pressures. In order to compare laboratory dissipated energies to equivalent-linear dissipated energies, Green proposed a correction factor be applied to the laboratory energies.
Mayfield (2007)

Mayfield (2007) proposed a liquefaction evaluation procedure based on $CAV_5$, the cumulative absolute velocity with a threshold of 5 cm/s. It is defined as (Kramer and Mitchell 2006):

$$CAV_5 = \int \chi \cdot |a(t)| \, dt$$  \hspace{1cm} (2.11)

where

$$\chi = \begin{cases} 
0 & \text{if } |a| < 5 \text{ cm/s}^2 \\
1 & \text{if } |a| \geq 5 \text{ cm/s}^2 
\end{cases}$$  \hspace{1cm} (2.12)

and $a$ is an acceleration time history. For a liquefaction/no-liquefaction case history database, Mayfield calculated $CAV_5$ from nearby ground motions, where available, or using an attenuation relationship developed by Kramer and Mitchell (2006). The resulting capacity curve is a function of both corrected SPT blow count and $CAV_5$. For forward analysis, the Mayfield procedure relies on the availability of earthquake recordings or the $CAV_5$ attenuation relationship.

Jafarian et al. (2014)

Jafarian et al. (2014) presented a liquefaction capacity curve based on cumulative kinetic energy density (CKED). For a given situation, CKED is a function of the effective density of the soil and the specific energy density (SED) of the incoming motion. SED, in turn, is defined as:

$$SED = \int v^2 \, dt$$  \hspace{1cm} (2.13)

where $v$ is the velocity time history at the surface of the profile. Jafarian et al. (2014) developed a regression equation for SED using 1436 acceleration time histories from 60 earthquakes and the soil profiles of Cetin (2000). Their proposed regression equation for SED is a function of magnitude, site-to-source distance, fault type, and the mean shear wave velocity of the upper
30 meters of the profile. Using this regression equation and liquefaction/no-liquefaction case history databases, Jafarian et al. developed their liquefaction capacity curve which is a function of CKED, effective overburden stress, corrected SPT blow count, and fines content.

In many ways, the Jafarian et al. (2014) procedure is similar to the procedure proposed herein (Chapter 6): equivalent-linear site response analyses are used to develop an equation to predict dissipated energy in a more simplified manner (i.e. a number of equivalent cycles correlation is developed in Chapter 4).

### 2.6.2 Laboratory-Based Capacity Curves

Several energy-based capacity curves have been developed from the results of laboratory testing. In most cases, the resulting capacity curve of the lab test is converted for use with an in-situ measurement such as SPT blow count. Despite the conversion to field test results, the original curve is generally regressed from the lab results without input from case history data. For forward analyses, this makes the demand energy difficult to determine in a manner consistent with the capacity energy.

**Case Western**

A large amount of research in energy-based liquefaction evaluation has been performed by researchers at Case Western Reserve University. This section discusses their work.

Based on the results of strain-controlled hollow cylinder torsional shear tests using sinusoidal loadings, Figueroa et al. (1994) provided an equation for the dissipated energy to liquefaction which is a function of effective confining stress and relative density of the sand. Their tests were performed on specimens with relative densities of 50, 60, and 70% and at effective confining stresses of 41, 83, and 124 kPa.

Similar to the work of Figueroa et al. (1994), Liang et al. (1995) performed hollow cylinder torsional shear tests with specimens at the same relative densities and under the same effective confining stresses, but these tests
used stress-controlled random earthquake-type loadings instead of strain-controlled sinusoidal loadings. They also provided an equation for the dissipated energy to liquefaction using the same functional form as Figueroa et al. (1994). They concluded that the differences between the regression coefficients for random loading and for sinusoidal loading were not statistically significant; in other words, the regressions can be considered to be the same. Both Figueroa et al. (1994) and Liang et al. (1995) suggest the use of their regressed equations in connection with forward analysis of liquefaction potential.

The proposed liquefaction evaluation procedure base on the Figueroa et al. (1994) and Liang et al. (1995) lab results is given in more detail in Liang (1995). The procedure requires torsional shear tests performed on recovered soil samples from the site of interest to determine the capacity dissipated energy. The demand is determined using site response analyses with a characteristic earthquake input motion. In the site response analyses, a nonlinear, lumped-mass model is used to account for soil softening as loading progresses and pore water pressures increase.

**Davis and Berrill (1996)**

Davis and Berrill (1996) use the results of equivalent-linear site response analyses to evaluate liquefaction potential. From the site response analyses, the frequency-domain displacement at the surface of the profile is used to calculate the dissipated energy demand. This dissipated energy is then used to estimate the excess pore water pressures using correlations obtained from laboratory data (Simcock et al. 1983). If the excess pore water pressures exceed the initial effective stress, liquefaction is considered to have occurred in the given layer. Unlike many of the other procedures, the Davis and Berrill (1996) procedure does not provide a limit state curve, but relies on an excess pore pressure model instead.

**Jafarian et al. (2012)**

Jafarian et al. (2012) performed a number of strain-controlled hollow cylinder cyclic torsional shear tests on Toyoura sand specimens. The specimens had relative densities ranging from 30 to 75% and experienced effective confining stresses ranging from 55 to 166 kPa. For each test, they calculated the
dissipated energy to liquefaction normalized by the initial effective vertical stress, and from these results they proposed a capacity curve that is a function of the at-rest earth pressure coefficient \((K_0)\) and the overburden- and energy-corrected SPT blow count (via the relative density of the specimens). They verified their capacity curve using dissipated energies calculated from stress and strain time histories from centrifuge testing, shaking table testing, and downhole array data from the Superstition Hills earthquake. Thus, for forward analysis of liquefaction potential, non-linear site response analyses are needed.

**Kokusho and Mimori (2015)**

Kokusho and Mimori (Kokusho 2013; Kokusho and Mimori 2015) developed an energy-based procedure with a capacity curve derived from the results of stress-controlled cyclic triaxial tests. They performed these tests on Futtsu sand specimens with relative densities ranging from 30 to 70% and fines contents ranging from 0 to 20%. From the results they correlated the normalized dissipated energy to liquefaction (normalized by the effective confining stress) to the cyclic stress ratio required to cause liquefaction in 20 cycles. This correlation they combined with a CSR-based capacity curve to obtain a capacity energy curve that is a function of SPT blow counts. For forward analyses, the capacity energy is compared with demand energy obtained from a velocity time history of an equivalent-linear site response analyses.

### 2.6.3 Summary of Energy-based Procedures

Many energy-based liquefaction evaluation procedures have been proposed. The field-based procedures depend on earthquake motion time histories or attenuation relationships. The laboratory-based procedures either require laboratory testing using soil from the site or compare the dissipated energy from site response analyses with the dissipated energy required to cause liquefaction in laboratory tests. For engineers accustomed to the existing stress-based simplified procedures, the energy-based liquefaction evaluation procedures would be foreign, difficult to implement, and require more resources to complete. Additionally, neither the existing energy-based nor the stress-based procedures are easy to implement for tectonic regimes like the stable-continental regime of the central-eastern United States.
2.7 References


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2.8 Figures

Figure 2.1: Triaxial specimen of Monterey 0/30 sand with vacuum applied.
Figure 2.2: A cyclic simple shear specimen in preparation.
Figure 2.3: Volumetric strain as a function of shear strain and a) relative density ($D_r$), or b) SPT blow count. (Tokimatsu and Seed, 1987) [Fair use.]
Figure 2.4: Shear modulus and damping degradation as a function of strain and overburden stress (Darendeli and Stokoe 2001). [Fair use.]
Figure 2.5: Cyclic stress ratio versus corrected SPT blow counts for liquefaction and non-liquefaction case histories for $M7.5$ earthquakes. (Seed et al. 1985) [Fair use.]
Figure 2.6: Stress-strain hysteresis loops of a stress-controlled cyclic simple shear test.
Chapter 3

Manuscript #1: An Approach for Estimating Seismic Compression Using Site Response Analyses

The following manuscript has been submitted to ASCE’s Journal of Geotechnical and Geoenvironmental Engineering.

Samuel Lasley made the following contributions:

- With Chen, established a testing procedure for the GCTS equipment and trained Chen on its use
- Performed the index testing of the sand with Chen (maximum and minimum void ratio tests, sieve analyses)
- Reduced all laboratory testing data
- Examined various functional forms for $r$, the exponential of the Richart-Newmark method, as well as alternate volumetric strain functional forms.
- Selected the best functional forms for $r$ and $N$; performed the regressions for both
- Used the Richart-Newmark and Byrne methods to estimate the volumetric strain under irregular strain loadings
- Performed all statistical analyses and prepared all figures and tables
• Wrote the first draft of the manuscript and incorporated subsequent edits

Dr. Green made the following contributions to this manuscript:

• Provided the impetus for using the Richart-Newmark method to estimate volumetric strains in sands
• Directed Chen in his laboratory work

Qingsheng Chen contributed in the following ways:

• Performed virtually all the laboratory cyclic simple shear testing and some of the index testing of the sand

Dr. Rodriguez-Marek:

• Provided statistical advice, including using the bootstrapping technique

Dr. Green and Dr. Rodriguez-Marek both:

• Provided valuable feedback throughout the research
• Edited the manuscript
An Approach for Estimating Seismic Compression Using Site Response Analyses

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3.1 Abstract

Seismic compression is the accrual of volumetric strains in unsaturated soils caused by cyclic loading and has caused significant damages to buildings and other structures during earthquakes. To date, the available methods for predicting the severity of seismic compression have mainly been “simplified” procedures, in which a number of equivalent cycles is used to represent the duration of earthquake loading. Often, however, the number of equivalent cycles is computed inconsistently with the underlying mechanics of seismic compression. Proposed herein is a “non-simplified” procedure for predicting the severity of seismic compression. The procedure is based on a modified version of the Richart-Newmark cumulative damage hypothesis, wherein volumetric strain is used as the damage metric. The proposed model was calibrated using data from 460 constant amplitude sinusoidal strain-controlled cyclic simple shear tests performed on clean sand and validated using test data from samples subjected to variable amplitude sinusoidal and earthquake loadings. In addition to predicting the severity of seismic compression, the proposed model can be used to compute number of equivalent shear strain cycles for use in simplified models, consistent with the seismic compression
phenomenon. In comparison with other proposed “non-simplified” models for computing seismic compression, the proposed model gives good agreement with the measured seismic compression.

3.2 Introduction

The objective of the research presented herein is the development of a novel approach for predicting the severity of seismic compression. Seismic compression is the phenomenon in which unsaturated/partially-saturated soils undergo volumetric strain (densification) when subjected to earthquake motions and other types of cyclic loading. This phenomenon has caused significant damage to buildings and other structures, especially those built upon compacted fills (e.g., Slosson 1975; Siddharthan and El-Gamal 1996; Stewart et al., 2002). The proposed methodology uses strain time histories obtained from site response analyses in contrast to existing “simplified” approaches which use a simpler parameterization of the time histories.

A large body of research has been performed to understand seismic compression and to predict its magnitude. Silver and Seed (1971) showed that the magnitude of seismic compression is a function of the amplitude of the applied cyclic shear strain and the relative density of the soil. Based on this work, Seed and Silver (1972) proposed one of the first “simplified” methods to estimate seismic compression. In this context, “simplified” methods are those that do not require numerical site response analyses be performed to estimate the shear stresses or strains induced by earthquake shaking. These methods often represent the earthquake loading as a sinusoidal motion with a duration quantified by number of equivalent cycles (e.g., Seed et al. 1975).

Since the initial procedure proposed by Seed and Silver (1972), several other simplified procedures have been proposed to predict the severity of seismic compression (e.g., Tokimatsu and Seed 1987; Pradel 1998; Stewart and Whang 2003; Duku et al. 2008). Additionally, several laboratory studies have examined the effect of saturation, relative density, fines content, mineralogy, fabric, OCR, plasticity index, overburden stress, and multi-directional shaking on seismic compression (e.g., Pyke et al. 1975; Chu and Vucetic 1992; Whang 2001; Hsu and Vucetic 2004; Stewart et al. 2004; Whang et al. 2004; Sawada et al. 2006; Duku et al. 2006, 2008; Carter et al. 2014).
As a result of this work, there is a good understanding of environmental and compositional factors that influence the magnitude of seismic compression.

In comparison to simplified procedures, very few “non-simplified” procedures have been proposed for evaluating seismic compression, Finn and Byrne (1976) being one of them. In this context, a “non-simplified” procedure is one that requires numerical site response analyses be performed, wherein the earthquake shaking is represented in a form similar to recorded motions (e.g., an acceleration time history). The main advantage of a non-simplified procedure is that it does not rely on number of equivalent cycles correlations to represent the earthquake shaking. The disadvantages are that a more detailed characterization of the site being analyzed is required and additional expertise and effort are required to select appropriate ground motions and to perform numerical site response analyses. However, most of these barriers have been reduced over the years as cost-effective methods for characterizing sites for dynamic analyses are becoming readily available (e.g., SASW/-MASW) and as protocols for selecting input time histories and performing the site response analyses have been developed (e.g., Kottke and Rathje 2008; Bradley 2012; Stewart and Kwok 2008).

The Finn and Byrne (1976) method for evaluating seismic compression is based on the Martin et al. (1975) model for computing volumetric strain in dry sands. This model has since been updated by Byrne (1991) and yields the cumulative volumetric strain at each half cycle of shear strain loading, whether the loading is constant or variable amplitude. As proposed by Finn and Byrne (1976), the shear strain time history used to compute the volumetric strain in a given layer in a soil profile is obtained from a numerical site response analysis, and the magnitude of the seismic compression is equal to summation of the volumetric strains in each layer in the profile. Inherent to the Finn and Byrne approach is the decoupling of the site response and volumetric strain computations, which allows equivalent linear site response analyses to be used (e.g., Schnabel et al. 1972). Alternatively, site response analyses could be performed using software that employ advanced elasto-plastic constitutive models to model the dynamic response of the soil (e.g., SUMDES: Li et al. 1992). Inherent to this approach is the coupling of shear and volumetric strains, yielding the magnitude of seismic compression directly. However, the effort and expertise required to calibrate advanced elasto-plastic constitutive models for use in site response analyses often limits their use to only high-end projects. In contrast, performing equivalent linear
site response analyses has become state-of-practice in many places, making non-simplified procedures similar to the one proposed by Finn and Byrne (1976) a viable option for predicting seismic compression in today’s practice.

Proposed herein is a non-simplified approach for predicting seismic compression that builds on that proposed by Finn and Byrne (1976). In the proposed approach volumetric strains are computed using a modified version of the Richart-Newmark (R-N) fatigue model (Richart and Newmark, 1948), wherein volumetric strain is used as the damage metric. An extensive laboratory testing program was performed to develop, calibrate, and validate the modified R-N model for clean sands. The proposed approach allows seismic compression to be predicted more rigorously than using simplified procedures, without the onus of calibrating advanced elasto-plastic constitutive models. Additionally, the modified R-N model proposed herein can be used to compute number of equivalent strain cycles for use in simplified procedures. The advantage of this is that a consistent damage metric (i.e., volumetric strain) is used to equate earthquake motions to an equivalently damaging (i.e., induces the same volumetric strain) sinusoidal motion having a specified number of cycles. This is in contrast to the number of equivalent cycle correlations commonly used with simplified seismic compression approaches, where the equivalent cycle correlations are developed using damage metrics other than volumetric strain (e.g., Green and Terri, 2005).

This paper starts by presenting an overview of fatigue models including: a description of the Palmgren-Miner (P-M) model, which has been extensively used in geotechnical earthquake engineering, the original R-N model, and the Byrne (1991) volumetric strain model. The results of sinusoidal cyclic simple shear tests, which were used to develop and calibrate the modified R-N model, are presented next. The modified R-N model is then validated for computing seismic compression using results from tests in which the samples were subjected to variable amplitude sinusoidal and earthquake loadings. A comparison of measured versus predicted volumetric strains is then made, where the modified R-N, Byrne (1991), and P-M models are used to make the predictions. Finally, a brief case history is presented to illustrate the proposed non-simplified approach for evaluating seismic compression.
3.3 Fatigue Models

Macro cumulative damage fatigue models were the focus of considerable research from the 1940s through the 1960s. Common to all macro cumulative damage fatigue models is the assumption that when a cyclic load above a certain magnitude is applied to a specimen, internal “damage” occurs in the specimen, such that its service life is shortened. As the loading continues, the damage accumulates until the specimen fails. This concept is illustrated in Figure 3.1, wherein the horizontal axis is the number of applied load cycles ($n$) and the vertical axis is degree of damage ($D$). As shown in this figure, failure occurs when the degree of damage reaches 100% (i.e., $D = 1$), with the corresponding number of load cycles designated as $N$.

Features that distinguish one cumulative damage fatigue model from another are: the assumed nature of damage accumulation as a function of the number of cycles of loading (e.g., linear accumulation, power function accumulation); whether the nature of damage accumulation is assumed to be a function of the amplitude of the load (i.e., load-dependent versus load-independent models); and whether the nature of damage accumulation is assumed to be influenced by previous loading (i.e., interaction versus interaction-free models) (e.g., Kaechele, 1963). Figure 3.2 conceptually shows the accumulation of damage in similar specimens subjected to cyclic loading of different amplitudes ($S_x$).

As intuitively expected, the specimen subjected to the largest amplitude load fails in the fewest number of cycles, the specimen subjected to the second largest amplitude load fails in the second fewest number of cycles, and so on. The distinction between load-dependent and load-independent models is highlighted when the number of load cycles is normalized by the respective number of cycles to cause failure in the specimens (i.e., cycle ratio, $R = n/N$). If the cumulative damage curves for all load amplitudes collapse into one curve, such as shown in Figure 3.3, the fatigue model is referred to as load-independent. On the contrary, if cumulative damage curves do not collapse into one curve (e.g., Figure 3.3), the fatigue model is referred to as load-dependent.

If the relationship between cumulative damage and number of cycles corresponding to a specified load amplitude is not influenced by previous load cycles, the fatigue model is referred to as interaction-free. On the contrary, a model that assumes that the nature of the accumulation of damage is altered by prior loading is referred to as an interaction model (e.g., Kaechele,
1963; Stallmeyer and Walker, 1968). Figure 3.3 is an example of a load-dependent, interaction-free model. In contrast, a load-dependent, interaction model would have a family of damage curves for each load amplitude as opposed to a single curve; the damage accumulated would follow a given curve based on the amplitude of the current applied load and the previous load history.

3.3.1 Palmgren-Miner (P-M) Model

The Palmgren-Miner (P-M) fatigue model (Palmgren 1924; Miner 1945) is a load independent, interaction free model that assumes that damage accumulates linearly, as shown in Figure 3.4. Thus, damage accumulates according to the form:

\[ D = \sum_{i=1}^{m} \frac{n_i}{N_i} \]

(3.1)

where \( m \) is the number of load sets (i.e., the number of different amplitudes of the peaks in the load time history), \( n_i \) is the number of cycles in load set \( i \), and \( N_i \) is the number of cycles to 100% damage for the amplitude of load set \( i \). Inherent to this model is the assumption that an increment in damage from a single cycle is directly proportional to the amplitude of the cycle (Seed et al. 1975; Annaki and Lee 1977; Liu et al. 2001). Also, the sequence of various amplitudes of cyclic loading does not affect the cumulative damage estimation at the end of loading, as illustrated in the right two panes of Figure 3.4. This is in contrast to load-dependent (interaction or interaction-free) cumulative damage models in which the sequence of load amplitudes affects the shape of the damage path and the accumulated damage at the end of loading (e.g., Green and Lee 2006; Carter et al. 2014). Consistent with the assumptions inherent to the P-M model, the model is also classified as a high-cycle fatigue model (Green and Terri 2005). This is because dissipated energy is used as the damage metric and the direct proportionality of the load amplitude and increment in damage implies the material remains in the linear range and has a constant damping ratio.

The P-M model is encapsulated in the equivalent-number-of-cycles concept which was introduced to geotechnical earthquake engineering in the late 1960s
and early 1970s (Lee and Chan 1972; Seed et al. 1975; Annaki and Lee 1977). The equivalent-number-of-cycles concept is widely used in geotechnical earthquake engineering and, in particular, for the analysis of liquefiable soils. Additionally, the equivalent-number-of-cycles concept has been adapted for use in seismic compression estimations (e.g. Tokimatsu and Seed 1975; Duku et al. 2008). However, unlike many fatigue-related phenomena in which the accumulation of “damage” is neither directly observable nor measurable at the macroscopic level, the accumulation of volumetric strain in dry and partially saturated sandy soils subjected to cyclic loading is both directly observable and measurable. Detailed laboratory tests (e.g., Silver and Seed 1971; Stewart et al. 2004; Whang et al. 2004; Duku et al. 2006, 2008) have shown that the rate of volumetric strain accumulation decreases with the increasing number of cycles. Additionally, the accumulation of volumetric strain when plotted as a function of R varies as a function of both load amplitude and load history (i.e., seismic compression is a load-dependent, interaction fatigue phenomenon). Based on this observed soil behavior, the validity of using the P-M model to compute number of equivalent cycles for use in evaluating seismic compression is questionable.

### 3.3.2 Richart-Newmark (R-N) Model

The Richart-Newmark (R-N) model, as originally proposed by Richart and Newmark (1948), is a load-dependent, interaction-free fatigue model and was proposed for use in seismic compression analyses by Green and Lee (2006). The R-N model has the form:

\[ D = R^r \]  \hspace{1cm} (3.2)

where \( r \) is a curve fitting parameter that varies as a function of the amplitude of loading. The model is plotted in Figure 3.5, and as shown in the left pane of this figure, the damage accumulation path for constant-amplitude cyclic loadings varies as a function of the amplitude of the applied load (i.e., the damage accumulation curve for each load amplitude has a different associated value of \( r \)). For variable-amplitude loading conditions, Eqn. 3.2 expands to
\( D_i = \left[ (D_{i-1})^{1/r_i} \left( \frac{n_i}{N_i} \right) \right]^{r_i} \text{ for } i = 1 \text{ to } m \) (3.3)

where \( D_i \) is the total damage after the \( i^{th} \) set of constant-amplitude cycles of loading, \( r_i \) is the \( r \) value corresponding to the amplitude of the \( i^{th} \) set of loading cycles, \( n_i \) is the number of cycles in the \( i^{th} \) set of loading cycles, \( N_i \) is the value of \( N \) corresponding to conditions of the \( i^{th} \) set of loading cycles, and \( m \) is the number of loading sets. The damage accumulation path for a variable-amplitude loading “jumps” from one curve for a given load amplitude to another as the cyclic amplitude changes. For each “jump”, the accumulated damage stays the same, but the cycle ratio will change. The center and right panes of Figure 3.5 illustrate how the damage accumulation paths jump from one constant-amplitude curve to another. Also illustrated in this figure is how the accumulated damage at the end of loading differs depending on the sequencing of the loading cycles, an inherent characteristic of a load-dependent fatigue behavior.

### 3.3.3 Byrne (1991) Model

Simplifying a previous model by Martin et al. (1975), Byrne (1991) proposed the following model to estimate volumetric strains in dry sands:

\[ \varepsilon_v = \sum_i (\Delta \varepsilon_{v,1/2})_i \] (3.4)

where \( \varepsilon_v \) is the accumulated volumetric strain at the end of loading and \( (\Delta \varepsilon_{v,1/2})_i \) is the increment in volumetric strain for the \( i^{th} \) half shear strain cycle having an amplitude \( \gamma_i \):

\[ (\Delta \varepsilon_{v,1/2})_i = 0.5 \gamma_i C_1 \exp \left[ -C_2 \frac{\varepsilon_{vi}}{\gamma_i} \right] \] (3.5)

The variables \( C_1 \) and \( C_2 \) are material parameters, and \( \varepsilon_{vi} \) is the volumetric strain at the beginning of the \( i^{th} \) load increment. Byrne (1991) provided
equations to estimate $C_1$ and $C_2$:

$$C_1 = 7600D_r^{-2.5}$$  \hspace{1cm} (3.6)$$

$$C_2 = 0.4/C_1$$  \hspace{1cm} (3.7)$$

where $D_r$ is the relative density of the sand in percent.

Although Martin et al. (1975) or Byrne (1991) never make reference to fatigue theories, their models are inherently load-dependent, interaction macro fatigue models in which volumetric strain is used as the damage metric. All-in-all, this is not surprising given that the detailed laboratory studies mentioned previously showed that the accumulation volumetric strains in soils subjected to cyclic loading is a load-dependent, interaction phenomenon.

### 3.4 Laboratory Testing Procedure

Strain-controlled cyclic simple shear tests were performed using a modified GCTS simple shear testing apparatus (SSH-100) (see Figure 3.6). The testing apparatus is capable of performing stress- or strain-controlled cyclic simple shear or cyclic triaxial tests with sinusoidal or user-defined (e.g., earthquake) loadings. Prior to these tests, the apparatus was slightly modified by the authors; external bracing was added to limit compliance during cyclic simple shear testing.

The cyclic simple shear tests were performed on poorly-graded quartz sand with an assumed specific gravity of 2.65. Table 3.1 summarizes the index properties of the sand, and Figure 3.7 is a plot of particle size gradation of the sand. The test specimens had dimensions of 101-mm diameter by approximately 24-mm high and were confined by stacked rings.

Sample specimens were prepared by dry pluviating the sand into the confining rings lined with a taut latex membrane. The left side of Figure 3.8 shows the confining rings with the freshly-pluviated sand. The top layer of the specimen was gently smoothed, the top platen was placed on the sand, and the membrane was affixed to the platens with o-rings (see the right photo in
Figure 3.8). The target density of each specimen was achieved by vibrating the specimen with the top platen in place.

After assembling the testing equipment around the specimen, an overburden pressure was applied to the specimen and further densification was allowed to occur. After the overburden-induced volumetric strains ceased to accumulate, the cyclic loading phase was initiated. One of three types of strain-controlled loading was applied to each specimen: (1) Constant-amplitude sinusoidal, (2) Variable-amplitude sinusoidal, or (3) Earthquake-type loading obtained from equivalent-linear site response analyses. Figure 3.9 shows examples of the three types of loading.

### 3.5 Modification and Calibration of the R-N Fatigue Model

The results of 460 constant-amplitude sinusoidal strain-controlled cyclic simple shear tests were used to modify and calibrate the R-N model. In order to characterize the influencing factors on seismic compression, tests were performed at three values of overburden pressure (i.e., 50, 100, and 250 kPa) and at four different nominal relative densities (i.e., 30, 45, 65 and 80%). Table 3.2 shows the number of tests performed at each combination of relative density and overburden pressure. For each combination, the specimens were subjected to cyclic shear strains ranging from 0.2 to 1% (single-amplitude). Figure 3.10 shows a typical result of the constant-amplitude sinusoidal strain-controlled cyclic simple shear tests.

#### 3.5.1 Model Modification

As mentioned previously, the original R-N model was modified to bring the model in accord with soil response observed in laboratory tests (the other two models did not lend themselves to modification). The modifications entailed changing the R-N model from a load-dependent, interaction-free model to a load-dependent, interaction model. This was achieved by making \( r \) a function of \( R \), as well as a function of the load amplitude and soil state. Several different functional forms of \( r \) were assessed, but the one that gave...
the best results, yet maintained a relatively simple form is:

\[ r = 0.1/R^{r_0} + r_0; \ 0 < r_0 < 1 \quad (3.8) \]

where \( r_0 \) is a calibration parameter that is a function of soil state and load amplitude.

### 3.5.2 Model Calibration

To use the modified R-N model for forward predictions of \( \varepsilon_v \), two calibration parameters are needed, \( r_0 \) and \( N \) (recall: \( R = n/N \), where \( N \) is a function of the load amplitude and soil state and \( n \) is from the applied loading function). Using the results from the 460 constant-amplitude sinusoidal strain-controlled cyclic simple shear tests, expressions for both \( r_0 \) and \( N \) were developed:

\[ r_0 = 0.238 - 0.002D_r + 35.23\gamma - 0.0603\frac{\sigma'_v}{P_a} + 7.093\gamma \cdot \frac{\sigma'_v}{P_a} + \varepsilon_{r_0} \quad (3.9) \]

\[ \ln(N) = -13.5 + -2.91\ln(\gamma) + 0.217\frac{\sigma'_v}{P_a} + 0.0244D_r + \varepsilon_{N} \quad (3.10) \]

where: \( D_r \) is the relative density (in percent) of the specimen at the start of the cyclic phase of testing, \( \gamma \) is the single-amplitude shear strain of the loading cycles (as a decimal), \( \sigma'_v \) is the effective overburden stress, \( P_a \) is atmospheric pressure in the same units as \( \sigma'_v \), and \( \varepsilon_{r_0} \) and \( \varepsilon_{N} \) are normally-distributed error terms with means of zero and standard deviations of 0.048 and 0.62, respectively. The distributions of the error terms were obtained via bootstrapping (Efron and Tibishirani 1994). Inherent to developing the expression for \( N \), \( \varepsilon_v \) corresponding to “failure” (i.e., \( D = 1 \)) needed to be specified. This value is somewhat arbitrary because the modified R-N model can predict damage states greater than 100% without issue. However, selecting a value of \( \varepsilon_v \) corresponding to \( D = 1 \) that is within the range of seismic compression expected in-situ during earthquakes ensures the modified R-N model is calibrated over the appropriate range of volumetric strains. Accordingly, for convenience, \( \varepsilon_v = 1\% \) was selected to correspond to “failure.” Note that this model should be used with caution outside the conditions...
for which it was calibrated (i.e., $30\% \leq D_r \leq 100\%; \ 50 \leq \sigma'_v \leq 250\ \text{kPa}; \ 0.2 \leq \gamma \leq 1.0\%)$.

### 3.6 Accuracy of the Fatigue Models

#### 3.6.1 Variable-Amplitude Sinusoidal Loading

To assess the accuracy of the three fatigue models in predicting the magnitude of seismic compression during earthquakes, the models were used to predict the volumetric strains in laboratory samples subjected to variable-amplitude sinusoidal and earthquake loadings. In total, twenty three variable-amplitude sinusoidal load tests were performed on samples having a relative density of 55% and an overburden pressure of 100 kPa. The amplitude of the sinusoids was increased or decreased twice (i.e., the load functions consisted of three sets of constant-amplitude sinusoids). Figure 3.11 shows one of the shear strain load functions used. About half of the load functions used started with high amplitude cycles and had step decreases in the load amplitudes with time and the other half started with low amplitude cycles and had step increases in load amplitudes with time.

For each of the 23 variable-amplitude laboratory tests, the seismic compression was estimated using the P-M, Byrne (1991), and the modified R-N models. For the Byrne (1991) model, the calibration parameters $C_1$ and $C_2$ were computed using Eqns. 3.6 and 3.7. For the P-M and modified R-N models, $N$ and $r_0$ were computed using Eqns. 3.9 and 3.10. Note that $N$ is the only calibration parameter for the P-M model. However, unlike the modified R-N model where the volumetric strain selected to correspond to $D = 1$ is arbitrary and inconsequential in computing seismic compression, this is not the case for the P-M model. As a result, to make a fair assessment of the P-M model, the volumetric strain corresponding to $D = 1$ was selected based on the slope of a plot of $\log(\gamma)$ vs. $\log(N)$ curve from the constant amplitude sinusoidal laboratory test data. The slope of the $\log(\gamma)$ vs. $\log(N)$ varied from 2.63 for $\varepsilon_v = 0.1\%$ to 0.34 for $\varepsilon_v = 1.0\%$. In comparison, the slope of the normalized $\log(CSR)$ vs. $\log(N)$ curve used by Liu et al. (2001) to compute number of equivalent stress cycles using the P-M model was approximately 0.35. Accordingly, using $N$ corresponding to $\varepsilon_v = 1\%$ for the P-M model is consistent with how the P-M model has been used in past
applications in geotechnical earthquake engineering. Using the models thusly calibrated, Figure 3.12 shows both the predicted and measured volumetric strains for the variable-amplitude loading function shown in Figure 3.11.

As expected, the modified R-N and Byrne models do much better at predicting the cumulative volumetric strain with time than does the P-M model. This is because both modified R-N and Byrne models are load-dependent, interaction models, while the P-M model is load-dependent, interaction free. Table 3.3 shows the median and interquartile range in the prediction errors for each model. (Interquartile range is the difference between the third and first quartile of the ordered data; the middle fifty percent of the data is encompassed within this range.)

Figure 3.13 shows boxplots of the percent error in prediction for each method. The top and bottom of each box show the location of the 3rd and 1st quartile of the data, and the horizontal line between these two is the median. Any points outside the whiskers are considered outliers. It can be seen that both the R-N and Byrne models generally over-predict volumetric strains, and the P-M model under-predicts it. The measured volumetric strains ranged from 0.5% to 0.97% with a median of 0.7%.

3.6.2 Earthquake Loading

A total of 16 strain-controlled cyclic simple shear laboratory tests were performed using earthquake motions as the loading function. Three different motions were used; these were shear strain time histories computed at the center of a layer in a soil profile using an equivalent-linear site response code. Per Ishihara and Yasuda (1973), one of these motions was a “vibration-type” motion having many high amplitude cycles, and the other two motions were “shock-type” motions having few large-amplitude cycles (Figure 3.14). All three motions were scaled to a maximum shear strain amplitude of 0.35%.

To estimate the volumetric strains for earthquake-type loadings using the fatigue models, it was necessary to define a “cycle” or, more appropriately, a “half cycle” of loading. The definition used in this study is a version of the mean crossing peak counting (also known as zero-crossing) method as described in ASTM E1049 (2011). In this method, zero-crossings define the half cycles and the amplitude of the half cycles was taken as the maximum load between the zero-crossings. Other methods of defining half cycles of
loading were also assessed, namely the rainflow and range counting methods (ASTM E1049 2011). However, these methods resulted in similar or larger errors in the predictions of all the models. Accordingly, given the simplicity (and precedence: Seed et al. 1975; Byrne 1991; Liu et al. 2001) of using the mean crossing peak counting definition, it was adopted by the authors. Also, in predicting the volumetric strains for the earthquake loadings using the three models, it was assumed that no volumetric strains resulted from shear strains having an amplitude less than the threshold shear strain of 0.02% (Dobry et al. 1982; Hsu and Vucetic 2004). This is consistent with how Byrne (1991) implemented his model for predicting pore pressure generation in saturated, undrained sandy soils.

Measured volumetric strains for the earthquake loadings ranged from 0.22 to 0.42% with a median value of 0.28%. Figure 3.15 shows the measured and predicted volumetric strains for the motion shown at the bottom of Figure 3.14. For these tests, all three models, on average, under-predict the volumetric strain. The Byrne model has the lowest median percent error. The P-M model gave the worst median prediction, but had the smallest interquartile range. The modified R-N model’s median prediction was slightly worst than Byrne’s, but the interquartile range was slightly better. Table 3.4 shows the median and interquartile range of the percent error in prediction for each model. Figure 3.16 shows the range and median of the predictions for all the earthquake loading tests.

3.6.3 Overall Prediction Results

Table 3.5 lists the combined results of all the variable-amplitude sinusoidal and earthquake loadings. As may be observed from the results shown in this table, the Byrne model gave slightly more accurate predictions than the modified R-N model for the irregular loading tests. The Palmgren-Miner method yielded the least accurate predictions. It needs to be mentioned that the results shown in Table 3.5 only correspond to samples having a relative density of 55% and an effective overburden stress of 100 kPa. As discussed in the case history example in the next section, for conditions other than $D_r = 30\%$ and $\sigma'_v = 100$ kPa, the modified R-N model continues to yield accurate results, while the accuracy of the Byrne model decreases substantially, and the P-M model remains inaccurate. Finally, the same relative trends in the prediction errors of these three models for volumetric
strains would be expected in the computed number of equivalent cycles for the variable-amplitude sinusoidal or earthquake loads.

### 3.7 Case History

To illustrate the implementation of the proposed model for predicting seismic compression in a field setting, a case history presented in Stewart et al. (2002) is analyzed. The case history is of seismic compression in a deep canyon fill caused by the 1994 M\textsubscript{w} 6.7 Northridge Earthquake. ‘Site A’ is located approximately 12.2 km from the fault rupture plane and experienced settlements ranging from 0 to 18 cm.

Table 3.6 gives the soil layer properties used for the analysis. This layering represents the stratigraphy near the site where 15.2 cm of settlement was recorded. The relative compaction values (\(RC\)) were obtained by randomly sampling from a distribution given by Stewart et al. (2002). The relative densities were estimated using a correlation with relative compaction by Lee and Singh (1971). Also, six pairs of horizontal earthquake recordings were taken from the PEER NGA ground motion database (Chiou et al. 2008). These motions were from earthquakes with similar magnitudes and were sited at similar distances as this case history. Details of these motions are given in Table 3.7; the site to source distance listed in the table is the closest distance to the fault rupture.

Equivalent-linear site response analyses (Schnabel et al. 1972; Lasley et al. 2014) were performed for the site and shear strain time histories were computed at the center of each layer. From these, the volumetric strains were computed using the modified R-N model. The magnitude of seismic compression for the profile was computed by multiplying the computed volumetric strains for each layer by the layer thickness and summing the results for all the layers. Table 3.8 lists the predicted settlements for the profile for each ground motion. To obtain the total settlement, settlements from each motion of each pair were summed. The average settlement predicted for the six pairs of motions was 11.4 cm, slightly less than the measured 15.2 cm of settlement.

Volumetric strains were also computed using the Byrne and P-M models, but their predicted settlements averaged 2.7 cm for the Byrne model and 1.9 cm
for the P-M model, for this profile. The analyses were repeated for a profile wherein all the layers were assumed to have relative densities of 30%. Similar to the predictions of the laboratory results discussed previously for the variable amplitude sinusoidal and earthquake loadings, the modified R-N and the Byrne model predicted very similar magnitudes of seismic compression on average (R-N: 7.5 cm, Byrne: 10.6 cm), while the P-M model predicted an average settlement of 2.9 cm. Accordingly, it appears that the Byrne model is most accurate at low relative densities.

3.8 Summary and Conclusions

The authors proposed a “non-simplified” procedure for predicting the severity of seismic compression. It is based on a modified version of the R-N fatigue model in which volumetric strain is used as the damage metric. In contrast to “simplified” approaches for predicting seismic compression, the proposed model evaluates volumetric strains directly from shear strain time histories computed from equivalent linear site response analyses, thus negating the need for number of equivalent cycle correlations. Modifications were made to the R-N fatigue model to make it a load dependent, interaction model, in accord with the seismic compression phenomenon. To calibrate the modified R-N model, several hundred strain-controlled sinusoidal cyclic simple shear tests were performed on dry samples composed of quartz sand. The induced volumetric strain accumulation in the sand was found to be a function of the amplitude of shear straining, the relative density of the sand, the applied overburden pressure, and the cycle ratio.

In addition to the sinusoidal loadings, 23 variable-amplitude sinusoidal and earthquake-type loading cyclic simple shear tests were also performed on specimens having a relative density of 55% and subjected to an overburden pressure of 100 kPa. The modified R-N, Byrne, and P-M models were used to predict the volumetric strains for these laboratory tests. Of the three models, the P-M model gave the least accurate predictions (significantly less accurate than the other models), and the modified R-N and Byrne models provided comparatively accurate predictions. However, the accuracy of the Byrne model decreases for conditions of higher relative density, as was illustrated in the analysis of a case history, while the modified R-N model continued to yield reasonable results.
In addition to being used to compute seismic compression in a non-simplified approach, the modified R-N model can also be used to compute number of equivalent strain cycles for use in simplified procedures. The advantage of this is that a consistent damage metric (i.e., volumetric strain) is used to equate earthquake motions to an equivalently damaging (i.e., induces the same volumetric strain) sinusoidal motion having a specified number of cycles. This is in contrast to the number of equivalent cycle correlations commonly used with simplified seismic compression approaches, where the equivalent cycle correlations are developed using damage metrics other than volumetric strain.

### 3.9 Acknowledgements

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### 3.10 References


3.11 Tables

Table 3.1: Index properties of the quartz sand used in this study.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>$e_{\text{min}}$</td>
<td>0.68</td>
</tr>
<tr>
<td>$e_{\text{max}}$</td>
<td>0.90</td>
</tr>
<tr>
<td>$G_s$</td>
<td>2.65 (assumed)</td>
</tr>
<tr>
<td>$D_{50}$</td>
<td>0.58 mm</td>
</tr>
<tr>
<td>$C_u$</td>
<td>1.9</td>
</tr>
<tr>
<td>$\gamma_{d,\text{min}}$</td>
<td>1.39 g/cm(^3)</td>
</tr>
<tr>
<td>$\gamma_{d,\text{max}}$</td>
<td>1.58 g/cm(^3)</td>
</tr>
</tbody>
</table>

Table 3.2: Summary of Sinusoidal Tests

<table>
<thead>
<tr>
<th>$\sigma_v$</th>
<th>$D_{r,nom.}$</th>
<th>No. Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>30</td>
<td>42</td>
</tr>
<tr>
<td>50</td>
<td>45</td>
<td>37</td>
</tr>
<tr>
<td>50</td>
<td>65</td>
<td>32</td>
</tr>
<tr>
<td>50</td>
<td>80</td>
<td>28</td>
</tr>
<tr>
<td>100</td>
<td>30</td>
<td>82</td>
</tr>
<tr>
<td>100</td>
<td>45</td>
<td>66</td>
</tr>
<tr>
<td>100</td>
<td>65</td>
<td>49</td>
</tr>
<tr>
<td>100</td>
<td>80</td>
<td>29</td>
</tr>
<tr>
<td>250</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>250</td>
<td>45</td>
<td>25</td>
</tr>
<tr>
<td>250</td>
<td>65</td>
<td>19</td>
</tr>
<tr>
<td>250</td>
<td>80</td>
<td>21</td>
</tr>
<tr>
<td>-</td>
<td>Total:</td>
<td>460</td>
</tr>
</tbody>
</table>
Table 3.3: Median and Interquartile Range of the Percent Error Prediction for Variable-Amplitude Sinusoidal Loadings

<table>
<thead>
<tr>
<th>Method</th>
<th>Median % Error</th>
<th>25th Percentile</th>
<th>75th Percentile</th>
<th>IQR of % Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-N</td>
<td>-6.2</td>
<td>-17.2</td>
<td>6.2</td>
<td>23.4</td>
</tr>
<tr>
<td>Byrne</td>
<td>-3.3</td>
<td>-21.7</td>
<td>4.7</td>
<td>26.5</td>
</tr>
<tr>
<td>P-M</td>
<td>31.6</td>
<td>11.5</td>
<td>37.6</td>
<td>26.1</td>
</tr>
</tbody>
</table>

Table 3.4: Median and Interquartile Range of the Percent Error Prediction for Earthquake Motions

<table>
<thead>
<tr>
<th>Method</th>
<th>Median % Error</th>
<th>25th Percentile</th>
<th>75th Percentile</th>
<th>IQR of % Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-N</td>
<td>12.7</td>
<td>5.7</td>
<td>23.5</td>
<td>17.8</td>
</tr>
<tr>
<td>Byrne</td>
<td>5.3</td>
<td>-1.2</td>
<td>17.0</td>
<td>18.2</td>
</tr>
<tr>
<td>P-M</td>
<td>90.7</td>
<td>87.5</td>
<td>94.4</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Table 3.5: Median and Interquartile Range of the Percent Error Prediction for All Irregular Motions

<table>
<thead>
<tr>
<th>Method</th>
<th>Median % Error</th>
<th>25th Percentile</th>
<th>75th Percentile</th>
<th>IQR of % Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-N</td>
<td>5.3</td>
<td>-7.5</td>
<td>11.7</td>
<td>19.3</td>
</tr>
<tr>
<td>Byrne</td>
<td>1.9</td>
<td>-11.0</td>
<td>8.0</td>
<td>19.0</td>
</tr>
<tr>
<td>P-M</td>
<td>47.5</td>
<td>29.5</td>
<td>90.5</td>
<td>61.0</td>
</tr>
</tbody>
</table>
Table 3.6: Soil Profile at Location B-2 of Site A (after Stewart et al. 2002).

<table>
<thead>
<tr>
<th>Layer No.</th>
<th>Soil Type</th>
<th>Thickness (m)</th>
<th>$V_s$ (m/s)</th>
<th>$RC$ (%)</th>
<th>$D_r$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fill</td>
<td>1.0</td>
<td>200.0</td>
<td>96.0</td>
<td>81.0</td>
</tr>
<tr>
<td>2</td>
<td>Fill</td>
<td>1.3</td>
<td>214.0</td>
<td>97.0</td>
<td>83.0</td>
</tr>
<tr>
<td>3</td>
<td>Fill</td>
<td>1.4</td>
<td>190.0</td>
<td>95.0</td>
<td>77.0</td>
</tr>
<tr>
<td>4</td>
<td>Fill</td>
<td>1.7</td>
<td>239.0</td>
<td>96.0</td>
<td>80.0</td>
</tr>
<tr>
<td>5</td>
<td>Fill</td>
<td>1.4</td>
<td>199.0</td>
<td>94.0</td>
<td>71.0</td>
</tr>
<tr>
<td>6</td>
<td>Fill</td>
<td>1.6</td>
<td>143.0</td>
<td>89.0</td>
<td>44.0</td>
</tr>
<tr>
<td>7</td>
<td>Fill</td>
<td>1.4</td>
<td>272.0</td>
<td>93.0</td>
<td>65.0</td>
</tr>
<tr>
<td>8</td>
<td>Fill</td>
<td>1.7</td>
<td>299.0</td>
<td>95.0</td>
<td>77.0</td>
</tr>
<tr>
<td>9</td>
<td>Fill</td>
<td>1.4</td>
<td>268.0</td>
<td>95.0</td>
<td>74.0</td>
</tr>
<tr>
<td>10</td>
<td>Fill</td>
<td>1.5</td>
<td>354.0</td>
<td>89.0</td>
<td>45.0</td>
</tr>
<tr>
<td>11</td>
<td>Fill</td>
<td>1.6</td>
<td>253.0</td>
<td>92.0</td>
<td>62.0</td>
</tr>
<tr>
<td>12</td>
<td>Claystone</td>
<td>2.1</td>
<td>455.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Claystone</td>
<td>2.5</td>
<td>537.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Half-space</td>
<td>Claystone</td>
<td>-</td>
<td>886.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 3.7: Earthquake Recordings Used in This Case History Study

<table>
<thead>
<tr>
<th>NGA No.</th>
<th>Earthquake</th>
<th>Station</th>
<th>$M_w$</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>164</td>
<td>Imperial Valley-06</td>
<td>Cerro Prieto</td>
<td>6.53</td>
<td>15.19</td>
</tr>
<tr>
<td>265</td>
<td>Victoria, Mexico</td>
<td>Cerro Prieto</td>
<td>6.33</td>
<td>14.37</td>
</tr>
<tr>
<td>285</td>
<td>Irpinia, Italy-01</td>
<td>Bagnoli Irpinio</td>
<td>6.9</td>
<td>8.18</td>
</tr>
<tr>
<td>763</td>
<td>Loma Prieta</td>
<td>Gilroy - Gavilan Coll.</td>
<td>6.93</td>
<td>9.96</td>
</tr>
<tr>
<td>828</td>
<td>Cape Mendocino</td>
<td>Petrolia</td>
<td>7.01</td>
<td>8.18</td>
</tr>
<tr>
<td>1787</td>
<td>Hector Mine</td>
<td>Hector</td>
<td>7.13</td>
<td>11.66</td>
</tr>
</tbody>
</table>

### Table 3.8: Estimated Settlements (cm) Across the Entire Profile for Each Input Ground Motion

<table>
<thead>
<tr>
<th>Motion</th>
<th>From Motion 1</th>
<th>From Motion 2</th>
<th>Total Settlement</th>
</tr>
</thead>
<tbody>
<tr>
<td>164</td>
<td>4.6</td>
<td>4.2</td>
<td>8.8</td>
</tr>
<tr>
<td>828</td>
<td>15.4</td>
<td>9.0</td>
<td>24.4</td>
</tr>
<tr>
<td>265</td>
<td>5.9</td>
<td>4.6</td>
<td>10.5</td>
</tr>
<tr>
<td>1787</td>
<td>4.0</td>
<td>5.9</td>
<td>9.9</td>
</tr>
<tr>
<td>763</td>
<td>4.7</td>
<td>4.5</td>
<td>9.1</td>
</tr>
<tr>
<td>285</td>
<td>3.5</td>
<td>2.4</td>
<td>5.9</td>
</tr>
</tbody>
</table>
3.12 Figures

Figure 3.1: Relationship between cumulative damage \((D)\) and the number of applied load cycles \((n)\) having amplitude \(S\). Failure occurs when \(D=1\), with the corresponding number of applied cycles designated as \(N\). (Adapted from Stallmayer and Walker, 1968) [Fair use.]
Figure 3.2: Damage-cycle relationship for various load amplitudes. (Adapted from Stallmeyer and Walker, 1968) [Fair use.]
Figure 3.3: Damage-cycle ratio relationships for a) load-independent material, and b) load-dependent material. (Adapted from Stallmeyer and Walker, 1969) [Fair use.]

Figure 3.4: The left plot shows the damage accumulation path according to the Palmgren-Miner hypothesis. Two different cyclic loading time histories will follow the same damage accumulation path, as shown in the center and right plots. This is because the P-M hypothesis is load-independent.
Figure 3.5: At left, various load accumulation paths predicted by the Richart-Newmark hypothesis for a range of $r$ values. Right and center, the R-N hypothesis is load-dependent, meaning that the ordering of load cycles affects the damage accumulation path and the amount of predicted damage.

Figure 3.6: The GCTS testing apparatus used for this study with triaxial specimen. (Modifications not shown.)
Figure 3.7: The particle size gradation of the quartz sand used in this study.

Figure 3.8: On the left, confining rings with pluviated sand. Right, specimen with top platen in place and under vacuum. (Note: the pictured sand was not used in this study.)
Figure 3.9: Examples of the constant-amplitude sinusoidal, variable-amplitude sinusoidal, and earthquake-type loadings used for the cyclic simple shear testing.
Figure 3.10: Typical results from a constant-amplitude strain-controlled cyclic simple shear test on dry sand.
Figure 3.11: Shear strain time history of a variable-amplitude sinusoidal test.
Figure 3.12: Predicted and actual damage paths for a variable-amplitude sinusoidal loading function.
Figure 3.13: Boxplots of the percent error in prediction of volumetric strains for irregular-sinusoid loadings. Negative values signify overprediction.
Figure 3.14: At top, a \textit{shock-type}, and, at bottom, a \textit{vibration-type} motion used as the loading function.
Figure 3.15: Actual and predicted volumetric strains for a vibration-type motion.
Figure 3.16: Boxplots of the percent error in prediction of volumetric strains for earthquake motion loadings.
Chapter 4

Manuscript #2: Number of Equivalent Cycles for Liquefaction Evaluations in Active Tectonic and Stable Continental Regimes

The authors of the following manuscript intend to submit it to ASCE’s *Journal of Geotechnical and Geoenvironmental Engineering*.

Samuel Lasley made the following contributions to this manuscript:

- wrote the entire first draft of the manuscript under the general direction of the other two authors.
- digitized and otherwise prepared the soil profiles from the figures given by Cetin (2000)
- acquired the WUS earthquake ground motions from the PEER database and the CEUS motions from Jongwon Lee.
- wrote ShakeVT2, the equivalent-linear site response program mentioned in the paper
- performed all the equivalent-linear site response analyses
- examined the resulting data and developed functional forms for each regression
• performed all regressions using R and python and selected the best models
• compared the regressed functional forms with those from other researchers
• prepared all original tables and figures

Dr. Green made the following contributions to this manuscript:

• provided the framework for the proposed energy-based liquefaction evaluation procedure and associated equivalent number of cycles correlation (see Green 2000)
• suggested the use of the Cetin (2000) soil profiles and the earthquake motions

Dr. Rodriguez-Marek made the following contributions:

• suggested some functional forms for the $r_d$ models and provided the technical know-how to regress using maximum likelihood
• gave valuable feedback about the soil profiles, site response analyses, regressions

Dr. Green and Dr. Rodriguez-Marek both:

• provided feedback during all stages of the research
• edited the manuscript
Number of Equivalent Cycles for Liquefaction Evaluations in Active Tectonic and Stable Continental Regimes

Samuel J. Lasley¹, Russell A. Green², Adrian Rodriguez-Marek²

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² Professor, Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, Virginia, U.S.A.; rugreen@vt.edu; adrianrm@vt.edu

4.1 Abstract

The number of equivalent cycles ($n_{eq}$) concept plays an important role in geotechnical earthquake engineering and underlies the accounting for ground motion duration in simplified liquefaction evaluation procedures, whether explicitly or implicitly. In this regard, several $n_{eq}$ correlations have been proposed over the years that were developed using a similar variant of the Palmgren-Miner (P-M) fatigue theory. The correlations presented herein were developed using an alternative implementation of the P-M theory that better accounts for the non-linear response of the soil and for multidirectional shaking. The resulting $n_{eq}$ values computed using this alternative implementation of the P-M theory show a stronger correlation to significant duration of strong motion than values computed using the more commonly used variant of the P-M theory. $n_{eq}$ correlations are proposed herein for shallow crustal earthquakes in both active tectonic and stable continental regimes. Additionally, two forms of the correlations are presented, one being expressed as a function of peak ground acceleration ($a_{max}$). This relation shows a strong negative correlation between $a_{max}$ and $n_{eq}$, implying that motions with high amplitudes have short durations and vice versa. This negative correlation is not accounted for in most previously proposed $n_{eq}$ correlations, which could result in the erroneous weighting of the unlikely scenarios of high amplitude-longer duration and low amplitude-short duration motions in liquefaction hazard studies.
4.2 Introduction

Number of equivalent cycles ($n_{eq}$) correlations for use in liquefaction evaluations are proposed herein that were developed using the alternative implementation of the Palmgren-Miner (P-M) fatigue theory that was proposed by Green and Terri (2005). The $n_{eq}$ concept has long been used to quantify the damaging effects of earthquake motions on soil (e.g., Lee and Chan 1972; Seed et al. 1975; Annaki and Lee 1977). In early liquefaction studies, researchers used the results of cyclic laboratory tests (e.g., cyclic triaxial, cyclic simple shear, shake table) to quantify liquefaction susceptibility. In order to link liquefaction potential to specific earthquake ground motions, it was necessary to either develop laboratory equipment capable of imposing earthquake-type motions (costly) or to develop procedures to convert an earthquake load to an “equivalently-damaging” number of uniform (generally sinusoidal) cycles. This latter approach has the advantages of allowing comparisons between many different earthquake motions and of being relatively easy and cost-effective to implement. While recent liquefaction potential evaluation methods have moved away from the direct use of laboratory testing and towards field-based correlations (e.g., Peck 1979), the $n_{eq}$ concept still underlies the accounting for strong motion duration via magnitude scaling factors ($MSF$), whether explicitly (e.g., Boulanger and Idriss 2015) or implicitly (e.g., Cetin et al. 2004).

Over the years, several $n_{eq}$ correlations for use in liquefaction evaluations have been proposed (e.g., Seed et al. 1975; Haldar and Tang 1981; Liu et al. 2001; Biondi et al. 2004). With few exceptions (e.g., Green 2001 and Lee 2009), these correlations were developed using the variant of the P-M fatigue theory proposed by Seed et al. (1975), or a slight modification thereof. As detailed in Green and Terri (2005) this approach has shortcomings in accounting for non-linear soil response, as well as not being readily adaptable to account for multidirectional shaking. To overcome these limitations, Green and Terri (2005) proposed an alternative implementation of the P-M theory that is based on the direct equating of dissipated energy in a unit volume of soil subjected to an earthquake motion and to a sinusoidal motion having specified amplitude and equivalent number of cycles. Lee (2009) used this alternative procedure to develop $n_{eq}$ correlations for several simple soil profiles subjected to shallow crustal earthquake motions in both active tectonic and stable continental regimes.
Extending the work of Lee (2009), herein \( n_{eq} \) correlations are proposed that were developed using soil profiles representative of those in the liquefaction case history database. Fifty soil profiles characterized in post-earthquake site investigations in California (Cetin 2000) were used in equivalent linear site response analyses to develop the proposed \( n_{eq} \) correlations for active shallow crustal tectonic regimes (e.g., western US: WUS). These profiles were subjected to ground motions obtained from the PEER NGA database (Chiou et al. 2008). To develop \( n_{eq} \) correlations for stable continental tectonic regimes (e.g., central-eastern US: CEUS), the small strain shear wave velocities (\( V_S \)) of the bed rock of the aforementioned profiles were increased and subjected to motions from the McGuire et al. (2001) CEUS database. Additionally, three approaches of increasing rigor were used to account for multidirectional shaking, the simplest of which was used by Lee (2009). Mixed-effects regression analyses were used to develop the proposed correlations, wherein both the similarity in the soil profiles and motions from the same earthquake were considered as random events.

After a brief review of the P-M fatigue theory, overviews of select previous \( n_{eq} \) studies are presented; this overview is not all inclusive and is not intended to be. This is followed by a summary of the approach used in this study to develop the proposed \( n_{eq} \) correlations. Finally, a discussion and comparison of the approaches used and correlations proposed herein versus those of select previous studies is presented.

4.3 The Palmgren-Miner (P-M) Fatigue Theory

The P-M fatigue theory (Palmgren 1924; Miner 1945), often referred to as “Miner’s rule” in the US, is one of several macro-level cumulative damage hypotheses that has been proposed to assess the service life of a material (e.g., a piece of metal) due to fatigue. Detailed overviews of the P-M fatigue theory are presented in numerous papers and books (e.g., Kaechele 1963; Dowling 1972; Collins 1981; Pook 2007), and thus a complete review is not warranted herein. However, a brief summary is given to put into perspective the implementation of the P-M theory used in this study versus that used by others.
In its basic form, the P-M fatigue theory for uniform loading is expressed as (Miner, 1945):

\[
\frac{\omega_1}{W} = \frac{n_1}{N_1}
\]  \hspace{1cm} (4.1)

where: \( N_1 \) = number of stress cycles to failure at stress level \( S_1 \); \( n_1 \) = number of cycles having peak stress amplitude \( S_1 \); \( \omega_1 \) = absorbed work after \( n_1 \) cycles; \( W \) = absorbed work at failure; and \( S_1 \) = peak amplitude of applied cyclic stress. For an applied cyclic stress having varying peak amplitudes (as opposed to a uniform cyclic load), the P-M hypothesis expands to:

\[
\frac{1}{W} \sum_{i=1}^{m} \omega_i = \sum_{i=1}^{m} \frac{n_i}{N_i}
\]  \hspace{1cm} (4.2)

where the load history is comprised of \( m \) different peak stress amplitudes (i.e., \( S_1, S_2, \ldots, S_m \)); \( n_i \) is the number of cycles in the load history having a given peak stress amplitude \( S_i \); \( \omega_i \) is the absorbed work after \( n_i \) cycles; and \( N_i \) is number of stress cycles to failure at stress level \( S_i \).

Miner (1945) defined cumulative component damage \( (D) \) as the ratio of the absorbed work \( (\omega_i) \) after \( n_i \) cycles and the absorbed work at failure \( (W) \):

\[
D = \frac{1}{W} \sum_{i=1}^{m} \omega_i
\]  \hspace{1cm} (4.3)

Thus, per Eqn. 4.2 cumulative damage can also be written as:

\[
D = \sum_{i=1}^{m} \frac{n_i}{N_i}
\]  \hspace{1cm} (4.4)

In the above expressions, \( 0 \leq D \leq 1 \): \( D = 0 \) corresponds to the damage state of a component that has not been damaged (e.g., never been subjected to cyclic loading); \( D = 1 \) corresponds to the damage state of a failed component; and \( 0 < D < 1 \) corresponds to the damage state of a component that has been subjected to loading but has not yet failed. Inherent to the above expressions is the assumption that the absorbed work \( (\omega) \) and the absorbed work at failure \( (W) \) are independent of the frequency of the applied load.
and, additionally, that $W$ is independent of the amplitude of the applied load. Miner (1945) presents experimental data that reasonably validates these assumptions for aluminum alloy components subjected to thousands of cycles of loading, with failure (i.e., $D = 1$) defined as the initiation of a crack.

A mathematical expression to compute a sinusoidal load having a specified amplitude ($S_{ref}$) and $n_{eq}$ duration that induces the same amount of damage to a component as a variable amplitude load can be easily derived from Eqn. 4.4. This is done by equating the component damage caused by the variable amplitude load to that induced by a uniform cyclic load that induces failure in $N_{ref}$ cycles:

$$n_{eq} = \sum_i \frac{N_{ref} n_i}{n_i}$$

(4.5)

### 4.4 Previous $n_{eq}$ Studies for Liquefaction Evaluations

#### 4.4.1 Seed et al. (1975)

Seed et al. (1975) noted the analogy between metal fatigue and soil liquefaction and modified the P-M theory for computing $n_{eq}$ for earthquake motions for evaluating liquefaction potential. Per Eqn. 4.5, use of the P-M theory requires a correlation relating the amplitude of a sinusoidal load to the number of cycles required to cause failure in the object being loaded. For metal fatigue and liquefaction evaluations these correlations are experimentally determined and are referred to as $S-N$ and $CSR-N_{liq}$ curves, respectively. $CSR$ (i.e., cyclic stress ratio) is the peak amplitude of the applied cyclic shear stress ($\tau$) divided by the initial vertical effective confining stress ($\sigma'_{v0}$), and $N_{liq}$ is the corresponding number of applied cycles required to induce initial liquefaction, where initial liquefaction is commonly defined as either the excess pore pressure becoming equal to $\sigma'_{v0}$, or as the induced cyclic strain exceeding a limiting value.

The shape and position of the $CSR-N_{liq}$ curve is highly variable and depends on the soil fabric, soil density, effective confining stress, etc. To alleviate
the need to obtain soil/state specific CSR-\(N_{liq}\) curves, Seed et al. (1975) sought to normalize the CSR-\(N_{liq}\) curve such that the resulting shape was representative of most sands. The normalization process developed by Seed et al. (1975) is illustrated in Figure 4.1, wherein \(CSR_1\) is the cyclic stress ratio that causes liquefaction in one cycle, \(FS\) is a “safety factor”, and \(\alpha\) is the normalized peak amplitude of the resulting uniform cyclic load. The basis for applying the safety factor \((FS)\) was to account for ground motions that are not severe enough to induce liquefaction. In essence, the use of the \(FS\) was an attempt to develop a contour of constant \(D\) that is less than 1. The normalized peak amplitude \((\alpha)\) of the resulting uniform cyclic load was selected as 0.65 by Seed et al. (1975). The basis for \(\alpha = 0.65\) is likely a remnant of earlier studies where judgment was used to determine the CSR-\(n_{eq}\) combination for an earthquake motion (Seed and Idriss 1971; Whitman 1971). As noted in Seed et al. (1975), there is nothing rigorous about setting \(\alpha = 0.65\). The normalized curve developed by Seed et al. (1975) using \(FS = 1.5\) and \(\alpha = 0.65\) is shown in Figure 4.2.

Assuming that ground surface accelerations \((a)\) and corresponding shear stresses \((\tau)\) in the upper \(\sim 6\) m (20 ft) of a soil profile are proportional, Seed et al. (1975) used the normalized curve shown in Figure 4.2, in conjunction with Eqn. 4.5, to convert random surface acceleration time histories into equivalently damaging uniform cycles. Inherent to the Seed et al. procedure, the ratio of acceleration and peak ground acceleration \((a/a_{max})\) is assumed equal to \(FS \cdot CSR/CSR_1\). Alternatively stated, \(a/a_{max}\) is assumed equal to \(\tau/\tau_{max}\), where \(\tau_{max} = \tau_1/FS\) and \(\tau_1\) is the cyclic shear stress required to induce liquefaction in one cycle. However, it can be shown mathematically that for CSR-\(N_{liq}\) curves that plot as straight lines on log-log paper, which is the case for most soils, the assumed value of \(FS\) does not have any effect on the computed \(n_{eq}\) values. The Seed et al. procedure for computing \(n_{eq}\) consists of taking a weighted average of the peaks in an acceleration time history, wherein the normalized CSR-\(N_{liq}\) curve defines the weighting function. As a result, a normalized CSR-\(N_{liq}\) curve, such as that shown in Figure 4.2, is commonly referred to as a weighting factor (WF) curve (e.g., Liu et al. 2001 and Biondi et al. 2004).

There are several different “peak counting” methods (ASTM 2011) that are used in fatigue analyses to obtain the number and amplitudes of peaks in an irregular time history (e.g., an earthquake motions). Seed et al. (1975) used a version of the mean crossing peak counting (also known as zero-crossing)
method wherein the amplitude of one cycle is taken as the maximum value of the time history between successive zero crossings. Because the acceleration pulses or “peaks” in earthquake time histories are rarely symmetrical about the 0g axis, a peak above or below the 0g axis only represents a half cycle of loading, not a full cycle. To account for this Seed et al. computed the number of equivalent cycles separately for the positive and negative peaks in the time history, with the average of the two being $n_{eq}$ for the record. Also, Seed et al. excluded peaks having amplitudes less than approximately $0.3 \cdot F_S \cdot CSR/CSR_1$ (or equivalently $0.3 \cdot \tau/\tau_{max}$) in computing $n_{eq}$ because their contribution was considered to be negligible. To calculate the equivalent number of cycles from two components of motion, Seed et al. suggested two ways without giving a clear preference: (1) Normalize each component of motion by its own $a_{max}$; and (2) Normalize each motion by the larger $a_{max}$ of the two motions. Seed et al. used both methods to develop $n_{eq}$ correlations from a suite of ~ 60 motions from earthquakes in the WUS and South America. The mean curve obtained by treating each component of motion separately can be approximated as:

$$\ln(n_{eq}) = -1.405 + 0.547M$$

(4.6)

where $M$ is the magnitude of the earthquake. It should be noted that this procedure assumes that the ratio $a/a_{max}$ at the surface is equal to $CSR/CSR_{max}$ at depth in the soil profile, which is tenuous as depth increases.

### 4.4.2 Liu et al. (2001)

Liu et al. (2001) adopted the Seed et al. (1975) variant of the P-M theory to develop an $n_{eq}$ correlation from a ground motion database of 1,528 recordings from 107 earthquake events. All earthquake events were from active shallow crustal regimes; subduction and intraplate events were excluded. However, to account for multidirectional shaking, Liu et al. (2001) used the normalized vector sum of horizontal pairs of recordings to calculate $n_{eq}$. All acceleration values are positive in the normalized vector sum time history and the peak amplitude is equal to 1. Liu et al. (2001) do not explicitly state what peak counting method they used, but it is implied that each reversal in the normalized vector sum time history was treated as a “peak,” with an amplitude measured from the zero axis. This approach differs from all
established peak counting methods used in fatigue analyses (ASTM 2011). Liu et al. used two $WF$ curves to compute $n_{eq}$, referred to as “laboratory-based” and “field-based.” Assigning weights of $2/3$ and $1/3$ to the $n_{eq}$ values computed using these respective curves, Liu et al. developed the following $n_{eq}$ predictive equation:

$$
\ln(n_{eq}) = \ln \left[ \frac{\exp(1.53+1.51(M-5.8))}{4.9 \cdot 10^6 \beta} \right]^{-\frac{1}{3}} + 0.75S + 0.095R + \varepsilon \quad (4.7)
$$

where: $M$ is magnitude of the earthquake (moment magnitude preferred), $\beta$ is the shear wave velocity at the source (generally taken by Liu et al. as 3.2 km/s), $S$ is 0 for rock sites and 1 for soil sites, $R$ is site-to-source distance in kilometers, and $\varepsilon$ is a normally distributed error term with a mean of zero and a standard deviation of 0.56.

### 4.4.3 Biondi et al. (2004)

Biondi et al. (2004) used the Seed et al. (1975) variant of the P-M theory to develop $n_{eq}$ correlations from 1962 motions. They treated each component separately and used the same $WF$ curve (Figure 4.2) used by Seed et al. (1975). Biondi et al. (2004) proposed several regression models; their simplest functional form is:

$$
\ln(n_{eq}) = -4.995 - 0.4536 \ln(a_{max}) + 3.204 \ln(M) + \varepsilon \quad (4.8)
$$

where $M$ is the earthquake magnitude (moment magnitude preferred) and $\varepsilon$ is the error term with a mean of zero and a standard deviation of 0.68.

### 4.4.4 Green and Terri (2005)

Thus far, the $n_{eq}$ correlations that have been presented have been developed based on Eqn. 4.3 (via Eqn. 4.5). However, Green and Terri (2005) showed
that an equally valid interpretation of $n_{\text{eq}}$ can be obtained from Eqn. 4.4, resulting in:

$$n_{\text{eq}} = \frac{\sum \omega_i}{\omega_{\text{ref}}}$$

(4.9)

where $\sum \omega_i$ is the total absorbed work (or dissipated energy) in a unit volume of soil subjected to an earthquake motion, and $\omega_{\text{ref}}$ is the energy dissipated in a unit volume of soil subjected to one equivalent cycle of loading having a reference amplitude $\tau_{\text{ref}}$. The total dissipated energy is simply the cumulative area bound by stress-strain hysteresis loops. For vertically propagating shear waves in a soil profile, $\sum \omega_i$ can be calculated from shear stress and strain time histories at depth in the profile using the trapezoidal rule:

$$\sum \omega_i = \frac{1}{2} \sum_{j=1}^{k-1} (\tau_{j+1} + \tau_j)(\gamma_{j+1} - \gamma_j)$$

(4.10)

where $k$ is the total number of time steps in the time histories, and $\tau_j$ and $\gamma_j$ are the shear stress and shear strain at time step $j$, respectively.

The denominator of Eqn. 4.9, $\omega_{\text{ref}}$, can be related to the soil’s equivalent viscous damping ratio (Jacobsen 1960; Green and Terri 2005):

$$\omega_{\text{ref}} = \frac{2\pi D_\gamma \tau_{\text{ref}}^2}{G_\gamma}$$

(4.11)

where $G_\gamma$ and $D_\gamma$ are the degraded shear modulus and damping ratio at a shear strain corresponding to $\tau_{\text{ref}}$, defined consistently with CSR from the simplified liquefaction evaluation procedure as $0.65 \cdot \tau_{\text{max}}$. Substituting Eqn. 4.11 into Eqn. 4.9 yields:

$$n_{\text{eq}} = \frac{\sum \omega_i G_\gamma}{2\pi D_\gamma \tau_{\text{ref}}^2}$$

(4.12)

As discussed in Boulanger and Idriss (2015), $n_{\text{eq}}$ is a function of both the earthquake loading and the soil response, with the latter not fully accounted for in previous studies. However by computing $n_{\text{eq}}$ from both the applied $\tau$ and the induced $\gamma$, both the loading and soil response are fully and rigorously
taken into account in Eqn. 4.12. Additionally, both the $WF$ curve and the cycle counting method are inherent to this alternative implementation of the P-M theory.

Green and Terri (2005) performed a parametric study of $n_{eq}$ using 326 ground motion recordings from 29 different earthquakes. These motions were applied to a soil profile consisting of loose sand using the site response code SUMDES (Li et al. 1992). The results of paired horizontal components of motion were combined by summing the dissipated energies from each component. Also, $\omega_{ref}$ was computed for an equivalent cycle having an amplitude corresponding to 0.65 times the geometric mean of the maximum amplitudes of the pair of horizontal components of motion:

$$\tau_{ref} = 0.65 \cdot \sqrt{\max(|\tau_1|) \cdot \max(|\tau_2|)}$$

(4.13)

where $\max(|\tau_1|)$ and $\max(|\tau_2|)$ are the peak or maximum absolute values of the two components of shear stress induced in the soil profile at a given depth. Although they did not propose a functional form for $n_{eq}$, they showed that $n_{eq}$ could vary as a function of depth in a soil profile and increases with site-to-source distance as well as magnitude, supporting the trend shown by Liu et al. (2001).

### 4.4.5 Lee (2009)

Using the alternative approach to implement the P-M theory proposed by Green and Terri (2005), Lee (2009) performed equivalent linear site response analyses on 6 simple soil profiles to develop $n_{eq}$ correlations. All soil profiles were composed of 12 clean sand layers with the bedrock located at a depth of 30 m. The distinguishing feature between the soil profiles was the variation of small strain shear wave velocity ($V_S$) with depth. They ranged from a profile with a constant velocity of 139 m/s for all depths to a profile with shear wave velocities ranging from 75 m/s in the surface layer to 225 m/s in the deepest soil layer. The earthquake ground motions used in the site response analyses were obtained from two databases compiled by McGuire et al. (2001): one for the WUS (296 motions) and another for the CEUS (270 motions). The same soil profiles were used in the site response analyses for both the WUS and CEUS motions, but Lee (2009) increased the $V_S$ of
the bedrock by a factor of $\sim 3.8$ for the CEUS analyses. Each motion was treated separately and used to compute $n_{eq}$ at several depths in the profiles. The functional form of Lee’s $n_{eq}$ correlation is:

$$\ln(n_{eq}) = \exp(C_1z) + C_2R^{C_3} + C_4M_w + C_5 + \varepsilon$$  \hspace{1cm} (4.14)

where $z$ is depth in meters, $M_w$ is moment magnitude, $R$ is site-to-source distance in km, defined as the closest distance to the fault rupture plane, $C_1$-$C_5$ are regression coefficients, and $\varepsilon$ is an error term. Lee provided regression coefficients separately for each profile and each ground motion database (i.e., WUS and CEUS). Table 1 lists the regression coefficients and the standard deviation of $\varepsilon$ for one of the soil profiles considered by Lee (2009).

### 4.5 Approach Used to Develop Proposed Correlations

This study builds upon those of Green and Terri (2005) and Lee (2009), but uses different ground motion databases, soil profiles that are representative of those in the earthquake liquefaction case history databases, and uses three different approaches of increasing rigor to account for multidirectional shaking.

#### 4.5.1 Earthquake Databases

Equivalent linear site response analyses were performed using SHAKEVT2 (Lasley et al. 2014), a rewrite of SHAKE and SHAKE91 (Schnabel et al. 1971; Idriss and Sun 1992), wherein the Darendeli and Stokoe (2001) shear modulus reduction and damping curves were used to model the non-linear response of the soil. The earthquake motions used in the analyses came from two different earthquake databases. The first database is the PEER NGA database (Chiou et al. 2008), from which 194 pairs of rock components from 47 different earthquakes were obtained. The average small strain shear wave velocities of all the upper 30 m ($V_{S30}$) of the sites where the motions were recorded are greater than 650 m/s. The moment magnitudes ($M_w$) of the earthquake
motions range from 5.27 to 7.62, and site-to-source distances ($R$) range from 1.8 to 152 km. These shallow crustal earthquake motions are similar to those experienced in much of the WUS and are henceforth referred to as “WUS motions.”

The second ground motion database used in this study is the McGuire et al. (2001) CEUS database. Because few CEUS earthquake motions have been recorded, the majority of the 149 pairs of motions in the CEUS database are scaled WUS motions. The $M_w$ of these motions range from 4.5 to 7.6 and $R$ range from 0.1 to 199 km. The recorded motions include the 1988 Saguenay ($M_w$ 5.9 mainshock and $M_w$ 4.5 aftershock), the 1985 Nahanni ($M_w$ 6.8), and the 1989 New Madrid, MO ($M_w$ 4.7) earthquakes.

McGuire et al. (2001) scaled WUS motions for CEUS conditions using response spectral transfer functions generated from the single-corner frequency point source model in conjunction with random vibration theory (RVT) (e.g., Brune 1970; 1971; Boore 1983; McGuire et al. 2001; Silva and Lee 1987). The transfer functions account for the differences in seismic source, wave propagation path properties, and generic site effects between the WUS and CEUS regions. Many seismological publications have shown successful results of the RVT point source model for generating strong ground motions for both WUS and CEUS (Boore 1983; 1986; Hanks and McGuire 1981; McGuire et al. 1984; Schneider et al. 1993; Silva 1993). In generating the scaled CEUS motions, recorded WUS motions were used as “seed” motions in the spectral scaling process, resulting in scaled motions that have realistic characteristics. In this context, the stochastic point source model is a reliable and reasonable approach for estimating spectral characteristics of strong ground motions for engineering analyses. The scaling method however, should be validated as additional recordings of stable continental motions become available.

Tables 4.10 and 4.11 in the electronic supplement list the WUS and CEUS motions, respectively, used in the analyses. Also, Figure 4.3 shows the distribution of earthquake events as a function of magnitude and distance for both databases.

### 4.5.2 Soil Profiles

The soil profiles used in this study were compiled by Cetin (2000). The 50 well-characterized profiles are from post-earthquake site investigations in
California. For each profile, Cetin provides the qualitative description of the layers (e.g., clay, fine sand) and the shear wave velocities. Additional soil layer details (unit weight, plasticity index, at-rest lateral earth pressure coefficient, and friction angle) were randomly selected from a distribution of probable values corresponding to the qualitative description. The profiles were analyzed as-is with the WUS motions. For simulated conditions representative of those in the CEUS, the shear wave velocity of the bedrock layers of each profile was increased by a factor 3.5 and analyzed using the CEUS input motions. This factor of 3.5 brought the bedrock shear wave velocities into agreement with higher bedrock shear wave velocities of the CEUS. Several of the profiles had similar characteristics; Figures 4.4 and 4.5 show the grouped profiles for the WUS and CEUS, respectively.

### 4.5.3 Multidirectional Shaking

As discussed above, several different approaches have been used to account for multidirectional shaking. Specific to the alternative implementation of the P-M theory, Lee (2009) treated each motion separately, implying that multiplying \( n_{eq} \) by 2 will account for multidirectional shaking (e.g., Pyke et al., 1975). Henceforth, this approach is referred to as Approach 1. In contrast, Green and Terri (2005) accounted for multidirectional shaking by performing separate site response analyses for each horizontal component in a pair of motions, adding the energy dissipated at the respective depths for each component of motion, and setting the amplitude of the equivalent cycle as the 0.65 times the geometric mean of the maximum shear stresses experienced at a given depth. Henceforth, this approach is referred to as Approach 2. In addition to these two approaches, a third approach was also used in this study (i.e., Approach 3), summarized as follows.

1. Separately, each of the paired components was applied at the base of a given soil profile using the equivalent-linear algorithm.

2. Once both analyses converged, the degraded profiles were compared and a composite profile was constructed by using the softer layer properties of the two profiles.

3. The site responses analyses were performed again, holding the soil properties constant, and the energy dissipated at the respective depths in
the profile subjected to the two components of motion were summed.

4. The amplitude of the equivalent cycle was set as 0.65 times the geometric mean of the maximum shear stresses experienced at a given depth.

5. Eqn. 4.12 was used to compute $n_{eq}$.

The rationale for this approach is that in the field, it is likely that the strain induced in one direction of motion will influence the soil stiffness in other directions.

### 4.5.4 Regression Analysis

Regression was performed using the R (2013) package *lme4* (Bates et al. 2014), which implements a mixed effects regression. The average event residual and average profile group residuals are assumed to be random effects. The use of mixed effects regression avoids potential biases from earthquakes or profile groups that have a larger number of data points. For the CEUS dataset, the random effect of earthquake event was not included in the final regressions, rather only the profile group was included, because the earthquake event could not be properly constrained by the data. Earthquake faulting mechanism was also considered as a random effect, but it was found to be insignificant for both datasets and was not used in the final regression analyses. A bootstrapping technique (Efron and Tibshirani 1994) was employed to obtain the mean and standard deviation of all regression coefficients. It was done in the following way:

1. Ten thousand data points were randomly selected (without replacement) from the dataset of interest.

2. The regression coefficients that best fit the 10,000 data points for the functional form of interest were obtained.

3. Steps 1 and 2 were repeated for 1000 iterations and the regression coefficients for each iteration were recorded.

4. The mean and standard deviation of the distribution of each regression coefficient were calculated.
4.5.5 Proposed \( n_{eq} \) Correlations

\( n_{eq} \) correlations were developed for each of the three approaches discussed above to account for multidirectional shaking. Several functional forms of the regression equations were examined for the correlations, including the form used by Lee (2009). Of these, two functional forms were chosen because of their superior fit and the convenience of their predictive variables. As shown in Figures 4.6 and 4.7, \( n_{eq} \) computed using Approach 1 (i.e., \( n_{eq,A1} \)) for 0 to 4 m depths is strongly correlated with the peak ground acceleration (\( a_{max} \)) at the ground surface; this same trend was identified for the \( n_{eq} \) values computed using the other two approaches. Thus, the first functional form of the proposed correlation includes \( a_{max} \) as a predictor variable:

\[
\ln(n_{eq}) = a_1 + a_2 \ln(a_{max}) + a_3 M_w + \varepsilon_1
\]

(4.15)

where \( a_{max} \) is in units of \( g \), \( M_w \) is the moment magnitude of the earthquake, \( a_1-a_3 \) are regression coefficients, and \( \varepsilon_1 \) is an error term which is assumed to be normally distributed. Table 4.2 lists the mean values of the regression coefficients for both the WUS and CEUS datasets, and Table 4.3 lists the uncertainty for each component as determined by the standard deviations of each coefficient computed using the bootstrapping technique. The low value of the standard deviations indicates that both the \( M_w \) and \( a_{max} \) scaling are well constrained by the data. Table 4.4 summarizes the uncertainties in the correlation where \( \tau_{event} \) and \( \tau_{profile} \) are the standard deviations of the earthquake event and soil profile random effects, respectively, and \( \sigma_\varepsilon \) is the standard deviation of the residual. If these standard deviations are assumed to be independent, the total uncertainty is:

\[
\sigma_{Total} = \sqrt{\tau_{event}^2 + \tau_{profile}^2 + \sigma_\varepsilon^2}
\]

(4.16)

As shown in Table 4.4, Approach 2 provides the smallest total error for both earthquake databases, and overall, the WUS database has smaller errors than the CEUS database.

The functional form of this correlation lends itself for use with simplified liquefaction procedures because they require both the magnitude (for \( MSF \)) and \( a_{max} \) as input variables. It was expected that the \( V_S \) of the layer would
be a significant predictor variable, but it was found not to be significant when
used in conjunction with $a_{\text{max}}$.

The second functional form for the proposed $n_{eq}$ correlation is more in line
with that used by others (e.g., Liu et al. 2001 and Lee 2009) in that it
expresses $n_{eq}$ as a function of $M_w$ and $R$. This allows for better comparison
with previously proposed $n_{eq}$ correlations and is useful when $a_{\text{max}}$ is not
known:

$$\ln(n_{eq}) = b_1 + b_2 M_w + b_3 \ln(R) + \varepsilon_2$$  (4.17)

where $M_w$ and $R$ are defined the same as in Eqn. 4.14, $b_1$-$b_5$ are regression
coefficients, and $\varepsilon_2$ is a normally-distributed error term. Tables 4.5 and
4.6 give the mean and standard deviations of each regression coefficient,
respectively. Table 4.7 provides the inter- and intra-event errors as well as
the residual and total errors. Compared to Eqn. 4.15, the total errors are
slightly less for the WUS dataset and slightly greater for the CEUS dataset.
Once again, Approach 2 provides the smallest total errors.

The standard deviations of total error are of a similar magnitude as some
of the other studies, namely, Lee (2009), Liu et al. (2001), and Biondi et
al. (2004). Figure 4.8 shows a plot of the two functional forms for the $n_{eq}$
correlations (i.e., Eqns. 4.15 and 4.17) for the WUS and CEUS ground motion
datasets and for all three approaches used to account for multidirectional
shaking. For the WUS dataset, Approaches 1 and 2 predict very similar
values of $n_{eq}$; Approach 3, however, predicts greater values of $n_{eq}$, especially
at medium to large values of $a_{\text{max}}$ and most site-to-source distances. For
the CEUS, however, the $n_{eq,A3}$ values have a weaker dependence on $M_w$ and
predict larger $n_{eq}$ values at low magnitudes. For all approaches, the CEUS
correlations predict higher values of $n_{eq}$ at low $a_{\text{max}}$ but lower values of $n_{eq}$
at longer site-to-source distance when compared to the WUS correlations.
4.6 Comparison of $n_{eq}$ Correlations

4.6.1 Green and Terri (2005) vs. Seed et al. (1975) Approaches

As discussed in Green and Terri (2005) and summarized above, the alternative implementation of the P-M theory that they propose and the more commonly used implementation proposed by Seed et al. (1975) are both underlain by the original P-M theory. To illustrate this, $n_{eq}$ values computed using the two implementations are compared in Figures 4.9 and 4.10. In calculating the $n_{eq}$ values per Seed et al. (1975), both the Seed et al. (1975) and the Liu et al. (2001) variants were used. However, for consistency with the Darendeli and Stokoe (2001) shear modulus and damping degradation curves used in the site response analyses performed to compute $n_{eq}$ per Green and Terri (2005), the $WF$ curve used in conjunction with Seed et al. (1975) and Liu et al. (2001) plots as a straight line on log-log paper and had a slope of -0.34. In addition to being consistent with the Darendeli and Stokoe (2001) shear modulus and damping degradation curves for the densities and confining stresses of interest, this assumed curve is consistent with laboratory curves developed from high-quality undisturbed samples obtained by freezing (Yoshimi et al. 1984).

To allow for as consistent of a comparison as possible, $n_{eq}$ values shown in Figures 4.9 and 4.10 computed using Green and Terri (2005) are for a shallow depth in the profiles (0 to 4 m), while the $n_{eq}$ values computed using Seed et al. (1975) and Liu et al. (2001) were computed from the acceleration time histories at the profile’s surface output by SHAKEVT2. Also, consistent with how each of the methods accounts for multidirectional shaking, the $n_{eq}$ values computed using Seed et al. (1975) (i.e., $n_{eq,Sea75}$) are compared with $n_{eq}$ values computed using Approach 1 (i.e., $n_{eq,A1}$), while the $n_{eq}$ values computed using Liu et al. (2001) (i.e., $n_{eq,Lea01}$) are compared with $n_{eq}$ values computed using Approaches 2 and 3 (i.e., $n_{eq,A2}$ and $n_{eq,A3}$), respectively.

As may be observed from Figures 4.9 and 4.10, there is almost a one to one correlation between $n_{eq,Sea75}$ and $n_{eq,A1}$, as indicated by Pearson’s $r$ values of 0.95 and 0.92 for WUS and CEUS motions, respectively. Again, this is not surprising because both procedures are underlain by the P-M theory (i.e., Eqn. 4.4 vs Eqn. 4.3). However, this one to one correlation becomes tenuous
at deeper depths in the profiles because of the inherent assumption in Seed et al. (1975) that the ground surface accelerations are directly proportional to shear stresses in the upper \( \sim 6 \) m (20 ft) of the soil profiles. Also from Figures 4.9 and 4.10, it may be observed that the \( n_{eq,\text{Lea}01} \) values have a strong correlation with the \( n_{eq,A2} \) and \( n_{eq,A3} \) values, as indicated by Pearson’s \( r \) values of 0.77 and 0.81 for WUS and CEUS motions for \( n_{eq,\text{Lea}01} \) versus \( n_{eq,A2} \) and 0.83 and 0.82 for WUS and CEUS motions for \( n_{eq,\text{Lea}01} \) versus \( n_{eq,A3} \). However, the \( n_{eq,\text{Lea}01} \) values tend to be systematically less than both the \( n_{eq,A2} \) and \( n_{eq,A3} \) values. This is attributed to Liu et al. (2001) using the normalized vector sum approach to account for multidirectional shaking, which is not conducive to using any of the established fatigue peak counting methods.

**4.6.2 Correlation with Other Ground Motion Duration Metrics**

Although its units are number of cycles as opposed to units of time, \( n_{eq} \) is a ground motion duration metric. Accordingly, \( n_{eq} \) should correlate with other ground motion duration metrics. Towards this end, Figures 4.11 and 4.12 show plots of \( n_{eq,A1} \) for 0 to 4 m depths versus bracketed duration (±0.05g threshold), 5-95% strong motion duration, and 5-75% strong motion duration. As may be observed from these figures, \( n_{eq,A1} \) has the strongest correlation with 5-75% strong motion duration. This is not surprising because 5-75% strong motion duration has been recognized as the duration metric that can be predicted with the least uncertainty (Abrahamson and Silva 1996). In fact, the functional form of the Liu et al. (2001) \( n_{eq} \) prediction equation (Eqn. 4.7) was adopted from the Abrahamson and Silva (1996) prediction equation for 5-75% strong motion duration.

To compare the strengths of the \( n_{eq,A1}, n_{eq,A2}, \) and \( n_{eq,A3} \) correlations with other duration metrics to the strengths of correlations among \( n_{eq,\text{Sea}75} \) and \( n_{eq,\text{Lea}01} \) and the same duration metrics, the Pearson correlation coefficient, \( r \), for each correlation is presented in Tables 4.8 and 4.9 for the WUS and CEUS, respectively. However, direct correlations between \( n_{eq,A2}, n_{eq,A3}, \) and \( n_{eq,\text{Lea}01} \) and the other duration metrics is not possible. This is because Approaches 2 and 3 and Liu et al. (2001) yield a single, combined \( n_{eq} \) value for both components of motion, while the other duration metrics yield duration values
for each component of acceleration at the profile’s surface. To allow for a
correlation, \( n_{eq,A2} \), \( n_{eq,A3} \), and \( n_{eq,Lea01} \) were compared to the geometric mean
of the time durations of the two components of motion. As may be observed
from Tables 4.8 and 4.9, \( n_{eq,A1} \), \( n_{eq,A2} \), and \( n_{eq,A3} \) have stronger correlations
to the other duration metrics than do \( n_{eq,Sea75} \) and \( n_{eq,Lea01} \), for every case
except bracketed duration of WUS motions.

4.6.3 Comparison of \( n_{eq} \) Predictive Equations

Figure 4.13 shows a comparison of various \( n_{eq} \) correlations for an \( M_w5.5 \)
earthquake where Eqn. 4.15 was used to compute \( n_{eq,A1} \). In this and the
subsequent figure, the curve labeled as Lee (2009) is for WUS. Also, the pre-
dicted values of \( n_{eq,Lea01} \) are divided by 2 to allow better comparison with
the other correlations. As may be observed in this figure, the correlation
for \( n_{eq,A1} \) for the WUS compares well with the \( n_{eq,Lea01} \) correlation at short
and long distances, but not at intermediate distances. Lee (2009) and the
correlation for \( n_{eq,A1} \) for the WUS give similar results for site-to-source dis-
tances less than about 100 km but diverge some at distances greater than
100 km. The correlation for \( n_{eq,Sea75} \) gives similar results as the other WUS
relations for short distances, but significantly underpredicts \( n_{eq} \) at longer
distances. Finally, \( n_{eq,A1} \) for the CEUS is less sensitive to site-to-source distance
than the comparable correlation for the WUS; it predicts larger \( n_{eq} \) at short
distances and fewer \( n_{eq} \) at longer distances relative to the WUS relation.

Figure 4.14 is similar to Figure 4.13, but for an \( M_w7.5 \) earthquake. As may
be observed in this figure, Lee (2009) and the correlation for \( n_{eq,A1} \) for the
WUS give similar results for site-to-source distances less than about 100 km
but diverge some at distances greater than 100 km, the same trend identified
for an \( M_w5.5 \) event. The correlation for \( n_{eq,Lea01} \) predicts larger \( n_{eq} \) than the
correlation proposed herein for the WUS at distances less than \( \sim 50 \) km, but
the two relations predict very similar \( n_{eq} \) values at greater distances. The
correlation for \( n_{eq,Sea75} \) predicts a larger \( n_{eq} \) than the correlation proposed
herein for the WUS at distances less than \( \sim 75 \) km, but underpredicts \( n_{eq} \)
at longer distances. Finally, similar to the trends identified for a \( M_w5.5 \)
event, \( n_{eq,A1} \) for the CEUS is less sensitive to site-to-source distance than
the comparable correlation for the WUS; again it predicts larger \( n_{eq} \) at short
distances and fewer \( n_{eq} \) at longer distances relative to the WUS relation.
Because the Biondi et al. (2004) correlation (Eqn. 4.8) and Eqn. 4.15 both have $a_{\text{max}}$ as a predictor variable, they are compared in Figure 4.15. Both correlations show a trend of decreasing $n_{\text{eq}}$ with increasing $a_{\text{max}}$, and Biondi et al. (2004) predicts similar $n_{\text{eq}}$ values for a $M_w7.5$ earthquake as Eqn. 4.15 for WUS. However for $M_w5.5$, Biondi et al. (2004) predicts smaller $n_{\text{eq}}$ than Eqn. 4.15 for the WUS. Eqn. 4.15 for the CEUS is less sensitive to $M_w$ than it is for the WUS and predicts larger $n_{\text{eq}}$ for $a_{\text{max}}$ less than $\sim 0.8g$ for the WUS and CEUS, with the predicted $n_{\text{eq}}$ values for both regimes tending to converge for larger values of $a_{\text{max}}$.

### 4.7 Summary and Conclusions

The use of number of equivalent cycle ($n_{\text{eq}}$) concept in liquefaction evaluations extends from the late 1960s to the present day. It forms an important part of the simplified liquefaction evaluation procedure by accounting for ground motion duration, whether explicitly or implicitly. The majority of the proposed $n_{\text{eq}}$ correlations were developed using the Seed et al. (1975) variant of the Palmgren-Miner (P-M) fatigue theory (e.g., Seed et al. 1975; Haldar and Tang 1981; Liu et al. 2001; Biondi et al. 2004). However, Green and Terri (2005) detailed shortcomings of this variant and proposed an alternative implementation of the P-M theory that is based on the direct equating of dissipated energy in a unit volume of soil subjected to an earthquake motion and to a sinusoidal motion having specified amplitude and equivalent number of cycles.

This study builds upon those of Green and Terri (2005) and Lee (2009), but uses different ground motion databases, soil profiles that are representative of those in the earthquake liquefaction case history databases, and uses three different approaches of increasing rigor to account for multidirectional shaking. Mixed effects regression analyses were used to develop the two proposed correlations, wherein both the similarity in the soil profiles and motions from the same earthquake were considered as random events. The first correlation (Eqn. 4.15) has $a_{\text{max}}$ and $M_w$ as predictor variables and the second (Eqn. 4.17) has $M_w$ and $R$ as predictor variables. Eqn. 4.15 lends itself for use with simplified liquefaction procedures because both $M_w$ and $a_{\text{max}}$ are already required as input variables. Also, similar to the correlation proposed by Biondi et al. (2004), Eqn. 4.15 shows a strong negative correlation be-
tween $n_{eq}$ and $a_{max}$. This is not accounted for in most previously proposed $n_{eq}$ correlations, which could result in the erroneous weighting of the unlikely scenarios of high amplitude-longer duration and low amplitude-short duration motions in liquefaction hazard studies. The proposed correlations are applicable for site-to-source distances up to 150 km for the WUS and up to 200 km for CEUS and for earthquakes with magnitudes ranging from 5.3 to 7.6 for the WUS and 4.5 to 7.6 for CEUS.

4.8 Acknowledgments

This research is partially funded by National Science Foundation (NSF) grants CMMI-1030564 and CMMI-1306261. This support is gratefully acknowledged. However, any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

4.9 References


4.10 Tables

Table 4.1: Regression Coefficients for Lee’s (2009) $n_{eq}$
Correlation

<table>
<thead>
<tr>
<th>Motion Database</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_4$</th>
<th>$C_5$</th>
<th>$\sigma_\varepsilon$</th>
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</thead>
<tbody>
<tr>
<td>WUS</td>
<td>-0.0101</td>
<td>1.664</td>
<td>0.131</td>
<td>0.122</td>
<td>-2.11</td>
<td>0.59</td>
</tr>
<tr>
<td>CEUS</td>
<td>-0.0190</td>
<td>1.857</td>
<td>0.136</td>
<td>0.050</td>
<td>-1.77</td>
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Table 4.2: Regression Coefficients for $n_{eq}$ Form #1

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<thead>
<tr>
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<th>$a_3$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>WUS</td>
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<tr>
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<td>0.4654</td>
<td>-0.5626</td>
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<tr>
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<td>-0.4082</td>
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</tr>
<tr>
<td>2</td>
<td>CEUS</td>
<td>1.147</td>
<td>-0.3772</td>
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<tr>
<td>3</td>
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<td>1.19</td>
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<td>0.2051</td>
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<tr>
<td>3</td>
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<td>2.092</td>
<td>-0.5133</td>
<td>0.04894</td>
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Table 4.3: Standard Deviations of the Regression Coefficients for $n_{eq}$ Form #1

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<th>$\sigma_{a2}$</th>
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<td>0.05652</td>
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Table 4.4: Inter-event, Intra-event and Total Errors from Eqn. 4.15

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</tr>
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<td>1</td>
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</tr>
<tr>
<td>2</td>
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<td>0.5319</td>
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</tr>
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<td>WUS</td>
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Table 4.5: Regression Coefficients for $n_{eq}$ Form #2

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<td>1</td>
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<td>WUS</td>
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<td>0.1396</td>
<td>0.3489</td>
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<tr>
<td>2</td>
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<td>0.1688</td>
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<td>3</td>
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<td>CEUS</td>
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<td>-0.03238</td>
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Table 4.6: Standard Deviations of the Regression Coefficients for $n_{eq}$ Form #2

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<td>3</td>
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<td>0.07537</td>
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Table 4.7: Inter-event, Intra-event and Total Errors from Eqn. 4.17

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<th>$\sigma_{\varepsilon}$</th>
<th>$\sigma_{\text{Total}}$</th>
</tr>
</thead>
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<tr>
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<td>0.3588</td>
<td>0.1424</td>
<td>0.4749</td>
<td>0.6120</td>
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<tr>
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<td>0.7369</td>
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<td>WUS</td>
<td>0.3695</td>
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<td>0.3952</td>
<td>0.5585</td>
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<tr>
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<td>0.6494</td>
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<td>3</td>
<td>WUS</td>
<td>0.3775</td>
<td>0.1191</td>
<td>0.4477</td>
<td>0.5976</td>
</tr>
<tr>
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<td>0.6777</td>
<td>0.6988</td>
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</table>

Table 4.8: Strength of Correlation Between Various Measures of Duration and $n_{eq}$ (WUS Dataset)

<table>
<thead>
<tr>
<th>Duration</th>
<th>Relationship</th>
<th>$r_{n_{eq},A1}$, $r_{n_{eq},\text{Sea75}}$</th>
<th>$r_{n_{eq},A2}$, $r_{n_{eq},\text{Lead01}}$</th>
<th>$r_{n_{eq},A3}$, $r_{n_{eq},\text{Lead01}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bracketed (±0.05g)</td>
<td>log-log</td>
<td>0.05, 0.12</td>
<td>0.11, 0.19</td>
<td>0.11, 0.15</td>
</tr>
<tr>
<td>Significant (5 to 95%)</td>
<td>log-log</td>
<td>0.52, 0.39</td>
<td>0.48, 0.40</td>
<td>0.58, 0.51</td>
</tr>
<tr>
<td>Significant (5 to 75%)</td>
<td>log-log</td>
<td>0.59, 0.47</td>
<td>0.56, 0.50</td>
<td>0.64, 0.57</td>
</tr>
</tbody>
</table>
Table 4.9: Strength of Correlation Between Various Measures of Duration and $n_{eq}$ (CEUS Dataset)

<table>
<thead>
<tr>
<th>Duration</th>
<th>Relationship</th>
<th>$r_{n_{eq}, A1}$, $r_{n_{eq}, Sea75}$</th>
<th>$r_{n_{eq}, A2}$, $r_{n_{eq}, Lea01}$</th>
<th>$r_{n_{eq}, A3}$, $r_{n_{eq}, Lea01}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bracketed ($\pm 0.05g$)</td>
<td>log-log</td>
<td>0.13, 0.11</td>
<td>0.19, 0.18</td>
<td>0.26, 0.26</td>
</tr>
<tr>
<td>Significant (5 to 95%)</td>
<td>log-log</td>
<td>0.61, 0.53</td>
<td>0.60, 0.59</td>
<td>0.62, 0.61</td>
</tr>
<tr>
<td>Significant (5 to 75%)</td>
<td>log-log</td>
<td>0.65, 0.59</td>
<td>0.60, 0.62</td>
<td>0.64, 0.65</td>
</tr>
</tbody>
</table>
4.11 Figures

Figure 4.1: The sequence of steps used by Seed et al. (1975) to normalize a CSR-\(N_{\text{liq}}\) curve. Step 1: Designate the CSR required to induce liquefaction in one cycle as \(CSR_1\); Step 2: Normalize the ordinate values by dividing CSR by \(CSR_1\); Step 3: Apply a FS to \(CSR_1\) (i.e., divide \(CSR_1\) by FS) and determine the number of cycles required to induce liquefaction (\(N_{\text{ref}}\)) corresponding to the normalized peak amplitude (\(\alpha\)) of the uniform cyclic load; and Step 4: Normalize the abscissa values as \(N_{\text{ref}}/N_{\text{liq}}\).
Figure 4.2: Normalized $CSR-N_{liq}$ curve ($FS = 1.5$) used by Seed et al. (1975) to compute $n_{eq}$. Such curves are commonly referred to as weighting factor (WF) curves. The $CSR-N_{liq.}$ curve used to develop the WF curve came from De Alba et al. (1975): large-scale, undrained, cyclic simple shear tests performed on reconstituted Monterey No. 0 sand specimens having a relative density of approximately 65%. (adapted from Seed et al. 1975)
Figure 4.3: Magnitude versus distance distribution of the motions used in this study.
Figure 4.4: WUS profiles used in this study. The number in the corner of each subplot is the number of profiles in that grouping.
Figure 4.5: CEUS profiles used in this study. The number in the corner of each subplot is the number of profiles in that grouping.
Figure 4.6: Scatterplots of $a_{\text{max}}$, $M_w$, and $R$ versus $n_{\text{eq,A1}}$ from the WUS database. The number of equivalent cycles has a much higher correlation to the $a_{\text{max}}$ at the ground surface than to $M_w$.

Figure 4.7: Scatterplots of $a_{\text{max}}$, $M_w$, and $R$ versus $n_{\text{eq,A1}}$ from the CEUS database. The number of equivalent cycles has a much higher correlation to the $a_{\text{max}}$ at the ground surface than to $M_w$. 
Figure 4.8: Values of $n_{eq}$ predicted by the correlations proposed herein. The top plots show the relationship using Eqn. 4.15 and the bottom figures are for Eqn. 4.17. The $n_{eq}$ correlations corresponding to the WUS are to the left; CEUS correlations are plotted on the right.
Figure 4.9: Comparison of $n_{eq}$ values computed using Seed et al. (1975) and Liu et al. (2001) (i.e., $n_{eq,Sea75}$ and $n_{eq,Lea01}$, respectively) with values computed using Approaches 1, 2, and 3 for 0 to 4 m depths (i.e., $n_{eq,A1}$, $n_{eq,A1}$, and $n_{eq,A1}$, respectively) for WUS.

Figure 4.10: Comparison of $n_{eq}$ values computed using Seed et al. (1975) and Liu et al. (2001) (i.e., $n_{eq,Sea75}$ and $n_{eq,Lea01}$, respectively) with values computed using Approaches 1, 2, and 3 for 0 to 4 m depths (i.e., $n_{eq,A1}$, $n_{eq,A1}$, and $n_{eq,A1}$, respectively) for CEUS.
Figure 4.11: Plots of $n_{eq,A1}$ for 0 to 4 m depths versus other ground motion duration metrics: bracketed duration ($\pm 0.05g$ threshold), 5-95% significant duration, and 5-75% significant duration for WUS.

Figure 4.12: Plots of $n_{eq,A1}$ for 0 to 4 m depths versus other ground motion duration metrics: bracketed duration ($\pm 0.05g$ threshold), 5-95% significant duration, and 5-75% significant duration for CEUS.
Figure 4.13: Comparison of $n_{eq}$ correlations for $M = 5.5$. “WUS” and “CEUS” refer to the WUS and CEUS correlations developed herein from approach 1 ($n_{eq,A1}$ values).

Figure 4.14: Comparison of $n_{eq}$ correlations for $M = 7.5$. “WUS” and “CEUS” refer to the WUS and CEUS correlations developed herein from approach 1 ($n_{eq,A1}$ values).
Figure 4.15: Comparison of functional form #1 (approach 1, $n_{eq,A1}$) and the Biondi et al. (2004) $n_{eq}$ correlations.
4.12  Electronic Supplement

4.12.1  NGA Database (WUS)

The distance given in the tables, \( R \), is the closest distance to the rupture area (an \( \text{nan} \) indicates that the value is not known). The units of \( PGA \) and \( R \) are \( g \) and km, respectively.

Table 4.10: WUS (NGA) Earthquake Motions

<table>
<thead>
<tr>
<th>No.</th>
<th>Names</th>
<th>Event</th>
<th>( M_w )</th>
<th>( PGA )</th>
<th>( R )</th>
<th>Mechanism</th>
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<td>1</td>
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<td>0.13</td>
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<td>Reverse</td>
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<td>6.69</td>
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<td>19.1</td>
<td>Reverse</td>
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<td>3</td>
<td>1012_LA0000</td>
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<td>4</td>
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<td>Northridge</td>
<td>6.69</td>
<td>0.08</td>
<td>31.7</td>
<td>Reverse</td>
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<td>0.08</td>
<td>31.7</td>
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<tr>
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<td>Northridge</td>
<td>6.69</td>
<td>0.08</td>
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<td>No.</td>
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### 4.12.2 McGuire et al. (2001) Database (CEUS)

The distance given in the tables, $R$, is the closest distance to the rupture area (an `nan` indicates that the value is not known). The units of $R$ and $PGA$ are km and g, respectively.

Table 4.11: Central-Eastern United States (CEUS)
Earthquake Motions

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Chapter 5

Manuscript #3: A New Stress Reduction Coefficient Relationship for Liquefaction Triggering Analyses

The authors of the following technical note intend to submit it to ASCE’s Journal of Geotechnical and Geoenvironmental Engineering.

Samuel Lasley made the following contributions to this technical note:

- wrote the first draft of the note under the general direction of the other two authors.
- conceived the functional form for the proposed $r_d$ relationship and obtained all regression coefficients.
- Created all tables and figures except for the first figure.
- coded and performed all comparisons with the other $r_d$ relationships

Dr. Green made the following contributions to this technical note:

- provided the impetus to examine and develop a new $r_d$ relationship
- provided valuable feedback to the first drafts of note and polished the final draft
• wrote the section detailing the creation of CEUS motions by McGuire et al. (2001).
• created the first figure showing the soil column

Dr. Rodriguez-Marek made the following contributions to this technical note:

• provided guidance on regression and curve fitting. This included the use of a likelihood function and pseudo-mixed effects modeling (which was not included in the final version of the note).
A New Stress Reduction Coefficient Relationship for Liquefaction Triggering Analyses

Samuel J. Lasley¹, Russell A. Green², Adrian Rodriguez-Marek³

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5.1 Abstract

Since its inception in the early 1970s the stress-based simplified procedure has become the standard of practice worldwide for evaluating liquefaction triggering potential. Central to this procedure is the stress reduction coefficient, \( r_d \), which allows the computation of the seismically induced stresses at depth in a soil profile without the need to perform a numerical site response analysis. Proposed herein is a new \( r_d \) relationship that was developed from equivalent-linear site response analyses performed on soil profiles representative of those in the liquefaction case history databases. The input motions used in the analyses are representative of those from shallow crustal earthquakes. Two variants of the \( r_d \) relationship are presented that allow it to be used when the profile’s shear wave velocities are either known or unknown, with the former yielding values having less uncertainty. Additionally, calibration coefficients are provided for both active and stable continental tectonic regimes. In comparison with other \( r_d \) relationships that are commonly used, the relationship proposed herein yields values having less bias and uncertainty.
5.2 Introduction

Herein a new stress reduction coefficient, $r_d$, relationship is proposed that yields values that have less bias and uncertainty than those computed by commonly used relationships. The stress reduction coefficient is defined as the ratio of the maximum seismically induced shear stress at the base of a flexible soil column to that at the base of a rigid soil column, both having depth $z$ (Seed and Idriss, 1971). Because the stress at the base of a rigid soil column can be computed using Newton’s second law, $r_d$ allows the computation of the seismically induced stresses at depth in a soil profile (i.e., flexible soil column) without the need to perform a numerical site response analysis (Figure 5.1). As a result, $r_d$ is integral to the stress-based simplified procedure which is the worldwide standard of practice for evaluating liquefaction triggering potential.

The first $r_d$ relationship was proposed by Seed and Idriss (1971), and several others have been proposed since then, with the vast majority of these being empirically based; Cetin (2000) provides a detailed review of some of these latter relationships. In the study presented herein, equivalent-linear site response analyses were performed to develop an empirically derived $r_d$ relationship. The site response analyses were performed on 50 soil profiles compiled by Cetin (2000) that are representative of those in the liquefaction case history databases. However, a larger set of recorded input motions were used in the analyses than were available at the time Cetin (2000) performed his study. Furthermore, in addition to using the Cetin (2000) profiles directly, the soil profiles were also modified to be representative of conditions in the central-eastern United States (CEUS). The input motions used in the analysis of this latter set of profiles were from the McGuire et al. (2001) CEUS database. Statistical analysis of the site response results were used to develop two variants of the $r_d$ relationship that allow it to be used when a profile’s shear wave velocities are either known or unknown. Additionally, calibration coefficients are provided for both active and stable continental tectonic regimes (e.g., western United States: WUS and CEUS).

In the following, brief descriptions of the earthquake motion databases and the soil profiles are given. Next, the proposed $r_d$ relationship is presented, followed by a comparison with commonly used relationships.
5.3 Earthquake Motions

The earthquake motions used in the site response analyses in this study came from two different ground motion databases. The first database is the PEER NGA strong motion database (Chiou et al., 2008) which is composed of 3551 multi-component records from 173 shallow crustal earthquakes. Of these 3551 records, 194 pairs of horizontal rock motions recorded during 47 earthquakes were used. The average shear wave velocities of the upper 30 m ($V_{S30}$) of the all sites where the motions were recorded are greater than 650 m/s. The earthquake magnitudes associated with the motions range from 5.3 to 7.6, and site-to-source distances (closest distance from the recording site to the fault rupture plane, Chiou et al. 2008) range from 1.8 to 152 km. These shallow crustal earthquake motions are representative of those generated by earthquakes in much of the WUS and are henceforth referred to as “WUS motions.”

The second ground motion database used in this study is the McGuire et al. (2001) CEUS database. Because few CEUS earthquake motions have been recorded, the majority of the 149 pairs of motions in the CEUS database are scaled WUS motions. The earthquake magnitudes associated with these motions range from 4.5 to 7.6 and site-to-source distances range from 0.1 to 199 km. The recorded motions include the 1988 Saguenay ($M_w$5.9 mainshock and $M_w$4.5 aftershock), the 1985 Nahanni ($M_w$6.8), and the 1989 New Madrid, MO ($M_w$4.7) earthquakes; a brief summary of the scaling procedure used to generate the remaining CEUS motions is provided below.

McGuire et al. (2001) scaled WUS motions for CEUS conditions using response spectral transfer functions generated from the single-corner frequency point source model in conjunction with random vibration theory (RVT) (e.g., Brune 1970; 1971; Boore 1983; McGuire et al. 2001; Silva and Lee 1987). The transfer functions account for the differences in seismic source, wave propagation path properties, and generic site effects between the WUS and CEUS regions. Many seismological publications have shown successful results of the RVT point source model for generating strong ground motions for both WUS and CEUS (Boore 1983; 1986; Hanks and McGuire 1981; McGuire et al. 1984; Schneider et al. 1993; Silva 1993). In generating the scaled CEUS motions, recorded WUS motions were used as “seed” motions in the spectral scaling process, resulting in scaled motions that have realistic characteristics. In this context, the stochastic point source model is a reliable and reasonable
approach for estimating spectral characteristics of strong ground motions for engineering analyses. The scaling method however, should be validated as additional recordings of stable continental motions become available.

Tables 5.5 and 5.6 in the electronic supplement list the WUS and CEUS motions, respectively, used in the analyses. Also, Figure 5.2 shows the distribution of earthquake events as a function of magnitude and distance for both databases.

### 5.4 Soil Profiles

The soil profiles used in the equivalent-linear site response analyses were compiled by Cetin (2000). The 50 well-characterized profiles are from post-earthquake site investigations in California. For each profile, Cetin provides a qualitative description of the layers (e.g. clay, fine sand) and the shear wave velocities. Additional soil layer details (unit weight, plasticity index, and at-rest lateral earth pressure coefficient) were randomly selected from a distribution of probable values corresponding to the qualitative description. The profiles were analyzed as-is with the WUS input motions. For simulated conditions representative of those in the CEUS, the shear wave velocity of the bedrock of each profile was increased by a factor of 3.5 and analyzed using the CEUS input motions. This factor of 3.5 brought the bedrock shear wave velocities into agreement with higher bedrock shear wave velocities of the CEUS. Several of the profiles had similar characteristics; Figures 5.3 and 5.4 show the grouped profiles for the WUS and CEUS, respectively.

### 5.5 Proposed \( r_d \) Relationship

Several functional forms for \( r_d \) were examined, and the following form was selected for its simplicity and shape (i.e., relatively low standard deviation of the regressed data):

\[
r_d = (1 - \alpha) \exp \left( \frac{-z}{\beta} \right) + \alpha \tag{5.1}
\]
where $\alpha$ is the limiting value of $r_d$ at large depths and can range from 0 to 1. The variable $\beta$ controls the curvature of the function at shallow depths, and $z$ is the depth in meters. The term ‘$(1 - \alpha)$’ scales the exponential so that $r_d$ is equal to one at the ground surface.

For each combination of profile group and earthquake event, values of $\alpha$ and $\beta$ were obtained using a non-linear least-squares curve-fitting algorithm (Jones et al. 2001). From the results of the curve-fitting algorithm, regressions were performed to predict $\alpha$ and $\beta$ using magnitude ($M_w$), $a_{max}$, average shear wave velocity in the upper 12 meters of the profile ($V_{S12}$), $V_{S30}$, and distance to the fault rupture plane ($R$). Of these predictors, $M_w$ and $V_{S12}$ were found to be most strongly correlated with $\alpha$ and $\beta$.

Two different sets of expressions for $\alpha$ and $\beta$ are proposed, one set being a function of $M_w$ and $V_{S12}$ and the other being solely a function of $M_w$. This allows the use of the $r_d$ relationship for profiles having varying levels of characterization. The first set of expressions for $\alpha$ and $\beta$ is:

$$\alpha_1 = \exp(b_1 + b_2 M_w + b_3 V_{S12})$$

(5.2)

$$\beta_1 = \exp(b_4 + b_5 M_w + b_6 V_{S12})$$

(5.3)

and the second set is:

$$\alpha_2 = \exp(b_1 + b_2 M_w)$$

(5.4)

$$\beta_2 = b_3 + b_4 M_w$$

(5.5)

where $b_1$ - $b_6$ are regression coefficients.

While the functional forms of the above two sets of expressions were developed using the least-squares curve fitting, the regression coefficients (Tables 5.1 and 5.2) were obtained by maximizing the likelihood, $L$, defined as:

$$L = \sum \left[ \ln \left( \frac{1}{\sigma \sqrt{2\pi}} \right) - \frac{(r_d, \text{Predicted} - r_d, \text{Actual})^2}{2\sigma^2} \right]$$

(5.6)
where \( \sigma \) is an error parameter regressed as part of the likelihood maximization. As with any empirical relationship, care should be used when applying these equations for conditions outside the ranges from which they were regressed. For the earthquake databases, magnitudes ranged from 5.3 to 7.6 and 4.5 to 7.6, for the WUS and CEUS, respectively. Average shear wave velocities in the upper 12 meters ranged from 130 to 220 m/s for both data sets. In particular, erroneous values will result when \( \beta \) is less than or equal to zero.

5.6 Discussion

Figure 5.5 shows the trends in the proposed \( r_d \) relationship (using the second set of expressions for \( \alpha \) and \( \beta \)) for magnitudes of 5.5 and 7.5 along with the \( r_d \) values predicted by a few commonly used \( r_d \) relationships. The Liao and Whitman (1986) relationship is solely a function of depth and was adopted for use in the in Youd et al. (2001) liquefaction evaluation procedures, which are widely used in practice. Cetin (2000) proposed two variants of an \( r_d \) relationship (Cetin-1 and Cetin-2), Cetin-1 being a function of \( M_w, a_{max}, \) depth and Cetin-2 being a function of \( M_w, a_{max}, V_{S12}, \) and depth. These relationships were adopted for use in the Cetin et al. (2004), Moss et al. (2006), and Kayen et al. (2013) liquefaction evaluation procedures. The Idriss (1999) \( r_d \) relationship is a function of \( M_w \) and depth and was adopted for use in the Idriss and Boulanger liquefaction evaluation procedures.

Relative to the relationship proposed herein, all three of the \( r_d \) relationships discussed above yield high values at shallow depths. Furthermore, the Idriss (1999) and Liao and Whitman (1986) relationships predict higher values of \( r_d \) for almost all depths shown relative to the proposed relationship. The Cetin (2000) relationship is less dependent on earthquake magnitude than the proposed relationship and yields values that fall in between the M5.5 and M7.5 curves of the proposed relationship; the proposed relationship predicts a greater range of \( r_d \) values overall. Because the proposed relationship generally predicts lower values of \( r_d \), the use of this relationship will predict smaller values of \( \tau_{max} \) at depth in a profile for a given value of \( a_{max} \).

Figure 5.6 shows the predicted values of the relationships above a heat map of the actual \( r_d \) values from the WUS site response analyses. In the top row of the figure are the results from the proposed relationship using the two
different sets of expressions for $\alpha$ and $\beta$ along with the results from the Liao and Whitman (1986) relationship. At the bottom of the figure are the Idriss (1999) and Cetin (2000) 1 & 2 relationships. The value $E$ in the upper left corner of each subplot is the Nash-Sutcliffe (1970) model efficiency coefficient. For these comparisons, it is calculated as follows:

$$E = 1 - \frac{\sum (r_{d,\text{Actual}} - r_{d,\text{Predicted}})^2}{\sum (r_{d,\text{Actual}} - \bar{r}_{d,\text{Actual}})^2}$$  \hspace{1cm} (5.7)$$

where $r_{d,\text{Actual}}$ are the values given by the results of the site response analyses, $r_{d,\text{Predicted}}$ are the values predicted by the relationship in question, and $\bar{r}_{d,\text{Actual}}$ is the mean of the $r_{d,\text{Actual}}$ values. The model efficiency coefficient value can range from 1 to $-\infty$. A value of 1 signifies that the model perfectly predicts; values of $E$ less than zero signify that the mean value of $r_{d,\text{Actual}}$ is a better predictor than the model. Based on the model efficiency coefficient and the visual spread of the data points, the proposed $r_d$ relationship performs better than the other relationships, with the Liao and Whitman (1986) and Cetin (2000) relationships having the poorest and best performances, respectively, of the three. The relatively good performance of the Cetin (2000) relationships is not surprising since they were derived from a more comprehensive site response study than the others.

From Figure 5.6 it appears that the relationship proposed herein gives poorer predictions at the shallower depths (<10m) where occurrence of liquefaction has been more pronounced. However, to test this, $E$ values were computed for each of the relationships for 2-m depth increments ranging from 2 m to 12 m, as well as a 2 to 8 m increment. The results of this for WUS analyses are presented in Table 5.3. As may be observed from the tabulated values, the relationship proposed herein performs better than the others at all depths.

As shown in Figure 5.5, the CEUS $r_d$ values tend to be lower than comparable WUS values. In comparing the predicted CEUS values using the relationship proposed herein to those predicted by the other relationships (Figure 5.7 and Table 5.4), the relative accuracy of the other relationships is poorer than when they are used for WUS conditions. This is not surprising given all the other relationships were developed using data that is representative of the WUS conditions.

Finally, although few liquefaction events have been recorded for depths greater than 20 m and the use of the simplified procedure may be question-
able at depths greater than this, the relationship proposed herein provides reasonable $r_d$ values at depths up to and exceeding 100 meters.

5.7 Conclusion

Based on a large number of recent equivalent-linear site response analyses, a new relationship for the stress reduction coefficient ($r_d$) has been proposed. $r_d$ plays an important role in the stress-based simplified liquefaction evaluation procedure because it allows the computation of the seismically induced stresses at depth in a soil profile without the need to perform a numerical site response analysis. Two different sets of expressions are presented for $\alpha$ and $\beta$, one being a function of $M_w$ and $V_{S12}$ and the other solely being a function of $M_w$. This allows the use of the $r_d$ relationship for profiles having varying levels of characterization. Additionally, calibration coefficients are provided for both active and stable continental tectonic regimes. Compared to the $r_d$ relationships proposed by Liao and Whitman (1986), Idriss (1999), and Cetin (2000), the relationship proposed herein yields values with less bias and uncertainty at all depths.

5.8 References


### 5.9 Tables

Table 5.1: Regression Coefficients of the \( r_d \) Relationship for the WUS Database

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<tr>
<th>Form</th>
<th>( b_1 )</th>
<th>( b_2 )</th>
<th>( b_3 )</th>
<th>( b_4 )</th>
<th>( b_5 )</th>
<th>( b_6 )</th>
<th>( \sigma )</th>
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Table 5.2: Regression Coefficients of the \( r_d \) Relationship for the CEUS Database

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<th>( b_3 )</th>
<th>( b_4 )</th>
<th>( b_5 )</th>
<th>( b_6 )</th>
<th>( \sigma )</th>
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Table 5.3: Values of \( E \) for the WUS Dataset

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<th>This Study-2</th>
<th>Liao and Whitman</th>
<th>Idriss</th>
<th>Cetin-1</th>
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<tr>
<td>8-10m</td>
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<td>0.09</td>
</tr>
<tr>
<td>10-12m</td>
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<td>0.19</td>
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<td>0.53</td>
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Table 5.4: Values of $E$ for the CEUS Dataset

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<th>Depths</th>
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<th>Idriss</th>
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5.10 Figures

Maximum seismically induced shear stress at the base of a flexible soil column:

\[ F_{\text{max}} = m \cdot a_{\text{max}} \]
\[ = z \cdot A \cdot \frac{\gamma_s}{g} \cdot a_{\text{max}} \]
\[ \tau_{\text{rigid max}} = \frac{F_{\text{max}}}{A} = \frac{a_{\text{max}}}{g} \cdot \sigma_v \]
\[ r_d = \frac{\tau_{\text{flexible max}}}{\tau_{\text{rigid max}}} \]
\[ \tau_{\text{flexible max}} = \frac{a_{\text{max}}}{g} \cdot \sigma_v \cdot r_d \]

- \( F_{\text{max}} \) = maximum seismically induced inertial force in rigid soil column
- \( m \) = mass of soil column of having a cross-sectional area \( A \) and length \( z \)
- \( a_{\text{max}} \) = peak ground acceleration at the surface of the soil profile
- \( \gamma_s \) = total unit weight of soil
- \( g \) = coefficient of acceleration due to gravity
- \( \sigma_v \) = total vertical stress at the base of the soil column
- \( \tau_{\text{rigid max}} \) = maximum seismically induced shear stress at the base of a rigid soil column
- \( \tau_{\text{flexible max}} \) = maximum seismically induced shear stress at the base of a flexible soil column

Figure 5.1: Stress reduction coefficient \((r_d)\) is defined as the ratio of the maximum seismically induced shear stress at the base of a flexible soil column to that at the base of a rigid soil column, both having length \( z \).
Figure 5.2: Magnitude versus distance distribution of the motions used in this study.
Figure 5.3: WUS profiles used in this study. The number in the corner of each subplot is the number of profiles in that grouping.
Figure 5.4: CEUS profiles used in this study. The number in the corner of each subplot is the number of profiles in that grouping.
Figure 5.5: The proposed models at magnitudes of 5.5 and 7.5, compared with Idriss (1999), Liao and Whitman (1986), and Cetin (2000).
Figure 5.6: Predicted $r_d$ values from several predictive equations above a heat map showing the density of $r_d$. Actual values from the WUS dataset. The value $E$ is the Nash-Sutcliffe (1970) model efficiency coefficient.
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Figure 5.7: Predicted $r_d$ values above a heat map showing the density of $r_d$. Actual values from the CEUS dataset. The value $E$ is the Nash-Sutcliffe (1970) model efficiency coefficient.
5.11 Electronic Supplement

5.11.1 NGA Database (WUS)

The distance given in the tables, $R$, is the closest distance to the rupture area (an $nan$ indicates that the value is not known). The units of $PGA$ and $R$ are $g$ and km, respectively.

Table 5.5: WUS (NGA) Earthquake Motions

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<th>$R$</th>
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187
### 5.11.2 McGuire et al. (2001) Database (CEUS)

The distance given in the tables, \( R \), is the closest distance to the rupture area (an *nan* indicates that the value is not known). The units of \( R \) and \( PGA \) are km and \( g \), respectively.

Table 5.6: Central-Eastern United States (CEUS) Earthquake Motions

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Chapter 6

Manuscript #4: An SPT Liquefaction Evaluation Procedure Based on Dissipated Energy

The authors of the following manuscript intend to submit it to ASCE’s *Journal of Geotechnical and Geoenvironmental Engineering*.

Samuel Lasley made the following contributions to this manuscript:

- wrote the first draft of the manuscript under the general direction of the other two authors.
- performed all regression and analysis
- investigate various functional forms for the limit state curve
- performed comparisons with the stress-based procedures
- created all tables and figures

Dr. Green made the following contributions to this manuscript:

- provided the framework for the proposed energy-based liquefaction evaluation procedure and associated equivalent number of cycles correlation (see Green 2000)
suggested the inclusion of the curve-fit to the Tokimatsu and Seed procedure
suggested the case history databases
suggested looking at comparisons between the proposed procedure and the stress-based procedures for extreme conditions

Dr. Rodriguez-Marek made the following contributions:

- Directed and instructed in the application of input parameter uncertainties to the limit state curve-fitting, including the first-order approximations
- Helped troubleshoot code and procedures
- aided in crafting the likelihood function for both including and excluding uncertainties
- Suggested the use of the Nash-Sutcliffe model efficiency coefficient

Dr. Green and Dr. Rodriguez-Marek both:

- provided feedback during all stages of the research
- edited the manuscript and provided valuable feedback between revisions

Dr. James K. Mitchell provided the motivation to develop an energy-based liquefaction evaluation procedure.
An SPT Liquefaction Evaluation Procedure Based on Dissipated Energy

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6.1 Abstract

The stress-based simplified liquefaction evaluation procedure was proposed in 1971 and continues to be an important tool for geotechnical earthquake engineering. However, at its core it remains a semi-empirical procedure with uncertain application outside the case history database from which it was regressed. Proposed herein is a simplified liquefaction evaluation procedure based on dissipated energy and presented in a form that will be familiar to geotechnical earthquake engineering practitioners. The proposed form is a function of peak ground acceleration, earthquake magnitude, SPT blow-count, and fines content, and it returns probability of liquefaction and/or factor of safety against liquefaction. The predictive accuracy of the proposed procedure rivals that of other popular stress-based procedures and is compatible with the results of equivalent-linear site response analyses. By using dissipated energy to quantify demand instead of the cyclic stress ratio, the capacity curves of the proposed procedure are insensitive to the shape of the demand earthquake time history. Thus, the proposed procedure can utilize the response of any arbitrary loading time history, including those of non-earthquake origin. The result is a robust liquefaction evaluation procedure that is simple to implement and with a wider sphere of application.
6.2 Introduction

Proposed herein is a liquefaction evaluation procedure based on dissipated energy. Soil liquefaction continues to be a source of significant hazard in seismically-active regions of the world. The current state-of-the-practice in liquefaction evaluation is the stress-based simplified procedure. Most stress-based simplified procedures predict the probability of liquefaction (and/or factor of safety against liquefaction) from the peak ground acceleration, total and initial effective overburden stresses, earthquake magnitude, and some in-situ measure of soil state (e.g. SPT blow count, CPT tip resistance, shear wave velocity). These procedures are semi-empirical (based on liquefaction/no-liquefaction case histories) and their validity beyond the limits of the case history databases from which they were derived is uncertain. For example, few liquefaction case histories exist for the central-eastern United States and a stress-based simplified procedure derived from western United States liquefaction case histories may not be directly applicable.

Dissipated energy has been shown to be a good indicator of the soil breakdown that leads to liquefaction, and the dissipated energy required to initiate liquefaction is relatively insensitive to the shape of the loading function (Figueroa et al. 1994; Liang et al. 1995). The energy-based procedure proposed herein accepts the same inputs as the stress-based simplified procedures and predicts the occurrence of liquefaction for the same case history database with the same success rate. Additionally, the form of the proposed energy-based procedure allows for application to other tectonic regimes via a regime-specific number of equivalent cycles ($n_{eq}$) correlation which accounts for differences in ground motion shape and duration between tectonic regimes. The procedure proposed herein allows the results of equivalent-linear site response analyses to be directly applied, and thus can be used to evaluate liquefaction potential for any arbitrary loading, be it of earthquake origin or otherwise.

The approach adopted in this research is to use a liquefaction/no-liquefaction case history database to compute a capacity curve. The functional form for this curve is first explored via a program of laboratory testing. In this paper, brief summaries of the stress-based simplified and energy-based liquefaction evaluation procedures are given. The results of laboratory data are presented showing the relationship between normalized dissipated energy ($\Delta W/\sigma'_v$) and relative density. Using the same general functional form from the labo-
ratory results, an empirical limit state (capacity) curve is regressed from an SPT database of liquefaction/no-liquefaction case histories. This proposed capacity curve is compared with the laboratory curve via a correlation between $N_{1,60cs}$ and relative density. The empirical field-based curve is recommended for practice and, as such, is also compared with two commonly-used stress-based liquefaction evaluation procedures. Finally, implications of the proposed procedure with regards to the effects of initial effective overburden stress are discussed.

### 6.3 Existing Stress-based Methods

The stress-based “simplified” liquefaction evaluation procedure was first proposed by Seed and Idriss (1971) and, separately, Whitman (1971). The demand term of the procedure, $CSR$, is determined using the peak ground acceleration of the expected earthquake:

$$ CSR = \frac{\tau_{avg}}{\sigma'_{v0}} = 0.65 \cdot \frac{a_{\text{max}}}{g} \cdot \frac{\sigma_v}{\sigma'_{v0}} \cdot r_d $$

(6.1)

where $\tau_{avg}$ is the average seismically-induced shear stress, $a_{\text{max}}$ is the peak ground acceleration, $g$ is the acceleration due to gravity, $\sigma_v$ is the total overburden stress, $\sigma'_{v0}$ is the initial effective overburden stress, and $r_d$ is the stress reduction coefficient (assumed by Whitman to be 1).

Over the years, this simplified procedure has moved from being laboratory-based to field-based (e.g. SPT, CPT) and undergone various improvements. These improvements can be summarized in the following equation for the factor of safety (Youd et al. 2001):

$$ FS = \frac{CRR}{CSR} \cdot MSF \cdot K_\sigma \cdot K_\alpha $$

(6.2)

where $CRR$ is the cyclic resistance ratio for a $M7.5$ earthquake, $MSF$ is the magnitude scaling factor, $K_\sigma$ is the overburden correction factor, and $K_\alpha$ is a correction factor for non-level ground conditions.

Cetin et al. (2004) proposed a probabilistic SPT procedure which allowed uncertainties in input parameters and the location of the $CRR$ capacity curve
to be quantified. Cetin et al. obtained their capacity curve by means of the maximization of a likelihood function. The same likelihood function is used in the research presented in this paper. Idriss and Boulanger (2008) presented deterministic, stress-based simplified liquefaction evaluation procedures for the SPT and CPT. Their procedures retain the same general form of Youd et al. (2001) but provide updated relationships for $r_d$, $MSF$, and $K_σ$. Boulanger and Idriss (2012) presented a probabilistic update to the 2008 deterministic SPT procedure.

6.4 Dissipated Energy and Liquefaction

Cyclic loading of soil causes a dissipation of energy. The dissipated energy per unit volume of the soil is the cumulative area bound by stress-strain hysteresis loops. Nemat-Nasser and Shokooh (1977) first introduced the idea of using dissipated energy to estimate liquefaction initiation, and numerous studies since have been performed to validate the idea. The results of laboratory testing (Simcock et al. 1983; Law et al. 1990; Green et al. 2000) have produced several pore water pressure models based on dissipated energy. The laboratory results have also shown that dissipated energy is a good predictor of excess pore water pressure generation, irrespective of the shape of the loading function (Figueroa et al. 1994; Liang et al. 1995) or whether an initial static shear stress is applied (Jafarian et al. 2012).

Numerous energy-based liquefaction evaluation procedures have been proposed over the years, based on both field case histories (e.g. Davis and Berrill 1982; Triunfa 1995; Green 2001; Mayfield 2007) and laboratory testing (e.g. Liang 1995; Davis and Berrill 1996; Kokusho 2013). Forward analyses of field-based procedures rely on attenuation relationships (e.g. radiated energy, cumulative absolute velocity, peak ground acceleration), and, perhaps with the exception of peak ground acceleration, these attenuation relationships are not available for all tectonic regimes and have difficulty predicting near-field effects or site-specific conditions. Moreover, few of these relationships exist in the literature. Forward analyses using the energy-based procedures that derive their capacity curves from laboratory test results require that lab tests are performed on soil specimens sampled from the site of interest and/or non-linear effective-stress site response analyses. A few lab-based procedures use equivalent-linear site response analyses to quantify demand and then
compare this demand with a capacity curve derived from laboratory results. However, this comparison is not appropriate since the equivalent-linear response assumes single values of shear modulus and damping for the entire time history, neglecting the effect of soil softening on the total dissipated energy to liquefaction (Green 2001).

The liquefaction evaluation procedure proposed herein is based on the procedure developed by Green (2001) and overcomes the limitations of the other energy-based procedures. Although the functional form of the capacity curve is inspired by the results of laboratory testing, it is not directly based on laboratory test results, removing the need for laboratory tests in forward analyses. Instead, it is based on field case histories and, for forward analyses, relies on peak ground acceleration attenuation relationships and number of equivalent cycles correlations. Both of these have a long history in stress-based simplified liquefaction procedures, and peak ground acceleration attenuation relationships are well-developed for various tectonic regimes. A new number-of-equivalent-cycles correlation has been developed by the authors (Lasley et al. 2015a) for both active shallow-crustal (e.g. western United States) and stable continental (e.g. central-eastern United States) tectonic regimes. This $n_{eq}$ correlation is based on dissipated energy and low-cycle fatigue. Finally, the procedure proposed herein has been developed in a format intended to be familiar to users of traditional stress-based procedures.

### 6.5 Laboratory Approach

Stress-controlled constant-volume (Finn et al. 1979) cyclic simple shear tests were performed by the authors on Monterey 0/30 sand. These tests were performed on specimens prepared via dry pluviation (Vaid and Negussey 1988) with relative densities ranging from approximately 30 to 80%, and cyclically loaded while overburden stresses of 60, 100, and 250 kPa were imposed on the specimens. Liquefaction was deemed to have occurred when a shear strain of 3.75% single-amplitude was exceeded (Vaid and Sivathayalan 1996; Sivathayalan and Ha 2011).

Figure 6.1 shows the stress-strain hysteresis loops and the shear stress versus normal stress plot for one of the tests. For each of the tests, the dissipated energy to liquefaction was computed. Figure 6.2 shows the accumulation of dissipated energy as a function of the cycle ratio ($N/N_{liq}$). In addition to
the dissipated energy to liquefaction ($\Delta W_{\text{Effect.}}$), another value of dissipated energy, $\Delta W_{\text{Total}}$, was obtained for each test by drawing a best fit line through the accumulated dissipated energy of the first half of the test. The value of this line at a cycle ratio of 1 is the dissipated energy corresponding to total stress analyses. This value of dissipated energy removes the dissipated energies due to the softening of the soil profile with increasing pore water pressure (Green 2000). It is especially useful when comparing lab results with those from equivalent-linear site response analyses because the equivalent-linear site response does not allow for soil softening as the loading progresses (i.e. $G_\gamma$ and $D_\gamma$ are constant for the entire loading time history of a given layer).

Figure 6.3 shows the cyclic stress ratio versus cycles to liquefaction for all of the tests with contour lines of equal normalized dissipated energy (corresponding to total stress analysis) to liquefaction. Dissipated energies were normalized by dividing the value by the initial effective normal stress, leaving a unit-less quantity. As can be seen in the figure, as relative density increases, the normalized dissipated energy to liquefaction also increases. Figure 6.4 illustrates the relationship between the normalized dissipated energy to liquefaction ($\Delta W_{\text{Total}}$) and the relative density of the test specimen. A strong relationship between the logarithm of normalized dissipated energy and the square of relative density is readily apparent. This functional form inspired the subsequent limit state functional form between normalized dissipated energy and SPT blow counts.

6.6 Case History-Based Approach

Similar to recent stress-based liquefaction evaluation procedures, the proposed energy-based procedure is based on field data in the form of a liquefaction/no-liquefaction case history database. The case history database of Boulanger et al. (2012) was adopted for use in this study. This SPT database contains the details of 115 liquefaction, 112 no-liquefaction, and 3 marginal liquefaction cases. Boulanger et al. gathered case histories from the Seed et al. (1984) and Cetin et al. (2004) databases, but then reevaluated and corrected the magnitude ($M_w$), $a_{\text{max}}$, and SPT blow counts, as necessary. From this database $M_w$, $a_{\text{max}}$, overburden- and fines content-corrected SPT blow count ($N_{1,60cs}$), total overburden stress ($\sigma_v$),
and initial effective overburden stress ($\sigma'_v0$) were used to calibrate the limit state curve proposed herein. In addition to the data from the Boulanger et al. (2012) database, shear wave velocities corresponding to 46 case histories (25 liquefaction; 21 no liquefaction) were taken from the Kayen et al. (2013) shear wave velocity database for sites matched between the two databases.

### 6.6.1 Methodology

As mentioned, dissipated energy is the cumulative area bound by stress-strain hysteresis loops, and can be estimated using the trapezoidal rule (Green and Terri 2005):

$$\Delta W = \frac{1}{2} \sum_{i=1}^{j-1} \left( (\tau_{i+1} + \tau_i) \cdot (\gamma_{i+1} - \gamma_i) \right)$$  \hspace{1cm} (6.3)

where $\Delta W$ is the dissipated energy per unit volume of soil in units of stress; $\tau_i$ and $\gamma_i$ are the stress and strain, respectively, at point $i$; and $j$ is the number of data points in the stress/strain time history. (The dissipated energy referred to in the remaining sections of this paper is $\Delta W_{\text{Total}}$, the dissipated energy corresponding to total stress analyses. For convenience, it will be referred to as dissipated energy or $\Delta W$ without the additional $\text{Total}$ subscript.) Because the case history database does not contain full stress and strain time histories, the dissipated energy of each case history cannot be estimated using Eqn. 6.3. Instead, the dissipated energy is estimated by multiplying the dissipated energy in one equivalent cycle ($\Delta W_{1,\text{eq}}$) by the number of equivalent cycles ($n_{eq}$). The dissipated energy in one cycle is derived from the equation for damping ratio ($D$) (Jacobsen 1960):

$$D = \frac{1}{4\pi} \frac{\Delta W_{1,\text{eq}}}{W_{\text{stored}}}$$  \hspace{1cm} (6.4)

where $\Delta W_{1,\text{eq}}$ is the dissipated energy from one cycle and $W_{\text{stored}}$ is the stored energy which is equal to $1/2\tau\gamma$. Substituting in the definition of stored energy, letting $\tau = \tau_{\text{avg}}$ and $\gamma = \tau_{\text{avg}}/G_\gamma$, and rearranging terms, we
As previously mentioned, the quantity $\tau_{\text{avg}}$ is the amplitude of shear strain in one equivalent cycle and is estimated in the same way as the stress-based procedure (Eqn. 6.1). A new stress reduction coefficient was developed as part of this research (Lasley et al. 2015b), and takes the following form:

$$r_d = (1 - \alpha) \exp \left( \frac{-z}{\beta} \right) + \alpha$$  \hspace{1cm} (6.6)

where $z$ is in meters, and

$$\alpha = \exp(a_1 + a_2 \cdot M_w)$$  \hspace{1cm} (6.7)

$$\beta = a_3 + a_4 \cdot M_w$$  \hspace{1cm} (6.8)

Regression coefficients $a_1-a_4$ are given in Table 6.1.

The values of $D_\gamma$ and $G_\gamma$ are obtained from shear modulus reduction and damping versus strain curves in a way similar to equivalent-linear site response analysis: $G_\gamma/G_{\text{max}}$ is function of shear strain, $\gamma$, and must be chosen to be consistent with $\tau_{\text{avg}}/G_\gamma = \gamma$. Tokimatsu and Seed (1987) proposed a direct approach to obtain these values. Figures 6.5 through 6.7 provide graphical implementations tailored for the liquefaction evaluation procedure proposed herein and correspond to clean sands, sands with high fines contents, and silts, respectively. (The diamonds in these figures indicate a threshold shear strain of 0.01%; no liquefaction is expected for shear strains below the threshold.) Thus, for given values of $\tau_{\text{avg}}$, small strain shear modulus $(G_{\text{max}})$, and mean effective stress, the quantity $\Delta W_{1,eq}/G_{\text{max}}$ is readily obtained. Furthermore, the curves in Figures 6.5 and 6.6 have been fit with a fifth-order polynomial to ease computations (an appropriate fit was not obtained for the silt curve in Figure 6.7). For a given mean effective stress,
the dissipated energy in one cycle divided by the small-strain shear modulus can be approximated as:

$$\log_{10} \left( \frac{\Delta W_{1,eq}}{G_{\text{max}}} \right) = d_1 \Gamma^5 + d_2 \Gamma^4 + d_3 \Gamma^3 + d_4 \Gamma^2 + d_5 \Gamma + d_6 \quad (6.9)$$

where:

$$\Gamma = \log_{10} \left( 0.65 \cdot a_{\text{max}} \cdot \sigma_v \cdot r_d / (g \cdot G_{\text{max}}) \right); \sim -5 \leq \Gamma \leq -3 \quad (6.10)$$

and the regression coefficients ($d_1$-$d_6$) for a range of mean effective stresses are given in Table 6.2 for clean sands and Table 6.3 for sands with high fines content. In obtaining $G_\gamma$ and $D_\gamma$ values from the shear modulus reduction and damping curves, a lower limit of 40 kPa was imposed for the initial effective overburden stress. This roughly corresponds to the lowest mean initial effective stress ($\sigma_{\text{m0}}' = 0.25 \text{ atm}$) curve given by Darendeli and Stokoe (2001).

The small-strain shear modulus, $G_{\text{max}}$ is calculated from the shear wave velocity, where available, or estimated using the corrected SPT blow count (Seed et al. 1986; Ohta and Goto 1976):

$$G_{\text{max}} = 440 \cdot N_{1,60 \text{cs}} \cdot \frac{P_a}{\sigma_{\text{m0}}'} \cdot \sqrt{\frac{\sigma_{\text{m0}}'}{P_a}} \quad (6.11)$$

where $P_a$ is standard atmospheric pressure, and $\sigma_{\text{m0}}'$ is the mean initial effective stress ($\sigma_{\text{m0}}' = (1 + 2K_o)\sigma_{\text{e0}}'/3$) in the same units as $P_a$. Recent research (Wair et al. 2012) has suggested that $N_{60}$, the SPT blow count uncorrected for overburden stress, should be used in relationships of this kind instead of $N_{1,60}$. However, the overburden stress-corrected SPT blow count is used here as presented by Seed et al. (1986).

The number of equivalent cycles are calculated using a low-cycle fatigue (Green and Terri 2005) correlation developed as part of this research (Lasley et al. 2015a). Dissipated energies from equivalent-linear site response analyses were used as the damage metric to obtain the $n_{eq}$ correlations. Thus, the $n_{eq}$ values are consistent with the procedure proposed herein:

$$n_{eq} = \exp \left( b_1 + b_2 \ln(a_{\text{max}}) + b_3 M_w \right) \quad (6.12)$$
Regression coefficients \((b_1-b_4)\) for active shallow-crustal tectonic regimes (e.g. the western United States) and for stable continental tectonic regimes (e.g. the central-eastern United States) were provided by Lasley et al. 2015a and are given in Table 6.4. For either tectonic regime, the number of cycles is multiplied by 2 to account for bi-directional motions. The normalized dissipated energy demand term, \(\Delta W/\sigma'_{v0}\), can then be calculated as:

\[
\frac{\Delta W}{\sigma'_{v0}} = \left( \frac{\Delta W_{1,eq}}{G_{max}} \right) \cdot \frac{G_{max}}{\sigma'_{v0}} \cdot (2 \cdot n_{eq}) \tag{6.13}
\]

Alternatively, if \(G_\gamma\) and \(D_\gamma\) are obtained without using either Figure 6.5 or Eqns. 6.9 and 6.10 (e.g. for conditions of mean initial effective stresses greater than 200 kPa), the normalized dissipated energy is calculated as:

\[
\frac{\Delta W}{\sigma'_{v0}} = \frac{2\pi \cdot D_\gamma [0.65 \cdot \sigma_{max} \cdot \sigma_v \cdot r_d]^2}{\sigma'_{v0} \cdot G_\gamma \cdot g^2} \cdot (2 \cdot n_{eq}) \tag{6.14}
\]

This is the same general form given by Green (2001), except the initial effective overburden stress is used here instead of the mean effective stress.

### 6.6.2 Definition of the Limit State Curve

The limit state curve delineates the liquefaction and no-liquefaction regions. The functional form proposed herein was chosen based on the laboratory liquefaction curve and the distribution of liquefaction/no-liquefaction case histories in normalized dissipated energy-SPT blow count space:

\[
g = c_1 N_{1,60cs} - \ln \left( \frac{\Delta W}{\sigma'_{v0}} \right) + c_2 + \varepsilon \tag{6.15}
\]

where \(c_1\) and \(c_2\) are regression coefficients and \(\varepsilon\) is an error term with a mean of zero and a standard deviation of \(\sigma_\varepsilon\). If \(g \leq 0\), liquefaction is predicted; if \(g > 0\) no liquefaction is predicted.

For a given liquefaction case history, if it is assumed that there is no uncertainty in the input parameters and that the error term \(\varepsilon\) is normally
distributed, the probability of liquefaction is (Boulanger and Idriss 2012):

\[ P[g \leq 0] = 1 - \Phi \left[ \frac{g}{\sigma_\varepsilon} \right] \]  

where \( \Phi[\cdot] \) is the standard normal cumulative distribution function. Equal-probability curves for normalized dissipated energy are thus:

\[ \left( \frac{\Delta W_{liq}}{\sigma'_{v0}} \right)_{P_{liq}} = \exp \left( c_1 N_{1.60cs} + c_2 + \Phi^{-1} [P] \cdot \sigma_\varepsilon \right) \]  

where \( \Delta W_{liq} \) is the dissipated energy required to cause liquefaction under the given conditions. For deterministic forward analyses, a probability of 15% is commonly used to define the limit state curve (e.g. Cetin 2004; Boulanger and Idriss 2012), giving the following:

\[ \left( \frac{\Delta W_{liq}}{\sigma'_{v0}} \right) = \exp \left( c_1 N_{1.60cs} + c_2 - 1.036 \cdot \sigma_\varepsilon \right) \]  

This expression (Eqn. 6.18) is analogous to the CRR curve of stress-based procedures. Using this deterministic limit state curve, a factor of safety can be calculated as:

\[ FS_{liq} = \frac{\ln \left( \frac{\Delta W_{liq}}{\sigma'_{v0}} \right) - c_{FS}}{\ln \left( \frac{\Delta W}{\sigma'_{v0}} \right) - c_{FS}} \]  

where \( c_{FS} \) is equal to 1.2 \cdot c_2. Because the capacity (\( \ln(\Delta W_{liq}/\sigma'_{v0}) \)) and demand (\( \ln(\Delta W/\sigma'_{v0}) \)) terms used to compute the factor of safety are logarithms whose values are negative, \( c_{FS} \) is necessary to obtain factor of safety values comparable to those of other simplified procedures.

Alternatively, uncertainties in the input parameters may be included in the calculation of the probability of liquefaction:

\[ P[g \leq 0] = \int_\eta \int_\omega 1 - \Phi \left[ \frac{g}{\sigma_\varepsilon} \right] f_N(\eta) f_W(\omega) \, d\eta \, d\omega \]  

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where $\eta$ is the corrected SPT blow count ($N_{1,60cs}$), $\omega$ is the natural logarithm of the normalized dissipated energy ($\Delta W/\sigma_{v0}'$), and $f_N(\eta)$ and $f_W(\omega)$ are the probability density functions of the SPT blow count and the natural logarithm of normalized dissipated energy, respectively.

### 6.6.3 Regression Approach

The coefficients of $g$ (Eqn. 6.15) are obtained from a maximum likelihood estimation. A likelihood function, by definition, returns the likelihood that the limit state model correctly predicts liquefaction for all liquefied sites, and no liquefaction for all the sites without liquefaction. Thus, the likelihood function is defined as (Cetin 2000; Cetin et al. 2002):

$$L = \prod_{\text{Liq. Cases}} P[g \leq 0] \times \prod_{\text{Nonliq. Cases}} 1 - P[g \leq 0]$$  \hspace{1cm} (6.21)

However, the log-likelihood is used in this study. It is defined as:

$$\ln L = \sum_{\text{Liq. Cases}} \ln (P[g \leq 0]) + \sum_{\text{Nonliq. Cases}} \ln (1 - P[g \leq 0])$$  \hspace{1cm} (6.22)

The log-likelihood can be maximized either by assuming that input values of normalized dissipated energy and SPT blow count are known exactly (using Eqn. 6.16), or by accounting for the uncertainties in each of the input parameters (Eqn. 6.20). The uncertainties in both the normalized dissipated energy and the clean-sand corrected SPT blow count were estimated using a first-order approximation (Ditlevsen and Madsen 1996). Table 6.5 summarizes the uncertainty values used in this estimation.

### 6.6.4 Performance of the Proposed Procedure

The regression coefficients for Eqn. 6.15 are given in Table 6.6 for four different scenarios:

1. Small-strain shear modulus values were estimated only from $N_{1,60cs}$ using Eqn. 6.11.
2. Small-strain shear modulus values were calculated from measured shear wave velocities, where available, and estimated from $N_{1,60cs}$ where measured shear wave velocity values were not available. The cases with measured shear wave velocities were weighted four times that of the others in the likelihood maximization.

3. Same as #1 except uncertainties in the values of $N_{1,60cs}$ and $\Delta W/\sigma_v^{*0}$ were incorporated into the likelihood maximization using Eqn. 6.20.

4. Same as #2 except incorporating uncertainties as in #3.

Figure 6.8 shows the limit state curves obtained from scenario #1 for probabilities of 15, 50, and 85%. Similar to the stress-based simplified procedures, at low SPT blow counts the curves become flat and at high SPT blow counts the curves are nearly vertical. This latter fact indicates that at blow counts above $\sim 30$, most soils are dense enough to experience dilation, inhibiting liquefaction. At low SPT blow counts and low energies, shear straining below the threshold shear strain will also preclude the initiation of liquefaction. In this paper, the limit state curves in these areas are plotted as dashed lines to highlight these conditions. Figure 6.9 shows the same limit state curves with the normalized dissipated energy on a logarithmic scale.

The median limit state curve ($P = 50\%$) is shown in Figures 6.10 through 6.13 with the liquefaction/no-liquefaction case histories for various ranges of fines content, initial effective overburden stress, peak ground acceleration, and magnitude. For all given ranges of fines content, initial effective overburden stress, peak ground acceleration, and magnitude, the dissipated-energy limit state curve does well dividing the liquefaction and no-liquefaction case histories.

Table 6.7 compares the predictive performance of the four scenarios for this case history database. Included also in the table are the Boulanger and Idriss (2012) and Cetin (2004) liquefaction procedures using their median ($P = 50\%$) liquefaction curves. The competing liquefaction evaluation scenarios/procedures are compared by examining the number of case histories that were correctly and incorrectly predicted. The incorrectly predicted points can be further separated as the number of false positive and number of false negative events. In this case, a false positive event is an event that was predicted to liquefy but did not; a false negative event was predicted to not liquefy but did liquefy. In addition to these counts, the predictive ability of the models was also evaluated using the Nash-Sutcliffe model efficiency
coefficient, $E$. For this comparison, the value of $E$ is calculated as follows (Nash and Sutcliffe 1970):

$$E = 1 - \frac{\sum_{i=1}^{m} (g_{\text{Actual}} - \text{sign}(g_{\text{Predicted}}))^2}{\sum_{i=1}^{N} (g_{\text{Actual}} - \bar{g_{\text{Actual}}})^2}$$

(6.23)

where $g_{\text{Actual}}$ indicates whether the case history liquefied and has values of -1, 0, or 1 for liquefaction, marginal liquefaction, and no liquefaction, respectively. The ‘sign()’ function returns values of -1, 0, or 1 depending on the sign of the input, and $g_{\text{Predicted}}$ is obtained using Eqn. 6.15 (with the regression values of scenario #1), the Boulanger and Idriss (2012) procedure, or the Cetin et al. (2004) procedure. The variable $m$ is the number of case histories in the database. The Nash-Sutcliffe model efficiency coefficient, $E$, can range in value from 1 to $-\infty$. A value of unity indicates the model is a perfect fit to the data, and a value of less than zero indicates that the mean value of the actual case history results ($g_{\text{Actual}}$) is a better predictor than the model. Since the sign function is used in Eqn. 6.23, the value of $E$ is simply a single-point summary of the number of correct and incorrect predictions.

As seen in Table 6.7, the Boulanger and Idriss (2012) and the Cetin et al. (2004) limit state curves predict almost equally well for this case history database, with the Boulanger and Idriss (2012) procedure predicting slightly better with 197 out of 230 case histories predicted correctly. This is not surprising because their limit state curve was regressed using this case history data. The Cetin et al. (2004) procedure predicted 195 case histories correctly. The dissipated energy scenarios 1 and 3 predicted 193 and 198 cases correctly, respectively. Scenario 3 and Boulanger and Idriss (2012) have the same number of false negatives (20) and nearly the same number of false positive predictions of 12 and 13, respectively. The Cetin et al. (2004) prediction, on the other hand, had only 9 false negative predictions, indicating a limit state curve shifted slightly toward lower $CSR$ for a given SPT blow count, in comparison to the other two procedures.

Scenarios 2 and 4, using the measured shear wave velocities where available, had much poorer performance overall; the measured shear wave velocities introduce an additional source of scatter into the dissipated energy calculations. For all case histories with measured shear wave velocity, the $G_{\text{max}}$
values calculated from the measured shear wave velocities were less than those estimated using the Seed et al. (1986) equation (6.11). To investigate the effect of Eqn. 6.11 on the overall analyses, new regression coefficients for Eqn. 6.11 were obtained using the measured shear wave velocity values and the corresponding $N_{1,60cs}$ values. New regression coefficients for the limit state curve were obtained for all scenarios using this alternate $G_{max}$-$N_{1,60cs}$ correlation and numbered from 5 to 8. The effect of using the new correlation between $G_{max}$ and $N_{1,60cs}$ is to increase the uncertainty in the location of the limit state curve ($\sigma_\varepsilon$) and decrease the accuracy for the scenarios that calculate $G_{max}$ from $N_{1,60}$ alone (scenarios 1 & 5 and 3 & 7; see Tables 6.8 and 6.9). The opposite is true for the scenarios that use the measured shear wave velocities (scenarios 2 & 6 and 4 & 8); uncertainties were decreased and the accuracy was increased. The dissipated energy to liquefaction is increased for all cases using the alternate correlation, as shown by the changes in the value of $c_2$ between Tables 6.6 and 6.8. The differences in the value of $c_1$ are less pronounced. Because the original Seed et al. (1986) equation has precedence and the resulting limit state curves have a slightly higher success rate in prediction, the regression coefficients given for scenarios 1 and 3 are suggested for forward analyses with SPT blow counts. However, the limit state curves for scenarios 6 and 8 may be more accurate for forward analyses involving measured shear wave velocities.

When incorporating uncertainties into the likelihood function via Eqn. 6.20 (scenarios 3 and 4), the predictive ability (measured in terms of the prediction of liquefaction or no-liquefaction for each the case histories) was improved. The uncertainty in the location of the limit state curve ($\sigma_\varepsilon$) was reduced, likely because the uncertainty in the input parameters masks uncertainty in the location of the limit state curve. A similar reduction in uncertainty was experienced by Boulanger and Idriss (2012).

### 6.6.5 Performance Compared to Boulanger and Idriss (2012)

Since the liquefaction evaluation procedure proposed herein was developed from the same case history database as Boulanger and Idriss (2012), it is fitting that the two procedures are compared in more detail. The two procedures give similar results, and, for this case history database, have very
similar success rates in prediction. In this section, the median liquefaction
curves ($P = 50\%; g = 0$) are used as the liquefaction criteria (i.e. a case
history was predicted to liquefy if the calculated probability of liquefaction
was greater than 50%).

Despite the similarity in overall success rate, the two procedures disagree in
a few cases. Figure 6.14 shows each procedure with its limit state curves
corresponding to probabilities of liquefaction of 15, 50, and 85% (using the
regression coefficients and uncertainty of scenario #1). The small white
squares indicate the case histories on which the two procedures agree and
are correct. The stars and dots indicate case histories for which the two pro-
cedures wrongly agree and disagree, respectively. For these latter two cases,
the marker is color-coded to show the reported liquefaction: dark markers are
cases that were reported to have liquefied and white markers (except for the
square markers) are case histories that reported no liquefaction. Almost all
of the cases where the two procedures disagree or are both wrong fall within
the bounds set by the 15 and 85% probability curves. Some exceptions are
given by a few no-liquefaction case histories at low SPT blow counts (white
dots at 5-10 blows/30cm). The Boulanger and Idriss (2012) procedure cor-
correctly predicted no-liquefaction in these cases; all of these cases are below the
$P = 50\%$ curve and four are below the $P = 15\%$ curve. The energy-based
procedure, however, predicts liquefaction for these cases.

Figure 6.15 shows how the two procedures compare for different values of
SPT blow count, peak ground acceleration, fines content, initial effective
overburden stress, and magnitude. The locations of the points in the y-
direction indicate whether the case history reported no liquefaction, marginal
liquefaction, or liquefaction. It can be seen that the Boulanger and Idriss
(2012) procedure more often correctly predicts no liquefaction at low SPT
blow counts and low peak ground acceleration where the procedure proposed
herein more often correctly predicts liquefaction at low SPT blow counts and
low peak ground acceleration. Similarly, the Boulanger and Idriss procedure
appears to be biased towards predicting liquefaction at low fines content. No
bias is apparent for either procedure for the range of initial effective overbur-
den stress. Finally, the procedure proposed herein appears to better predict
liquefaction at low magnitudes when compared to the Boulanger and Idriss
(2012) procedure. However, this result may be related to the aforementioned
trends at low SPT blow counts and peak ground accelerations.
6.6.6 Behavior at High Effective Overburden Pressures

Youd et al. (2001) and most stress-based procedures since then have suggested the use of $K_\sigma$ to correct the soil capacity ($CRR$) for initial effective overburden stresses other than 1 atm. Although the Cetin et al. (2004) procedure directly incorporates the correction as part of the limit state curve, Boulanger and Idriss (2012) maintain a separate $K_\sigma$ term to apply to the $CRR$ or factor of safety. The procedure proposed herein, however, does not require an overburden stress correction factor since the normalized dissipated energy required for liquefaction is constant over a range of initial effective overburden stresses, for a constant value of $N_{1,60cs}$.

To illustrate the consistency of the procedure proposed herein, dissipated energy principles were used to back-calculate an overburden stress correction factor for stress-based procedures. An inherent part of this is the shear modulus reduction and damping curves of Darendeli and Stokoe (2001) that are a function of mean initial effective stress. The back-calculated correction factor was obtained by scaling the applied shear stress, $\tau$, until the normalized dissipated energy in one hysteresis loop for a given initial effective overburden stress was equal to the normalized dissipated energy in a hysteresis loop for an overburden stress of 1 atm and a given shear stress, $\tau_{\sigma'\nu_0=1 \text{ atm}}$. The correction factor is simply the ratio of these stresses, normalized by initial effective overburden stress:

$$K_\sigma = \frac{\tau/\sigma'_{\nu_0}}{\tau_{\sigma'\nu_0=1 \text{ atm}}/1 \text{ atm}}$$  (6.24)

Figure 6.16 shows the $K_\sigma$ curves back-calculated from the normalized dissipated energy along with the Hynes and Olsen (1999) and Boulanger and Idriss (2004) curves for a range of soil densities. The Hynes and Olsen (1999) curves were suggested by the Youd et al. (2001) procedure, and the Boulanger and Idriss (2004) curves were suggested by the Idriss and Boulanger (2008) liquefaction procedure. The dissipated-energy-derived curves are insensitive to soil density but are affected by the parameters used to obtain the shear modulus reduction and damping curves. The figure shows a derived $K_\sigma$ curve for ‘clean sand’ and another for ‘sand with high fines content’ as given by the Darendeli and Stokoe (2001) degradation curves. The Hynes and Olsen
(1999) curves are given for relative densities between 40 and 60% only; thus only the Boulanger and Idriss (2004) curves are shown for a relative density of 30%. The dissipated-energy-derived curve for clean sand falls alongside the Hynes and Olsen (1999) curve for a relative density of 50%—right in the middle of the range given by the Hynes and Olsen curves. The derived curve for sand with high fines content lies between the curves given by Hynes and Olsen (1999) and those given by Boulanger and Idriss (2004).

While the normalized dissipated energy to liquefaction (or capacity term) is insensitive to overburden stress, the demand term is affected by the change in initial effective overburden stress and shows a different trend with depth when compared to the Cetin et al. (2004) and Boulanger and Idriss (2012) stress-based procedures. Figure 6.17 shows normalized demand, normalized capacity, and the factor of safety versus initial effective overburden stress for all three procedures for a soft profile and low intensity event. The corrected SPT blow count is constant with depth and the ground water table is shallow (0.5m). The demand and capacity are normalized by the respective demand and capacity at an initial effective overburden stress of 1 atm. For the stress-based procedures, the demand is the cyclic stress ratio (Eqn. 6.1).

All three demand curves show a peak value at low overburden stresses with the demand thereafter decreasing with depth. This peak is caused by the multiplication of the stress reduction coefficient that decreases with depth and the ratio of total and initial effective overburden stresses that increases with depth. The demand curve of the procedure proposed herein is also affected by the stiffening of the soil layer with increasing initial effective stress as predicted by the shear modulus reduction and damping curves (i.e. $D_\gamma$ decreases and $G_\gamma$ increases for a given shear strain in Eqn. 6.14).

Since the capacity curves in Figure 6.17 are normalized and incorporate the $K_\sigma$ correction factor, the stress-based curves are the $K_\sigma$ curves of the respective procedures. The capacity curve corresponding to the procedure proposed herein is constant with increasing initial effective overburden stress, reflecting the lack of overburden correction factor. The resulting factor of safety curves further illustrate the differences in the three procedures. For this earthquake scenario, the Boulanger and Idriss (2012)-predicted factor of safety briefly dips below the $FS = 1$ line, then returns to moderately-high factors of safety at high initial effective overburden stresses. The Cetin et al. (2004) procedure predicts liquefaction at nearly all initial effective over-
burden stresses, and the procedure proposed herein predicts low factors of safety at low initial effective overburden stresses, then a factor of safety of around unity as the initial effective overburden stresses increase.

Figure 6.18 shows the trends in demand, capacity, and factor of safety for an event of $M_w 7.5$, $a_{max} = 0.35g$, and an SPT blow count of 30. In this case, the demand curve of the proposed procedure has a peak at higher initial effective overburden stresses than the other two due to the influence of the shear modulus reduction and damping curves. This results in a factor of safety that remains lower for a greater range of low initial effective overburden stresses but increases with increasing initial effective overburden stress. For both events shown in Figures 6.17 and 6.18, the factor of safety of the procedure proposed herein changes less abruptly with increasing initial effective overburden stress than the factors of safety from the two stress-based procedures.

6.6.7 Application with Site Response Analyses

With conventional stress-based simplified procedures, site response analyses may be utilized to obtain a better estimate of the maximum shear stress at depth, thus bypassing the stress reduction coefficient, $r_d$. However, if any of the components of the stress-based procedure (e.g. $r_d$, MSF) are biased, the cyclic stress ratio obtained from site response analyses should not be compared directly with the stress-based capacity curve.

In contrast, the energy-based procedure proposed herein was consistently developed with equivalent-linear site response analyses in mind. For example, both the number of equivalent cycles, $n_{eq}$, and $r_d$ correlations were developed from the results of equivalent-linear site response analyses using 50 liquefaction site profiles (from Cetin 2000) and 194 pairs of horizontal rock motions from 47 earthquake events. For each layer of each site and motion combination, the number of equivalent cycles was calculated using dissipated energy as the damage metric (for details see Lasley et al. 2015a). Thus for a site that is well-characterized, equivalent-linear site response analysis can be performed, and the dissipated energy can be calculated using Eqn. 6.3. This dissipated energy incorporates the damaging effects of the entire motion, not just the peak value. Once normalized by the initial effective overburden stress, this normalized dissipated energy can be used directly in Eqns. 6.15,
6.16, and 6.19 to determine the predicted probability of liquefaction and factor of safety.

In this way, the energy-based procedure proposed herein could be used in more advanced site response analyses that modify the soil behavior once initial liquefaction occurs. For example, the strength of a soil element may be reduced to the residual strength once liquefaction occurs, thus influencing the response of adjacent soil elements. The proposed procedure provides a convenient indicator of initial liquefaction under these circumstances, provided that the total-stress dissipated energy is calculated in the analyses.

To ease the estimation of dissipated energy from equivalent-linear site response, both ShakeVT2 (Lasley et al. 2014; https://bitbucket.org/slasley/shakevt2.git) and Strata (Rathje and Kottke 2010; Kottke and Rathje 2008) have the option to compute the dissipated energy from an equivalent linear site response analysis and include the Darendeli and Stokoe (2001) shear modulus reduction and damping curves.

The easy application of equivalent-linear site response analyses also allows the proposed limit state curves to be used in conjunction with any cyclic loadings including non-earthquake seismic loadings such as those from remedial ground densification and other mechanical vibrations.

### 6.7 Comparison of Lab- and Field-Based Capacity Curves

In order to compare the lab-based capacity curve (Figure 6.4) to the field-based capacity curve, the following relationship was used (Meyerhof 1957; Idriss and Boulanger 2008):

\[ D_r \approx 15\sqrt{N_{1,60}} \]  

(6.25)

where \( D_r \) is in percent. Figure 6.19 shows the lab-based capacity curve plotted as a function of SPT blow count with the field-based curves (scenario 1) of 15, 50, and 85% probability of liquefaction. While both curves show similar trends of increasing dissipated energy to liquefaction with increasing SPT blow count, the slopes and intercepts disagree. Additional research is
needed to understand the differences between the curves. However, some of
the difference may be attributed to the fact that the lab curve is a liquefaction
triggering curve and the field curve is a manifestation curve.

6.8 Conclusion

Proposed herein is an energy-based simplified liquefaction evaluation proce-
dure. Soil liquefaction poses a hazard to life and property in seismically-
active regions. The current state-of-practice for evaluating liquefaction sus-
ceptibility is the use of any of a number of stress-based simplified procedures
based on field case histories. Instead of using the cyclic stress ratio in con-
junction with a magnitude scaling factor to quantify capacity and demand,
the procedure proposed herein uses dissipated energy normalized by the ini-
tial effective overburden stress. This normalized dissipated energy has been
shown in previous studies to be a good indicator of soil structure breakdown
and consequent liquefaction.

To ease adoption, the proposed procedure is presented in a form similar
to the stress-based procedures and is a function of SPT blow count, peak
ground acceleration, and earthquake magnitude. The result of the procedure
is a probability of liquefaction and/or a factor of safety against liquefaction.
For forward analyses, the regression coefficients for scenario #3 are recom-
mended. However, the uncertainty (σ_ε) in the location of the limit state curve
should not be regarded as less than the value given for scenario #1. Thus the
recommended capacity curve corresponding to a probability of liquefaction
of 15% is:

\[
\frac{\Delta W_{liq}}{\sigma' v_0} = \exp(0.30 N_{1,60cs} - 12.95) \quad (6.26)
\]

For a given normalized dissipated energy and corrected SPT blow count, the
probability of liquefaction can be estimated as:

\[
P_{liq} = 1 - \Phi \left[ \frac{0.30 N_{1,60cs} - \ln \left( \frac{\Delta W}{\sigma' v_0} \right) - 11.61}{1.29} \right] \quad (6.27)
\]
where $\Phi[\cdot]$ is the standard normal cumulative distribution function.

Compared to the Cetin et al. (2004) and Boulanger and Idriss (2012) liquefaction evaluation procedures, the proposed energy-based procedure has a similar success rate when predicting the occurrence of liquefaction for the set of cases histories from which it was calibrated. Differences between this procedure and the others can be seen at high initial effective overburden stresses beyond those of the case history database. The difference is manifest as a greater reduction in demand as well as a constant capacity with increasing initial effective overburden stress.

Because the procedure proposed herein uses normalized dissipated energy for its demand and capacity terms, the resulting limit state curve is insensitive to the shape of the input ground motion. This means the proposed procedure is more applicable to other tectonic regimes and to non-earthquake sources of cyclic loading. Additionally, the procedure proposed herein has been designed for use with equivalent-linear site response analyses allowing for greater flexibility and detail in liquefaction evaluations.

### 6.9 Acknowledgements

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### 6.10 References


### 6.11 Tables

Table 6.1: Regression Coefficients for \( r_d \) (Lasley et al. 2015b)

<table>
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<tr>
<th>EQ Regime</th>
<th>( a_1 )</th>
<th>( a_2 )</th>
<th>( a_3 )</th>
<th>( a_4 )</th>
<th>( \sigma )</th>
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<td>Active Shallow-Crustal</td>
<td>-4.031</td>
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<td>-28.47</td>
<td>7.798</td>
<td>0.1397</td>
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<td>Stable Continental</td>
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<td>0.439</td>
<td>-15.38</td>
<td>4.922</td>
<td>0.1586</td>
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Table 6.2: Regression Coefficients for the Fit of the \( \Delta W_{1,eq}/G_{\text{max}} \) Curves (Clean Sand)

<table>
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<tr>
<th>( \sigma_{m0}' ) (kPa)</th>
<th>( d_1 )</th>
<th>( d_2 )</th>
<th>( d_3 )</th>
<th>( d_4 )</th>
<th>( d_5 )</th>
<th>( d_6 )</th>
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<tr>
<td>25</td>
<td>0.242</td>
<td>5.848</td>
<td>56.101</td>
<td>267.91</td>
<td>640.3145</td>
<td>608.05276</td>
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<td>50</td>
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<td>52.685</td>
<td>249.053</td>
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<td>553.24074</td>
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<td>100</td>
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<td>5.219</td>
<td>49.129</td>
<td>229.977</td>
<td>538.6714</td>
<td>500.38834</td>
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<td>200</td>
<td>0.208</td>
<td>4.881</td>
<td>45.541</td>
<td>211.152</td>
<td>489.8841</td>
<td>450.27458</td>
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Table 6.3: Regression Coefficients for the Fit of the \( \Delta W_{1,eq}/G_{\text{max}} \) Curves (Sand with High Fines Content)

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<tr>
<th>( \sigma_{m0}' ) (kPa)</th>
<th>( d_1 )</th>
<th>( d_2 )</th>
<th>( d_3 )</th>
<th>( d_4 )</th>
<th>( d_5 )</th>
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<tr>
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<td>-0.4056</td>
<td>-1.7385</td>
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<td>50</td>
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<td>0.4993</td>
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Table 6.4: Regression Coefficients for \( n_{eq} \) (Lasley et al. 2015a)

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<th>( b_3 )</th>
<th>( b_4 )</th>
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<td>0.254</td>
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<td>Stable Continental</td>
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<td>EQ Regime</td>
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<td>$b_2$</td>
<td>$b_3$</td>
<td>$b_4$</td>
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Table 6.5: Values Used in the First-Order Approximation of Uncertainty. $\mu$ denotes the mean, $\sigma$ denotes the standard deviation, and $\delta$ is the coefficient of variation or $\sigma/\mu$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
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<tr>
<td>$\sigma_D$</td>
<td>Varies</td>
<td>Darendeli and Stokoe (2001), function of shear strain</td>
</tr>
<tr>
<td>$\sigma_{G/G_{max}}$</td>
<td>Varies</td>
<td>Darendeli and Stokoe (2001)</td>
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<td>$\rho_{D,G/G_{max}}$</td>
<td>-0.5</td>
<td>Rodriguez-Marek et al. (2014)</td>
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<tr>
<td>$\delta_{\ln PGA}$</td>
<td>0.3</td>
<td>Cetin (2000)</td>
</tr>
<tr>
<td>$\sigma_{rd}$</td>
<td>0.15</td>
<td>From model regression</td>
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<tr>
<td>$\delta_{\sigma_v}$</td>
<td>0.1</td>
<td>From assumed uncertainties in $\gamma$ and gwt</td>
</tr>
<tr>
<td>$\delta_{\sigma_v^0}$</td>
<td>0.1</td>
<td>From assumed uncertainties in $\gamma$ and gwt</td>
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<td>$\rho_{\sigma_v,\sigma_v^0}$</td>
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<td>Based on uncertainty in the location of the water table</td>
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<td>$\sigma_\gamma$</td>
<td>0.1</td>
<td>Moss (2003)</td>
</tr>
<tr>
<td>$\mu_\gamma$</td>
<td>19.5 kN/m$^2$</td>
<td>Assumed; 17.0 above water table</td>
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<tr>
<td>$\delta_{V_s}$</td>
<td>0.5</td>
<td>When calculated from SPT; 0.25 when measured</td>
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<tr>
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<td>(B.R. Cox, personal communication, 2015)</td>
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<td>$\sigma_{\ln n_{eq}}$</td>
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<td>From model regressions</td>
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<td>$\rho_{rd,\ln n_{eq}}$</td>
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<td>From model regressions/data</td>
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<td>$\delta_{N_{1,60}}$</td>
<td>0.2</td>
<td>Or $\sigma = 3$; from Cetin (2000)</td>
</tr>
<tr>
<td>$\delta_{FC}$</td>
<td>0.2</td>
<td>Cetin (2000)</td>
</tr>
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</table>

Table 6.6: Regression Coefficients for the Proposed Limit State Curve

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$\sigma_\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 $- G_{max} = f(N_{1,60cs})$</td>
<td>0.2691</td>
<td>-11.35</td>
<td>1.292</td>
</tr>
<tr>
<td>#2 $- G_{max} = f(V_s, meas., N_{1,60cs})$</td>
<td>0.3141</td>
<td>-10.9</td>
<td>3.368</td>
</tr>
<tr>
<td>#3 $- G_{max} = f(N_{1,60cs})$, with Uncertainties</td>
<td>0.2991</td>
<td>-11.61</td>
<td>4.944e-07</td>
</tr>
<tr>
<td>#4 $- G_{max} = f(V_s, meas., N_{1,60cs})$, with Uncert.</td>
<td>0.266</td>
<td>-10.18</td>
<td>1.937</td>
</tr>
</tbody>
</table>
Table 6.7: Success Rate of Prediction of the Occurrence of Liquefaction for the Case History Database

<table>
<thead>
<tr>
<th>Scenario/Procedure</th>
<th>Correct</th>
<th>False Pos.</th>
<th>False Neg.</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 - $G_{\text{max}} = f(N_{1,60cs})$</td>
<td>193</td>
<td>17</td>
<td>20</td>
<td>0.388</td>
</tr>
<tr>
<td>#2 - $G_{\text{max}} = f(V_s, \text{meas.}, N_{1,60cs})$</td>
<td>182</td>
<td>11</td>
<td>37</td>
<td>0.194</td>
</tr>
<tr>
<td>#3 - $G_{\text{max}} = f(N_{1,60cs})$, with Uncertainties</td>
<td>198</td>
<td>12</td>
<td>20</td>
<td>0.476</td>
</tr>
<tr>
<td>#4 - $G_{\text{max}} = f(V_s, \text{meas.}, N_{1,60cs})$, with Uncert.</td>
<td>181</td>
<td>11</td>
<td>38</td>
<td>0.176</td>
</tr>
<tr>
<td>Boulanger and Idriss 2012</td>
<td>197</td>
<td>13</td>
<td>20</td>
<td>0.458</td>
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<tr>
<td>Cetin et al. 2004</td>
<td>195</td>
<td>26</td>
<td>9</td>
<td>0.423</td>
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</table>

Table 6.8: Regression Coefficients for the Proposed Limit State Curve Using an Alternate $G_{\text{max}}$-$N_{1,60}$ Correlation.

The regression coefficients given in Table 6.6 are recommended for forward analyses using SPT blow count.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$\sigma_\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>#5 - $G_{\text{max}} = f(N_{1,60cs})$</td>
<td>0.2889</td>
<td>-9.58</td>
<td>1.61</td>
</tr>
<tr>
<td>#6 - $G_{\text{max}} = f(V_s, \text{meas.}, N_{1,60cs})$</td>
<td>0.2773</td>
<td>-9.27</td>
<td>2.324</td>
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<tr>
<td>#7 - $G_{\text{max}} = f(N_{1,60cs})$, with Uncertainties</td>
<td>0.2841</td>
<td>-9.249</td>
<td>2.698e-06</td>
</tr>
<tr>
<td>#8 - $G_{\text{max}} = f(V_s, \text{meas.}, N_{1,60cs})$, with Uncert.</td>
<td>0.2771</td>
<td>-9.38</td>
<td>1.395</td>
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</table>

Table 6.9: Success Rate of Prediction of the Occurrence of Liquefaction of Limit State Curves Using Alternative $G_{\text{max}}$-$N_{1,60}$ Correlation

<table>
<thead>
<tr>
<th>Scenario/Procedure</th>
<th>Correct</th>
<th>False Pos.</th>
<th>False Neg.</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>#5 - $G_{\text{max}} = f(N_{1,60cs})$</td>
<td>193</td>
<td>15</td>
<td>22</td>
<td>0.388</td>
</tr>
<tr>
<td>#6 - $G_{\text{max}} = f(V_s, \text{meas.}, N_{1,60cs})$</td>
<td>193</td>
<td>14</td>
<td>23</td>
<td>0.388</td>
</tr>
<tr>
<td>#7 - $G_{\text{max}} = f(N_{1,60cs})$, with Uncertainties</td>
<td>194</td>
<td>11</td>
<td>25</td>
<td>0.405</td>
</tr>
<tr>
<td>#8 - $G_{\text{max}} = f(V_s, \text{meas.}, N_{1,60cs})$, with Uncert.</td>
<td>192</td>
<td>16</td>
<td>22</td>
<td>0.37</td>
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</tbody>
</table>
Figure 6.1: Results of a constant-volume cyclic simple shear test: Left: Shear stress versus shear strain hysteresis loops, Right: Shear stress versus vertical stress.
Figure 6.2: Results of a constant-volume cyclic simple shear test: Dissipated energy increasing to liquefaction. A best fit line over the linear portion of the dissipated energy curve ($\Delta W_{\text{Effect.}}$) is used to obtain the dissipated energy corresponding to total stress analyses ($\Delta W_{\text{Total}}$). The difference between the two measures of dissipated energy is illustrated here and can be attributed to the softening of the soil with increasing pore water pressure.
Figure 6.3: Results of cyclic simple shear tests with contours of equal dissipated energy to liquefaction.
Figure 6.4: Results of cyclic simple shear tests plotted with normalized dissipated energy to liquefaction (corrected to remove softening effects) versus relative density.
Figure 6.5: Direct Method to estimate $\Delta W_{1eq}/G_{max}$ (after Tokimatsu and Seed 1987) using the Darendeli and Stokoe (2001) degradation curves. Lines correspond to a clean sand ($FC = 0\%$, $PI = 0$). To use the figure, calculate the value on the x-axis, read up to the appropriate curve, and obtain the corresponding value from the y-axis.
Figure 6.6: Direct Method to estimate $\Delta W_{1eq}/G_{\text{max}}$ (after Tokimatsu and Seed 1987) using the Darendeli and Stokoe (2001) degradation curves. Lines correspond to “sands with high fines content.” To use the figure, calculate the value on the x-axis, read up to the appropriate curve, and obtain the corresponding value from the y-axis.
Figure 6.7: Direct Method to estimate $\Delta W_{1eq}/G_{max}$ (after Tokimatsu and Seed 1987) using the Darendeli and Stokoe (2001) degradation curves. Lines correspond to a low-plasticity silt. To use the figure, calculate the value on the x-axis, read up to the appropriate curve, and obtain the corresponding value from the y-axis.
<table>
<thead>
<tr>
<th>$N_{1,60cs}$</th>
<th>$\Delta W/\sigma'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>0.005</td>
<td>0.005</td>
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<td>0.010</td>
<td>0.010</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
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<tr>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>0.030</td>
<td>0.030</td>
</tr>
</tbody>
</table>

$P_{liq} = 85\%$

Figure 6.8: Proposed limit state curve (scenario #1) with case history data.
Figure 6.9: Proposed limit state curve (scenario #1) with case history data and normalized dissipated energy on a log axis.
Figure 6.10: Proposed limit state curve (scenario #1, $P = 50\%$) with case history data for various ranges of fines content.
Figure 6.11: Proposed limit state curve (scenario #1, $P = 50\%$) with case history data for various ranges of initial effective overburden stress.
Figure 6.12: Proposed limit state curve (scenario #1, $P = 50\%$) with case history data for various ranges of peak ground acceleration.
Figure 6.13: Proposed limit state curve (scenario #1, $P = 50\%$) with case history data for various ranges of moment magnitude.
Figure 6.14: Comparison of proposed procedure and the Boulanger and Idriss (2012) procedure. Solid lines indicate the 15, 50, and 85% probabilities of liquefaction. Large dots signify case history data points for which the models do not agree; the color of the point indicates whether the case history site liquefied. White squares indicate points on which the two procedures agree correctly, and the stars indicate points where the two procedures agree incorrectly.
Figure 6.15: Comparison of proposed procedure and Boulanger and Idriss (2012). Points are separated on the y-axis by whether the case history liquefied or not. The shape of the points indicate which of the procedures predicted the case history correctly. The numbers in the left-most pane indicate the number of case histories in each row.
Figure 6.16: Overburden correction factor developed for stress-based methods assuming $\Delta W_{wq}/\sigma'_{vo}$ is insensitive to extreme overburden stresses.
$M_w = 5.5, a_{max} = 0.15g, FC = 0\%, N_{1,60} = 5.0 \text{ blows/30cm}$

Figure 6.17: Demand, capacity, and factor of safety as a function of initial effective overburden stress for a $M_w 5.5$, $a_{max} = 0.15g$ event. The ground water table is located at a shallow depth (0.5 m) for all initial effective overburden stresses.
Figure 6.18: Demand, capacity, and factor of safety as a function of initial effective overburden stress for a $M_w 7.5$, $a_{max} = 0.35g$ event. The ground water table is located at a shallow depth (0.5 m) for all initial effective overburden stresses.

$M_w = 7.5$, $a_{max} = 0.35g$, $FC = 0\%$, $N_{1,60} = 30.0$ blows/30cm
Figure 6.19: Proposed limit state curve (scenario #1, $P = 15, 50, \& 85\%$) compared with the laboratory data.
6.13 Electronic Supplement

The SPT case history database compiled by Boulanger et al. (2012)\(^1\) was used in this research to develop a liquefaction limit state curve as a function of dissipated energy and SPT blow count. Table 6.10 summarizes the data provided by their data files. Table 6.11 provides the data calculated as part of this research.

Table 6.10: SPT Case History Database- Earthquake and Site Info

<table>
<thead>
<tr>
<th>No.</th>
<th>Earthquake/Site</th>
<th>Liq?</th>
<th>(M_w)</th>
<th>PGA</th>
<th>(N_{1,60cs})</th>
<th>(z)</th>
<th>(\sigma_v)</th>
<th>(\sigma'_v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1944 Tohnankai Komei</td>
<td>Yes</td>
<td>8.1</td>
<td>0.2</td>
<td>9.3</td>
<td>5.2</td>
<td>98.0</td>
<td>68.0</td>
</tr>
<tr>
<td>2</td>
<td>1944 Tohnankai Ienaga</td>
<td>Yes</td>
<td>8.1</td>
<td>0.2</td>
<td>8.4</td>
<td>4.3</td>
<td>80.0</td>
<td>61.0</td>
</tr>
<tr>
<td>3</td>
<td>1944 Tohnankai Meiko</td>
<td>Yes</td>
<td>8.1</td>
<td>0.2</td>
<td>6.9</td>
<td>3.7</td>
<td>69.0</td>
<td>39.0</td>
</tr>
<tr>
<td>4</td>
<td>1948 Fukui Shonenji Temple</td>
<td>Yes</td>
<td>7.0</td>
<td>0.4</td>
<td>11.7</td>
<td>4.0</td>
<td>75.0</td>
<td>48.0</td>
</tr>
<tr>
<td>5</td>
<td>1948 Fukui Takaya 45</td>
<td>Yes</td>
<td>7.0</td>
<td>0.35</td>
<td>21.1</td>
<td>7.5</td>
<td>141.0</td>
<td>104.0</td>
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<td>1964 Niigata Arayamotomachi</td>
<td>Yes</td>
<td>7.6</td>
<td>0.09</td>
<td>4.6</td>
<td>3.3</td>
<td>63.0</td>
<td>41.0</td>
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<td>7</td>
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<td>Yes</td>
<td>7.6</td>
<td>0.16</td>
<td>10.0</td>
<td>7.0</td>
<td>132.0</td>
<td>72.0</td>
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<tr>
<td>8</td>
<td>1964 Niigata Cc17-2</td>
<td>Yes</td>
<td>7.6</td>
<td>0.16</td>
<td>13.0</td>
<td>5.3</td>
<td>85.0</td>
<td>43.0</td>
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<td>9</td>
<td>1964 Niigata Kawagishi-cho</td>
<td>Yes</td>
<td>7.6</td>
<td>0.16</td>
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<td>3.8</td>
<td>71.0</td>
<td>53.0</td>
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<tr>
<td>10</td>
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<td>No</td>
<td>7.6</td>
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<td>132.0</td>
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<td>11</td>
<td>1964 Niigata Old Town -2</td>
<td>No</td>
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<td>0.18</td>
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<td>190.0</td>
<td>109.0</td>
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<td>12</td>
<td>1964 Niigata Rail Road-1</td>
<td>Yes</td>
<td>7.6</td>
<td>0.16</td>
<td>11.0</td>
<td>10.1</td>
<td>190.0</td>
<td>100.0</td>
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<td>13</td>
<td>1964 Niigata Rail Road-2</td>
<td>Marginal</td>
<td>7.6</td>
<td>0.16</td>
<td>17.5</td>
<td>10.1</td>
<td>190.0</td>
<td>100.0</td>
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<td>0.16</td>
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<td>16</td>
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<td>0.16</td>
<td>7.4</td>
<td>4.3</td>
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<table>
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<tr>
<th>No.</th>
<th>Earthquake/Site</th>
<th>Liq?</th>
<th>$M_w$</th>
<th>PGA</th>
<th>$N_{1,60cs}$</th>
<th>$z$</th>
<th>$\sigma_v$</th>
<th>$\sigma'_v$</th>
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</thead>
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<td>17</td>
<td>Showa Br 4</td>
<td>No</td>
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<td>8.3</td>
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<td>$PGA$</td>
<td>$N_{1.60cs}$</td>
<td>$z$</td>
<td>$\sigma_v$</td>
<td>$\sigma'_v$</td>
</tr>
<tr>
<td>-----</td>
<td>------------------------</td>
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<td>------------</td>
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<td>Le Ting L8-14</td>
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1977 Argentina

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1978 Miyagiken-Oki

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**1979 Imperial Valley**

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| 80  | Heber Road A2        | Yes  | 6.5   | 0.78  | 7.0         | 3.7| 68.0       | 50.0       |
| 81  | Heber Road A3        | No   | 6.5   | 0.78  | 21.2        | 4.0| 79.0       | 56.0       |
| 82  | Kornbloom B          | No   | 6.5   | 0.13  | 11.7        | 4.3| 77.0       | 62.0       |
| 83  | McKim Ranch A        | Yes  | 6.5   | 0.51  | 10.0        | 2.1| 38.0       | 32.0       |
| 84  | Radio Tower B1       | Yes  | 6.5   | 0.2   | 8.4         | 3.4| 62.0       | 50.0       |
| 85  | Radio Tower B2       | No   | 6.5   | 0.2   | 20.6        | 2.3| 40.0       | 38.0       |
| 86  | River Park A         | Yes  | 6.5   | 0.24  | 10.2        | 1.8| 35.0       | 20.0       |
| 87  | Wildlife B           | No   | 6.5   | 0.17  | 15.7        | 4.6| 87.0       | 54.0       |

**1980 Mid-Chiba**

| 88  | Owi-1                | No   | 6.0   | 0.1   | 9.6         | 6.1| 108.0      | 57.0       |
| 89  | Owi-2                | No   | 6.0   | 0.1   | 9.1         | 14.3| 254.0     | 123.0      |

**1981 WestMorland**

252
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**1982 Urakawa-Oki**

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**1983 Nihonkai-Chubu**

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**1984**

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**1987**

**Superstition Hills**

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### 1993 Kushiro-
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6.13.1 Sample Calculations

This section provides sample calculations for one of the case histories in the database above. The calculations will follow case history number 8: site Cc17-2 of the 1964 M=7.6 Niigata earthquake - June 16. In this example, liquefaction did occur with a 7.6 magnitude earthquake producing a peak ground acceleration of 0.16g. The layer of interest was at a depth of 5.3m and had total and effective vertical overburden stresses of 85.0 kPa and 43.0 kPa.

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</tr>
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<td>36.39</td>
<td>6.7</td>
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<td>95.2</td>
<td>0.03</td>
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</tr>
<tr>
<td>210</td>
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<td>0.81</td>
<td>26.16</td>
<td>0.32</td>
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<td>83.8</td>
<td>0.28</td>
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</tr>
<tr>
<td>211</td>
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<td>0.87</td>
<td>22.41</td>
<td>0.38</td>
<td>0.0069</td>
<td>67.6</td>
<td>0.22</td>
<td>0.16</td>
<td>0.78</td>
</tr>
<tr>
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<td>21.39</td>
<td>0.54</td>
<td>0.015</td>
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<td>0.16</td>
<td>0.18</td>
<td>0.06</td>
</tr>
<tr>
<td>213</td>
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<td>0.86</td>
<td>17.41</td>
<td>0.061</td>
<td>0.00077</td>
<td>81.7</td>
<td>0.47</td>
<td>0.10</td>
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<td>214</td>
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<td>1.1</td>
<td>0.012</td>
<td>87.4</td>
<td>0.16</td>
<td>0.18</td>
<td>0.92</td>
</tr>
<tr>
<td>215</td>
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<td>98.6</td>
<td>0.28</td>
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<tr>
<td>216</td>
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<td>0.14</td>
<td>0.00</td>
</tr>
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<td>0.15</td>
<td>0.0031</td>
<td>59.0</td>
<td>0.30</td>
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<td>0.91</td>
</tr>
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<td>18.78</td>
<td>0.4</td>
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<td>68.4</td>
<td>0.14</td>
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<tr>
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<td>15.43</td>
<td>0.33</td>
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<td>0.19</td>
<td>0.17</td>
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<tr>
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<td>0.36</td>
<td>0.0045</td>
<td>88.0</td>
<td>0.18</td>
<td>0.17</td>
<td>0.15</td>
</tr>
<tr>
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<td>33.27</td>
<td>0.61</td>
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<td>87.3</td>
<td>0.24</td>
<td>0.16</td>
<td>0.98</td>
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<tr>
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<td>1.1</td>
<td>0.012</td>
<td>77.5</td>
<td>0.11</td>
<td>0.18</td>
<td>1.00</td>
</tr>
<tr>
<td>224</td>
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<td>32.14</td>
<td>0.53</td>
<td>0.0043</td>
<td>112.2</td>
<td>0.21</td>
<td>0.16</td>
<td>0.06</td>
</tr>
<tr>
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<td>0.75</td>
<td>36.62</td>
<td>0.76</td>
<td>0.0054</td>
<td>114.9</td>
<td>0.19</td>
<td>0.16</td>
<td>0.28</td>
</tr>
<tr>
<td>226</td>
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<td>0.17</td>
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<td>0.16</td>
<td>0.17</td>
<td>0.51</td>
</tr>
<tr>
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<td>34.6</td>
<td>0.72</td>
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</tr>
<tr>
<td>230</td>
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<td>0.87</td>
<td>13.11</td>
<td>0.32</td>
<td>0.0069</td>
<td>61.6</td>
<td>0.14</td>
<td>0.18</td>
<td>0.80</td>
</tr>
</tbody>
</table>
Calculate Small-Strain Shear Modulus

In the absence of shear wave velocity measurements, the small-strain shear modulus can be estimated using the SPT blowcount (Seed et al. 1986\(^2\)):

\[
G_{\text{max}} = 440 \cdot N_{1,60cs}^{\frac{1}{2}} \cdot P_a \cdot \sqrt{\frac{\sigma'_{m0}}{P_a}}
\]  
(6.28)

where \(\sigma'_{m0}\) is:

\[
\sigma'_{m0} = (1 + 2K_o)\sigma'_{v0}/3
\]

\[
= (1 + 2 \cdot 0.44)43.0/3
\]

\[
= 26.9
\]  
(6.29)

and \(P_a\) is the atmospheric pressure (101.325 kPa). \(K_o\) is estimated from \(N_{1,60cs}\) via \(\phi'\) (Sabatini et al. 2002\(^3\) after Hatanaka and Uchida 1996\(^4\)):

\[
\phi' = \sqrt{15.4 \cdot N_{1,60cs} + 20}
\]

\[
= \sqrt{15.4 \cdot 13.0 + 20}
\]

\[
= 34.1
\]  
(6.30)

---


and (Jaky 1944\textsuperscript{5}, 1948\textsuperscript{6}): 

\[
K_o = 1 - \sin (\phi') \\
= 1 - \sin(34.1) \\
= 0.44
\]

Thus:

\[
G_{max} = 440 \cdot 13.0^{\frac{1}{3}} \cdot 101.325 \cdot \sqrt{\frac{26.9}{101.325}} \\
= 54002 \text{kPa}
\]

\textbf{Calculate Stress-Reduction Coefficient}

The stress reduction coefficient is used to estimate the shear stress at depth using the peak ground acceleration at the surface of the profile. A stress reduction coefficient was developed as part of this research (see the Technical Note in Chapter 5):

\[
r_d = (1 - \alpha) \exp \left( \frac{-z}{\beta} \right) + \alpha
\]

where \(z\) is depth from the surface in meters, and

\[
\alpha = \exp(a_1 + a_2 \cdot M_w)
\]

\[
\beta = a_3 + a_4 \cdot M_w
\]


where \( a_1 = -4.031, a_2 = 0.364, a_3 = -28.47, \) and \( a_4 = 7.798. \) Thus:

\[
\alpha = \exp(-4.03 + 0.36 \cdot 7.6) \\
= 0.282 \\
\beta = -28.47 + 7.80 \cdot 7.6 \\
= 30.795 
\]  

\[ r_d = (1 - 0.28) \exp \left( \frac{-5.3}{30.79} \right) + 0.28 \\
= 0.89 \]  

(6.36)  

(6.37)

Calculate the Dissipated Energy in One Equivalent Cycle

For a liquefaction evaluation utilizing site response analyses, dissipated energy can be calculated directly using the stress and strain time histories from the depth of interest. For the simplified procedure, this dissipated energy must be estimated by multiplying the number of equivalent cycles by the dissipated energy in one equivalent cycle:

\[
\Delta W = \Delta W_{1,eq} \cdot n_{eq} 
\]  

(6.38)

The quantity \( \Delta W_{1,eq}/G_{max} \) can be estimated graphically using Figure 6.20. This figure was created using Darendeli and Stokoe’s (2001) shear modulus and damping degradation curves and Tokimatsu and Seed’s (1987) direct approach. We enter the figure from the x-axis using the following value:

\[
0.65 \cdot a_{max} \cdot \sigma_v \cdot r_d / (g \cdot G_{max}) = 0.65 \cdot 0.2 \cdot 85.0 \cdot 0.89 / (1 \cdot 54002) = 0.0001451 
\]  

(6.39)

\[ ^7 \text{Darendeli, M. B., and Stokoe, K. H. (2001). Development of a new family of normalized modulus reduction and material damping curves. Geotechnical Engineering Report GD01-1, University of Texas at Austin.} \]


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From this point on the x-axis, we read up to the curve corresponding to our mean effective overburden pressure ($\sigma'_0 = 26.9$ kPa). From there, we read left to the y-axis to read off the value of $\Delta W_{1,eq}/G_{max}$ which is equal to 1.768e-08. Multiplying this value by $G_{max}$, we obtain our value of $\Delta W_{1,eq}$ which is 0.000955 kPa. The diamonds in the figure correspond to a threshold shear strain of $10^{-2}$ %. If we had plotted below the diamonds, we could assume that no liquefaction would occur. Note that a fifth-order fit to these curves is presented in the body of the paper.

![Graphical method to obtain $\Delta W_{1,eq}$ using Darendeli and Stokoe’s shear modulus and damping degradation curves.](image)

Figure 6.20: Graphical method to obtain $\Delta W_{1,eq}$ using Darendeli and Stokoe’s shear modulus and damping degradation curves.
Calculate Number of Equivalent Cycles

The number of equivalent cycles can be calculated according to the following equation:

\[
    n_{eq} = 2 \cdot \exp \left( b_1 + b_2 \ln(a_{max}) + b_3 M_w \right) \tag{6.40}
\]

where \( b_1 = -0.3643 \), \( b_2 = -0.4105 \), and \( b_3 = 0.2553 \). Thus:

\[
    n_{eq} = 2 \cdot \exp \left( -0.3643 - 0.4105 \ln(0.16) + 0.2553 \cdot 7.6 \right) \tag{6.41}
\]

Calculate Total Dissipated Energy

With the dissipated energy in one cycle and the number of equivalent cycles, we are now able to calculate the total dissipated energy, \( \Delta W \):

\[
    \Delta W = \Delta W_{1,eq} \cdot n_{eq} = 0.000955 \cdot 20.5 \tag{6.42}
\]

\[
    = 0.0196 \text{ kPa}
\]

The normalized dissipated energy is easily computed:

\[
    \frac{\Delta W}{\sigma_v'} = \frac{0.0196}{43.0} = 0.000456 \tag{6.43}
\]

Calculate the Limit-State Value, \( g \)

The limit-state function is defined as follows:

\[
    g = c_1 N_{1,60cs} - \ln \left( \frac{\Delta W}{\sigma_v'} \right) + c_2 + \varepsilon \tag{6.44}
\]

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where $c_1 = 0.299$, $c_2 = -11.610$, and the standard deviation of $\varepsilon$, $\sigma_\varepsilon$, is 1.3. Thus:

$$
g = 0.30 \cdot 13.0 - \ln(0.000456) + -11.61 = -0.0329 \quad (6.45)
$$

Since $g$ is less than zero, we expect liquefaction to occur.

**Calculate Probability of Liquefaction**

With a values of $g$ and $\sigma_\varepsilon$, we can calculate the probability of liquefaction:

$$
P[g \leq 0] = 1 - \Phi \left[ \frac{g}{\sigma_\varepsilon} \right]
= 1 - \Phi \left[ \frac{-0.0329}{1.29} \right] \quad (6.46)
= 51\%
$$

Relatedly, we can define a normalized dissipated energy curve for a given probability of liquefaction:

$$
\left( \frac{\Delta W}{\sigma'_v} \right) = \exp \left( c_1 N_{1,60cs} + c_2 + \Phi^{-1} [P] \cdot \sigma_\varepsilon \right)
= \exp \left( 0.299 \cdot N_{1,60cs} + -11.610 + \Phi^{-1} [P] \cdot 1.3 \right) \quad (6.47)
$$

**Calculate the Dissipated Energy to Liquefaction**

For deterministic analyses, we can calculate the normalized dissipated energy required to cause liquefaction, $\Delta W_{liq}/\sigma'_v$. We define the deterministic curve
as the probabilistic curve at a probability of 15%:

\[
\left( \frac{\Delta W_{liq}}{\sigma'_{v0}} \right) = \exp (c_1 N_{1,60cs} + c_2 - 1.036 \cdot \sigma_\varepsilon)
\]

\[
= \exp (0.30 \cdot 13.0 + -11.61 - 1.036 \cdot 1.29)
\]

\[
= 1.1561e - 04
\] (6.48)

**Calculate the Factor of Safety**

Finally, the factor of safety against liquefaction is calculated as:

\[
F_{Sliq} = \frac{\ln \left( \frac{\Delta W_{liq}}{\sigma'_{v0}} \right) - c_{FS}}{\ln \left( \frac{\Delta W_{calculated}}{\sigma'_{v0}} \right) - c_{FS}}
\]

\[
= \frac{\ln (0.000116) - (1.2 \cdot -11.61)}{\ln (0.000456) - (1.2 \cdot -11.61)}
\]

\[
= 0.8
\] (6.49)

because \(c_{FS}\) is defined as:

\[
c_{FS} = 1.2 \cdot c_2
\] (6.50)
6.13.2 Procedure to Evaluate Liquefaction Potential

This section gives the step-by-step procedure to evaluate liquefaction potential using the energy-based procedure proposed in the attached paper. Two variations are presented: a “simplified” procedure, and a “non-simplified” procedure. All units used in these calculation should be SI units, unless otherwise specified.

Simplified Procedure

The “simplified” procedure does not require site response analyses. Instead, it relies on the expected peak ground acceleration and a number of equivalent cycles ($n_{eq}$) correlation.

1. Obtain parameters to characterize the capacity of the liquefiable layer and the demand of the earthquake motion. These are:
   - SPT blow count ($N_m$)
   - Fines Content ($FC$)
   - Depth ($z$)
   - Total overburden stress ($\sigma_v$)
   - Initial effective overburden stress ($\sigma_v^I$)
   - Various SPT details:
     - Energy Ratio ($ER$)
     - Borehole diameter
     - Rod length
     - Sampler information
   - Peak ground acceleration, $a_{max}$
   - Moment magnitude, $M_w$

2. Correct the measured SPT blow count ($N_m$) using the procedure of Idriss and Boulanger (2008):
   $$N_{00} = C_E \cdot C_B \cdot C_R \cdot C_S \cdot N_m$$
   where:
• $C_E$ is the energy ratio correction factor: $C_E = \frac{E_R}{60}$

The following ranges have been given (Seed et al. 1984; Skempton 1986; NCEER 1997):

– Doughnut Hammer: $0.5 \leq C_E \leq 1.0$
– Safety Hammer: $0.7 \leq C_E \leq 1.2$
– Automatic Triphammer: $0.8 \leq C_E \leq 1.3$

• $C_B$ is the borehole diameter correction factor (Skempton 1986):

– 65-115 mm: $C_B = 1.0$
– 150 mm: $C_B = 1.05$
– 200 mm: $C_B = 1.15$

• $C_R$ is the rod length correction factor (Youd et al. 2001). Assume a rod stick-up length of 1.5 m so that rod length = 1.5 + $z$:

– Rod length < 3 m: $C_R = 0.75$
– Rod length 3-4 m: $C_R = 0.80$
– Rod length 4-6 m: $C_R = 0.85$
– Rod length 6-10 m: $C_R = 0.95$
– Rod length 10-30 m: $C_R = 1.00$

• $C_S$ is the sampler correction factor (Seed et al. 1984; Seed et al. 2001):

– Standard split spoon without room for liners: $C_S = 1.0$
– Split spoon with room for liners but without the liner present: $C_S = 1 + \frac{N_{1,60}}{100}; 1.1 \leq C_S \leq 1.3$

\[ N_{1,60} = C_N \cdot N_{60} \]

where (Boulanger 2003):

\[ C_N = \left( \frac{P_a}{\sigma_{\alpha}} \right)^\alpha \leq 1.7 \]

$P_a$ is standard atmospheric pressure (1 atm = 101.325 kPa), and $\alpha$ is defined as:

\[ \alpha = 0.784 - 0.0768\sqrt{N_{1,60}} \]

Finally, the SPT blow count with fines content corrections is:

\[ N_{1,60cs} = N_{1,60} + \Delta N_{1,60} \]

where:

\[ N_{1,60cs} = N_{1,60} + \Delta N_{1,60} \]
$$\Delta N_{1,60} = \exp \left( 1.63 + \frac{9.7}{FC+0.01} - \left[ \frac{15.7}{FC+0.01} \right]^2 \right)$$

You will notice that both $C_S$ and $C_N$ are a function of $N_{1,60}$. Thus, you have to assume a value of $N_{1,60}$ to start and iterate until convergence is reached. If the corrected SPT blow count is greater than 30, liquefaction is not expected to occur.

3. Calculate the mean initial effective stress, $\sigma'_{m0}$:

- Estimate the effective friction angle, $\phi'$ (Hatanaka and Uchida 1996; Sabatini et al. 2002):
  $$\phi' = \sqrt{15.4N_{1,60cs} + 20}$$

- Estimate the at-rest earth pressure coefficient, $K_o$ (Jaky 1944; 1948):
  $$K_o = 1 - \sin \phi'$$

- Calculate the mean initial effective stress:
  $$\sigma'_{m0} = \frac{1+2K_o}{3} \cdot \sigma'_{v0}$$
  $\sigma'_{v0}$ should be limited to values above 40 kPa.

4. Estimate the small strain shear modulus, $G_{max}$ (Seed et al. 1986; Ohta and Goto 1976):

$$G_{max} = 440 \cdot N_{1,60cs}^{\frac{1}{3}} \cdot P_a \cdot \sqrt{\frac{\sigma'_{m0}}{P_a}}$$

where $P_a$ is standard atmospheric pressure (101.325 kPa).

5. Calculate the number of equivalent stress cycles, $n_{eq}$ (Lasley et al. 2015a):

$$n_{eq} = \exp \left( b_1 + b_2 \ln(a_{max}) + b_3M_w \right)$$

<table>
<thead>
<tr>
<th>EQ Regime</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
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<tbody>
<tr>
<td>Active Shallow-Crustal</td>
<td>0.806</td>
<td>-0.298</td>
<td>-8.98e-4</td>
<td>0.254</td>
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<tr>
<td>Stable Continental</td>
<td>0.557</td>
<td>-0.390</td>
<td>-1.80e-4</td>
<td>0.315</td>
</tr>
</tbody>
</table>
6. Calculate the depth reduction coefficient, \( r_d \) (Lasley et al. 2015b):
\[
    r_d = (1 - \alpha) \exp \left( \frac{-z}{\beta} \right) + \alpha
\]
where \( z \) is in meters, and
\[
    \alpha = \exp(a_1 + a_2 \cdot M_w)
\]
\[
    \beta = a_3 + a_4 \cdot M_w
\]

Table 6.13: Regression Coefficients for \( r_d \) (Lasley et al. 2015b)

<table>
<thead>
<tr>
<th>EQ Regime</th>
<th>( a_1 )</th>
<th>( a_2 )</th>
<th>( a_3 )</th>
<th>( a_4 )</th>
<th>( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Shallow-Crustal</td>
<td>-4.031</td>
<td>0.364</td>
<td>-28.47</td>
<td>7.798</td>
<td>0.1397</td>
</tr>
<tr>
<td>Stable Continental</td>
<td>-4.369</td>
<td>0.439</td>
<td>-15.38</td>
<td>4.922</td>
<td>0.1586</td>
</tr>
</tbody>
</table>

7. Estimate the dissipated energy in one equivalent cycle:

- Calculate \( \Gamma \):
\[
    \Gamma = \log_{10} \left( 0.65 \cdot a_{\text{max}} \cdot \sigma_v \cdot r_d / (g \cdot G_{\text{max}}) \right); \sim -5 \leq \Gamma \leq \sim 3
\]
- Calculate \( \Delta W_{1,eq}/G_{\text{max}} \):
\[
    \frac{\Delta W_{1,eq}}{G_{\text{max}}} = 10 \left( d_1 \Gamma^5 + d_2 \Gamma^4 + d_3 \Gamma^3 + d_4 \Gamma^2 + d_5 \Gamma + d_6 \right)
\]

Table 6.14: Regression Coefficients for the Fit of the \( \Delta W_{1,eq}/G_{\text{max}} \) Curves (Clean Sand)

<table>
<thead>
<tr>
<th>( \sigma'_{m0} ) (kPa)</th>
<th>( d_1 )</th>
<th>( d_2 )</th>
<th>( d_3 )</th>
<th>( d_4 )</th>
<th>( d_5 )</th>
<th>( d_6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.242</td>
<td>5.848</td>
<td>56.101</td>
<td>267.91</td>
<td>640.3145</td>
<td>608.05276</td>
</tr>
<tr>
<td>50</td>
<td>0.232</td>
<td>5.545</td>
<td>52.685</td>
<td>249.053</td>
<td>589.1456</td>
<td>553.24074</td>
</tr>
<tr>
<td>100</td>
<td>0.22</td>
<td>5.219</td>
<td>49.129</td>
<td>229.977</td>
<td>538.6714</td>
<td>500.38834</td>
</tr>
<tr>
<td>200</td>
<td>0.208</td>
<td>4.881</td>
<td>45.541</td>
<td>211.152</td>
<td>489.8841</td>
<td>450.27458</td>
</tr>
</tbody>
</table>
Table 6.15: Regression Coefficients for the Fit of the $\Delta W_{1,eq}/G_{\text{max}}$ Curves (Sand with High Fines Content)

<table>
<thead>
<tr>
<th>$\sigma'_{m0}$ (kPa)</th>
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<th>$d_3$</th>
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<th>$d_5$</th>
<th>$d_6$</th>
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<td>63.487</td>
<td>158.8015</td>
<td>156.90162</td>
</tr>
</tbody>
</table>

Alternatively, values of $\Delta W_{1,eq}/G_{\text{max}}$ can be obtained from Figures 6.21 through 6.23. In either case, use the figures to verify that the threshold shear strain is exceeded. (i.e. Do the values plot above the diamonds? As a rule of thumb, $\Gamma$ should be greater than approximately -4.5.) If the threshold shear strain is not exceeded, liquefaction is not likely for the given peak ground acceleration.

8. Calculate the total normalized dissipated energy for the given conditions. This is your demand term:

$$\frac{\Delta W}{\sigma'_{v0}} = \left( \frac{\Delta W_{1,eq}}{G_{\text{max}}} \right) \cdot \frac{G_{\text{max}}}{\sigma'_{v0}} \cdot (2 \cdot n_{eq})$$

9. Calculate the factor of safety ($FS$) against liquefaction:

$$FS = 0.30 N_{1,60cs} + 0.98 \ln \left( \frac{\Delta W}{\sigma'_{v0}} \right) + 13.93$$

10. Alternatively, calculate the probability of liquefaction, $P$:

$$P = 1 - \Phi \left[ \frac{0.30 N_{1,60cs} - \ln \left( \frac{\Delta W}{\sigma'_{v0}} \right) - 11.61}{1.29} \right]$$

Non-Simplified Procedure

The “non-simplified” procedure requires a well-characterized soil profile, representative earthquake ground motions, and equivalent-linear site response analyses.

1. Obtain information about the soil profile. For every layer down to the bedrock halfspace:
• Shear wave velocity \((V_S)\)
• Thickness of layer
• Unit weight
• Fines content \((FC)\) and plasticity index \((PI)\) for shear modulus reduction and damping curves

For layers of interest:

• SPT blow count \((N_m)\)
• Total overburden stress \((\sigma_v)\) via the unit weights
• Initial effective overburden stress \((\sigma_v')\) via the depth of the ground water table
• Various SPT details:
  – Energy Ratio \((ER)\)
  – Borehole diameter
  – Rod length
  – Sampler information

2. Correct your measured SPT blow counts using step 2 of the Simplified Procedure (above). If the corrected SPT blow count of a layer is greater than 30, it is unlikely to liquefy.

3. Obtain representative earthquake motions.

4. Perform equivalent-linear site response analyses for the profile using each of your motions. You should use Darendeli and Stokoe’s (2001) shear modulus reduction and damping curves. From the response strain time histories, verify that the threshold shear strain is exceeded for each layer of interest. If it is not exceeded, liquefaction in that layer is unlikely.

5. For each layer of interest:

   a. Calculate the dissipated energy. This can be done using the stress and strain time histories and the trapezoidal rule:

   \[
   \Delta W = \frac{1}{2} \sum_{j=1}^{J-1} \left( (\tau_{i+1} + \tau_i) \cdot (\gamma_{i+1} - \gamma_i) \right)
   \]
where $\tau$ and $\gamma$ are the response stress and strain time histories, respectively, of the layer of interest. $j$ is the total number of data points in the input motion.

b. Normalize the dissipated energy by the initial effective overburden stress ($\sigma'_v$). This is your demand term ($\Delta W/\sigma'_v$).

c. Calculate the factor of safety ($FS$) against liquefaction for each layer of interest:

$$FS = \frac{0.30N_{1,60cs}+0.98}{\ln\left(\frac{\Delta W}{\sigma'_v}\right)+13.93}$$

d. Alternatively, calculate the probability of liquefaction, $P$:

$$P = 1 - \Phi\left[\frac{0.30N_{1,60cs}-\ln\left(\frac{\Delta W}{\sigma'_v}\right)-11.61}{1.29}\right]$$

References


Figure 6.21: Direct Method to estimate $\Delta W_{\text{eq}}/G_{\text{max}}$ (after Tokimatsu and Seed 1987) using the Darendeli and Stokoe (2001) degradation curves. Lines correspond to a clean sand ($FC = 0\%$, $PI = 0$). To use the figure, calculate the value on the x-axis, read up to the appropriate curve, and obtain the corresponding value from the y-axis.
Figure 6.22: Direct Method to estimate $\Delta W_{1\text{eq}}/G_{\text{max}}$ (after Tokimatsu and Seed 1987) using the Darendeli and Stokoe (2001) degradation curves. Lines correspond to “sands with high fines content.” To use the figure, calculate the value on the x-axis, read up to the appropriate curve, and obtain the corresponding value from the y-axis.
Figure 6.23: Direct Method to estimate $\Delta W_{1eq}/G_{max}$ (after Tokimatsu and Seed 1987) using the Darendeli and Stokoe (2001) degradation curves. Lines correspond to a low-plasticity silt. To use the figure, calculate the value on the x-axis, read up to the appropriate curve, and obtain the corresponding value from the y-axis.
Chapter 7

Conclusions

7.1 Summary of Research

The purpose of the research presented herein is the application of fatigue theories to two important geotechnical earthquake engineering phenomena: 1. The development of a “non-simplified” seismic compression evaluation method, and 2. The development of an energy-based liquefaction potential evaluation procedure that will be familiar to users of the stress-based simplified procedure.

In pursuit of these research objectives, several sub-tasks and related research was performed. This section summarizes the results of the entire body of research.

7.1.1 Seismic Compression Method

Proposed in Chapter 3 is a “non-simplified” method for predicting the severity of seismic compression. It is based on a modified version of the Richart-Newmark (R-N; Richart and Newmark 1948) cumulative damage hypothesis and uses volumetric strain as the damage metric. The proposed method estimates volumetric strain from any shear strain time history. It was calibrated using the results of 460 cyclic simple shear tests performed on dry quartz sand specimens at Virginia Tech. The relative density of the test specimens ranged from 30 to 80%. At each relative density, specimens were subjected
to strain-controlled sinusoidal loading with shear strains ranging from 0.2 to 1%. The overburden pressures of the tests were 50, 100, and 250 kPa.

In addition to the 460 cyclic simple shear tests performed with sinusoidal loading, 23 tests were performed with variable-amplitude sinusoidal loading, and 16 tests were performed with earthquake strain time histories as the loading functions. These variable-amplitude and earthquake loading tests were used to validate the R-N-based seismic compression method. The proposed method accurately predicted volumetric strains, especially compared to the Palmgren-Miner (Palmgren 1924; Miner 1945) method. Additionally, a case history was presented in which the proposed R-N-based seismic compression method predicted reasonable volumetric strains using the strain time histories of equivalent-linear site response analyses.

In addition to accurately predicting seismic compression in a non-simplified approach, the proposed seismic compression method can be used to compute number of equivalent cycles for use in simplified procedures. Compared to the number of equivalent cycle correlations commonly used in other simplified seismic compression procedures, the number of equivalent cycles computed using the proposed method uses a consistent damage metric (volumetric strain) to equate earthquake motions to an equivalently-damaging sinusoidal motion with a specified number of cycles.

7.1.2 Number of Equivalent Stress Cycles Correlation

The number of equivalent stress cycles ($n_{eq}$) concept plays an important role in geotechnical earthquake engineering and, particularly, in liquefaction evaluations. It allows for the conversion of an earthquake motion into an equivalently-damaging number of sinusoidal cycles of equal amplitude. Most of the current applications of $n_{eq}$ in liquefaction evaluations assume high cycle fatigue conditions (many cycles to failure; loading remains in the elastic range) in conjunction with the Palmgren-Miner (Palmgren 1924; Miner 1945) cumulative damage hypothesis. Soil liquefaction, however, is associated with low-cycle fatigue (few cycles to failure; significant damage in each cycle) conditions. Proposed in Chapter 4 is a low-cycle alternative application of the Palmgren-Miner cumulative damage hypothesis using dissipated energy as the damage metric.

The $n_{eq}$ correlation proposed in Chapter 4 was developed using the results
of equivalent-linear site response analyses. These analyses were performed using 50 soil profiles from liquefaction sites (Cetin 2000) and 228 pairs of rock motions representing shallow-crustal and stable continental tectonic regimes. The \( n_{eq} \) correlation was regressed using two functional forms and incorporated the random effects of earthquake event and profile group. One of these correlations is a function of peak ground acceleration and earthquake magnitude, and the other correlation is a function of magnitude and site-to-source distance. Calibration coefficients are provided for both active shallow-crustal and stable continental tectonic regimes.

Because the \( n_{eq} \) correlations proposed herein are not a function of magnitude alone, they demonstrate the need for magnitude scaling factors (\( MSFs \)) that are likewise. Magnitude scaling factors play an important role in stress-based simplified liquefaction evaluation procedures and are based on \( n_{eq} \) correlations; most of the magnitude scaling factors currently in use are a function of magnitude alone.

Also demonstrated in the development of the \( n_{eq} \) correlation is that low-cycle \( n_{eq} \) values are more strongly correlated with earthquake intensity measures (i.e. magnitude, bracketed duration, significant duration, \( rms \) acceleration, and \( a_{max} \)) than traditional high-cycle \( n_{eq} \) values.

### 7.1.3 Stress Reduction Coefficient Correlation

Based on the results of the equivalent-linear site response analyses discussed in conjunction with the proposed \( n_{eq} \) correlation, a new stress reduction coefficient relationship (Chapter 5) was also developed. The stress reduction coefficient allows for the computation of the seismically induced stresses at depth in a soil profile without the need to perform site response analyses. As such, it is an important part of simplified liquefaction evaluation procedures. A simple functional form was developed with two variants. One variant is a function of earthquake magnitude, the average shear wave velocity in the upper 12 m of a profile (\( V_{S12} \)), and depth; the other variant is a function of magnitude and depth. Both variants yield \( r_d \) values with less bias and uncertainty than other common \( r_d \) relationships (i.e. Liao and Whitman 1986, Idriss 1999, Cetin 2000). Calibration coefficients for both variants are provided for both active shallow-crustal and stable continental tectonic regimes.
7.1.4 Dissipated-Energy-Based Liquefaction Evaluation

A simplified liquefaction evaluation procedure was developed based on dissipated energy and an SPT liquefaction case history database (Chapter 6). It was developed using the aforementioned $n_{eq}$ correlation and $r_d$ relationship and the Darendeli and Stokoe (2001) shear modulus and damping degradation curves. The normalized dissipated energy ($\Delta W/\sigma'_v$) was calculated for each case history in the database, and a limit state capacity curve was regressed as a function of corrected SPT blow count. The regression was performed in two different ways: by assuming the input values are known exactly and by accounting for uncertainties in each of the input parameters.

The resulting limit state capacity curve has a simple functional form and can be used both deterministically (returning a factor of safety against liquefaction) or probabilistically (returning a probability of liquefaction). Compared to two other common stress-based simplified procedures (i.e. Cetin et al. 2004; Boulanger and Idriss 2012), the energy-based procedure proposed herein has a similar rate of correct prediction of the occurrence/non-occurrence of liquefaction for the case histories of the case history database.

Overburden correction factors ($K_\sigma$) were derived for stress-based liquefaction procedures using dissipated energy as the damage metric. The derived correction factor curves are influenced by the shear modulus and damping degradation curves (Darendeli and Stokoe 2001, in this case) and compared favorably with two other sets of $K_\sigma$ curves (i.e. Hynes and Olsen 1999; Boulanger and Idriss 2004).

7.2 Recommendations for Future Work

Considerable progress has been made in the application of fatigue theories to seismic compression estimation and to the evaluation of liquefaction potential. In the case of seismic compression, a modified version of the Richart-Newmark cumulative damage hypothesis accurately predicts seismic compression using shear strain time histories. However, as mentioned previously, a number-of-equivalent-strain-cycles correlation still needs to be developed in order to develop a simplified seismic compression method based on the
In the case of liquefaction evaluation, an alternative, low-cycle application of the Palmgren-Miner hypothesis has been used to develop a dissipated-energy-based number-of-equivalent-cycles correlation. This correlation, in turn, was used to successfully develop an SPT-based liquefaction evaluation procedure. Using the same general framework, CPT- and shear wave velocity-based procedures could be developed to cover most use cases.

Finally, the procedures developed herein have been suggested for use in tectonic regimes such as that of the central-eastern United States and with non-earthquake sources of loading. A validation of these procedures in those use cases is warranted.

7.3 References


Appendix A

Contents of Appendices

A  Contents of Appendices
B  Seismic Compression Lab Test Results
C  Cycle Counting Methods for Seismic Compression
D  Cyclic Simple Shear Lab Test Results
E  Soil Profiles of the Equivalent-Linear Analyses
F  Earthquake Motions
G  Cyclic Simple Shear Testing Manual
H  Cyclic Triaxial Testing Manual
I  Conference Paper: Verification of ShakeVT2
J  Code
Appendix B

Seismic Compression Lab Test Results

This section contains the results of the strain-controlled, cyclic simple shear tests performed for seismic compression. The tests were performed on dry quartz (pool filter) sand. The overburden pressure was held constant during cyclic loading allowing seismic compression (volumetric strain) to occur. See Chapter 3 for more details. The first section contains the results of the constant-amplitude sinusoidal loading tests. The second section contains the results of the irregular loading tests.

B.1 Constant-Amplitude Results

Tables B.1 and B.2 give the results of the constant-amplitude sinusoidal tests. The variable $\gamma$ is the single-amplitude shear strain; $N_{\varepsilon_v=1\%}$ is the number of cycles to one percent volumetric strain; $r_0$ is the calibration coefficient for the Richart-Newmark cumulative damage hypothesis (asymptotic $r$); and $C_1$ and $C_2$ are the calibration coefficients for the Byrne method. The path of the file corresponds to the overburden pressure and relative density bins (e.g. ./Sinusoids/50Pa/Dr30/121.csv).

Table B.1: Details and Calibration Coefficients of All Constant-Amplitude CSS Tests

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<th>$D_{r,est.}$</th>
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Dr,est.

γ (SA)

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Nεv =1%

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Table B.2: Cycles to Various Levels of Volumetric Strain

<p>| No. | $N_{\varepsilon_v=0.1%}$ | $N_{0.2%}$ | $N_{0.3%}$ | $N_{0.4%}$ | $N_{0.5%}$ | $N_{0.6%}$ | $N_{0.7%}$ | $N_{0.8%}$ | $N_{0.9%}$ | $N_{1%}$ |
|-----|----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-----------|
| 1   | 2              | 4           | 10          | 20          | 39          | 73          | 140         | 263         | 485         | 862       |
| 2   | 1              | 2           | 5           | 8           | 11          | 21          | 27          | 40          | 59          | 82        |
| 3   | 1              | 1           | 2           | 2           | 3           | 4           | 5           | 5           | 6           | 8         |
| 4   | 1              | 3           | 5           | 10          | 17          | 29          | 50          | 88          | 148         | 262       |
| 5   | 2              | 4           | 10          | 20          | 37          | 65          | 111         | 186         | 392         | 482       |
| 6   | 2              | 5           | 11          | 21          | 43          | 79          | 137         | 237         | 362         | 526       |
| 7   | 2              | 4           | 11          | 24          | 50          | 105         | 208         | 417         | 775         | 1287      |
| 8   | 1              | 2           | 3           | 5           | 8           | 11          | 14          | 17          | 24          | 30        |
| 9   | 1              | 2           | 4           | 5           | 8           | 11          | 17          | 24          | 30          | 43        |
| 10  | 1              | 2           | 2           | 3           | 4           | 5           | 6           | 8           | 8           | 11        |
| 11  | 1              | 1           | 2           | 2           | 3           | 4           | 5           | 6           | 8           | 8         |
| 12  | 2              | 4           | 8           | 15          | 27          | 48          | 83          | 138         | 215         | 326       |
| 13  | 1              | 3           | 5           | 8           | 12          | 19          | 29          | 43          | 64          | 96        |
| 14  | 1              | 3           | 4           | 7           | 11          | 17          | 25          | 37          | 52          | 73        |
| 15  | 1              | 2           | 4           | 7           | 11          | 16          | 24          | 35          | 50          | 71        |
| 16  | 1              | 3           | 5           | 8           | 13          | 22          | 34          | 51          | 77          | 115       |</p>
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B.2 Irregular-Amplitude Results

Two types of irregular loading tests were performed: 1. Variable-amplitude sinusoidal loading, and 2. Earthquake-type loadings. Table B.3 summarizes the results of these tests. $D_r$ is the relative density of the test, $\gamma_{max}$ is the maximum shear strain of the test, and $\varepsilon_{v,fin}$ is the volumetric strain at the end of the test.

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</table>

The following figures give the results of the tests found in Table B.3.

![Figure B.1: Test results for irregular-loading seismic compression test 139.csv.](image-url)
Figure B.2: Test results for irregular-loading seismic compression test 140.csv.
Figure B.3: Test results for irregular-loading seismic compression test $141.csv$. 
Figure B.4: Test results for irregular-loading seismic compression test 143.csv.
Figure B.5: Test results for irregular-loading seismic compression test 144.csv.
Figure B.6: Test results for irregular-loading seismic compression test 145.csv.
Figure B.7: Test results for irregular-loading seismic compression test 146.csv.
Figure B.8: Test results for irregular-loading seismic compression test 162.csv.
Figure B.9: Test results for irregular-loading seismic compression test 163.csv.
Figure B.10: Test results for irregular-loading seismic compression test 164.csv.
Figure B.11: Test results for irregular-loading seismic compression test 178.csv.
Figure B.12: Test results for irregular-loading seismic compression test 179.csv.
Figure B.13: Test results for irregular-loading seismic compression test 180.csv.
Figure B.14: Test results for irregular-loading seismic compression test 181.csv.
Figure B.15: Test results for irregular-loading seismic compression test 142.csv.
Figure B.16: Test results for irregular-loading seismic compression test 147.csv.
Figure B.17: Test results for irregular-loading seismic compression test 177.csv.
Figure B.18: Test results for irregular-loading seismic compression test 100.csv.
Figure B.19: Test results for irregular-loading seismic compression test 101.csv.
Figure B.20: Test results for irregular-loading seismic compression test 102.csv.
Figure B.21: Test results for irregular-loading seismic compression test 105.csv.
Figure B.22: Test results for irregular-loading seismic compression test 106.csv.
Figure B.23: Test results for irregular-loading seismic compression test 107.csv.
Figure B.24: Test results for irregular-loading seismic compression test 108.csv.
Figure B.25: Test results for irregular-loading seismic compression test 110.csv.
Figure B.26: Test results for irregular-loading seismic compression test 111.csv.
Figure B.27: Test results for irregular-loading seismic compression test 112.csv.
Figure B.28: Test results for irregular-loading seismic compression test 113.csv.
Figure B.29: Test results for irregular-loading seismic compression test 115.csv.
Figure B.30: Test results for irregular-loading seismic compression test 116.csv.
Figure B.31: Test results for irregular-loading seismic compression test 117.csv.
Figure B.32: Test results for irregular-loading seismic compression test 118.csv.
Figure B.33: Test results for irregular-loading seismic compression test 120.csv.
Figure B.34: Test results for irregular-loading seismic compression test 97.csv.
Figure B.35: Test results for irregular-loading seismic compression test 98.csv.
Figure B.36: Test results for irregular-loading seismic compression test 99.csv.
Figure B.37: Test results for irregular-loading seismic compression test 104.csv.
Figure B.38: Test results for irregular-loading seismic compression test 109.csv.
Figure B.39: Test results for irregular-loading seismic compression test 114.csv.
Figure B.40: Test results for irregular-loading seismic compression test 119.csv.
Appendix C

Cycle Counting Methods for Seismic Compression

In order to estimate seismic compression using the Richart-Newmark (1948) method (Lasley et al., in preparation) for an irregular-loading situation, it is first necessary to obtain an array of loading sets with amplitudes and cycle counts (e.g. 2 cycles of amplitude $x$, 1 cycle of amplitude $y$, 3.5 cycles of amplitude $z$, etc.) from a loading time history. This technical note describes three methods or algorithms from ASTM Standard E1049 (2011) that were used in this research. In the ASTM specification, these methods are referred to as mean crossing peak counting (ZC), range counting (PP), and rainflow (RF) counting methods.

The mean crossing peak counting method counts as one cycle the largest peak between each mean-crossing. The mean used in this research was zero. Figure C.1 shows a random loading time history. For this loading time history, the load first crosses the mean (0) at about 7. Thus, the first cycle count is one cycle with an amplitude of 0.96. The mean is next crossed at about 10 with a peak between 7 and 10 of 0.7; the second cycle count is one cycle with an amplitude of 0.7. The pattern continues until there are no more mean crossings.

The range counting algorithm counts as one half cycle the difference between any two adjacent local peaks. Figure C.2 shows the amplitudes of two different one-half cycle counts. Each local peak is a stress reversal; the method counts as one half cycle the difference between each successive stress reversal. This method is arguably better for seismic compression than the mean crossing peak counting method because it takes into account all stress reversals.

The rainflow counting algorithm is somewhat different from the other two cycle counting algorithms. From a loading time history, the difference between three consecutive peaks/valleys is compared and a cycle is counted only if the second difference is greater than or equal to the first. If $Y$ contains the starting point, it is counted as one-half cycle, otherwise
it is counted as one full cycle. If the second difference isn’t greater than or equal to the first, the next peak or valley is added to the list and the differences between the last three peaks/valleys are compared. The differences between leftover peaks are added in at the end. In Figure C.3, the first and second differences between peaks/valleys of the first step are labeled $Y_1$ and $X_1$, respectively. Since $X_1$ is greater than $Y_1$, the first one half cycle with amplitude $Y_1$ is counted. The algorithm continues, as shown in Table C.1, until no peaks or valleys are left. One issue with the rainflow counting algorithm is that cycles are sometimes counted out-of-order which, for seismic compression with the R-N model, changes the predicted damage.

For use in this research, the returned amplitude of loading from the rainflow and range counting methods was divided by two to match the calibration of the models. Similarly, the cycle counts returned by the mean crossing peak counting method was also divided by two for use in these procedures. In this way, the cycle amplitudes and counts across methods are nearly the same for a sinusoidal time history.

Table C.2 shows the median and interquartile range of the percent error in prediction for both earthquake-type and variable-amplitude sinusoidal loadings. The results of all three cycle counting methods is shown. For the R-N and Byrne methods, the mean crossing peak counting (ZC) method gives slightly better predictions than the other two algorithms. For the P-M method, the best predictions are made using the range counting (PP) method.

\section*{C.1 References}


C.2 Tables

Table C.1: Stepwise Illustration of the Rainflow Counting Algorithm

<table>
<thead>
<tr>
<th>Step</th>
<th>Start Point</th>
<th>Y</th>
<th>X</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>[A-B]</td>
<td>[B-C]</td>
<td>$X \geq Y \Rightarrow [A-B]$ is one half cycle; discard A</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>[B-C]</td>
<td>[C-D]</td>
<td>$X &lt; Y \Rightarrow$ Read next peak or valley</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>[C-D]</td>
<td>[D-E]</td>
<td>$X &lt; Y \Rightarrow$ Read next peak or valley</td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td>[D-E]</td>
<td>[E-F]</td>
<td>$X \geq Y \Rightarrow$ is one cycle, discard D &amp; E</td>
</tr>
<tr>
<td>5</td>
<td>B</td>
<td>[B-C]</td>
<td>[C-F]</td>
<td>$X \geq Y \Rightarrow$ is one half cycle, discard B</td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>[C-F]</td>
<td>[F-G]</td>
<td>$X &lt; Y \Rightarrow$ Read next peak or valley</td>
</tr>
<tr>
<td>7</td>
<td>C</td>
<td>[F-G]</td>
<td>[G-H]</td>
<td>$X \geq Y \Rightarrow$ is one cycle, discard F &amp; G</td>
</tr>
<tr>
<td>8</td>
<td>C</td>
<td>[C-H]</td>
<td>[H-I]</td>
<td>$X \geq Y \Rightarrow$ is one half cycle, discard C</td>
</tr>
<tr>
<td>9</td>
<td>H</td>
<td>[H-I]</td>
<td>[I-J]</td>
<td>$X \geq Y \Rightarrow$ is one half cycle, discard H</td>
</tr>
<tr>
<td>10</td>
<td>I</td>
<td>[I-J]</td>
<td>[J-K]</td>
<td>$X &lt; Y \Rightarrow$ Read next peak or valley</td>
</tr>
<tr>
<td>11</td>
<td>I</td>
<td>[J-K]</td>
<td>[K-L]</td>
<td>$X &lt; Y \Rightarrow$ Read next peak or valley</td>
</tr>
<tr>
<td>12</td>
<td>I</td>
<td>[K-L]</td>
<td>[L-M]</td>
<td>$X &lt; Y \Rightarrow$ Read next peak or valley</td>
</tr>
<tr>
<td>13</td>
<td>I</td>
<td>[L-M]</td>
<td>[M-N]</td>
<td>$X \geq Y \Rightarrow$ is one cycle, discard L &amp; M</td>
</tr>
<tr>
<td>14</td>
<td>I</td>
<td>[I-J]</td>
<td>[J-K]</td>
<td>$X &lt; Y \Rightarrow$ Read next peak or valley</td>
</tr>
<tr>
<td>15</td>
<td>I</td>
<td>[J-K]</td>
<td>[K-N]</td>
<td>$X \geq Y \Rightarrow$ is one cycle, discard J &amp; K</td>
</tr>
<tr>
<td>15</td>
<td>I</td>
<td>[J-N]</td>
<td>[N-O]</td>
<td>$X \geq Y \Rightarrow$ is one half cycle, discard I</td>
</tr>
<tr>
<td>16</td>
<td>N</td>
<td></td>
<td></td>
<td>No more points $\Rightarrow$ is one half cycle</td>
</tr>
</tbody>
</table>

Table C.2: Comparison of Cycle Counting Methods As Used with Seismic Compression Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>R-N</th>
<th>Byrne</th>
<th>P-M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algorithm</td>
<td>median, $IQR$</td>
<td>median, $IQR$</td>
<td>median, $IQR$</td>
</tr>
<tr>
<td>PP</td>
<td>6.6, 20.1</td>
<td>2.9, 20.6</td>
<td>44.6, 64.1</td>
</tr>
<tr>
<td>RF</td>
<td>3.6, 22.5</td>
<td>-10.6, 34.7</td>
<td>44.5, 62.8</td>
</tr>
<tr>
<td>ZC</td>
<td>5.0, 18.1</td>
<td>-1.5, 17.2</td>
<td>43.6, 62.8</td>
</tr>
<tr>
<td>Mean</td>
<td>4.1, 22.2</td>
<td>-4.3, 20.6</td>
<td>43.3, 63.2</td>
</tr>
</tbody>
</table>
C.3 Figures

Figure C.1: An illustration of the mean crossing peak counting algorithm.
Figure C.2: Two one-half cycles as determined by the range counting algorithm.
Figure C.3: The rainflow counting algorithm.
Appendix D

Cyclic Simple Shear Lab Test Results

D.1 Introduction

A number of cyclic simple shear tests were performed as part of this research. Two different testing programs were followed in this research; one program studied seismic compression, and the other studied liquefaction triggering. The seismic compression testing programming was undertaken from January through April 2011. The liquefaction triggering program was undertaken from April 2014 to May 2015.

This chapter details the testing equipment and testing procedure of both programs and the testing results of the liquefaction triggering program.

D.2 Setup and Equipment

Cyclic laboratory testing was performed using the GCTS SSH-100 cyclic simple shear equipment. This equipment is capable of performing both cyclic simple shear and cyclic triaxial tests with stress- and strain-controlled motions. In addition, the equipment is capable of applying multiple load functions, from sinusoidal loadings to any arbitrary motion.

Two significant modifications were made to the testing equipment in order to obtain better cyclic simple shear test results. In the early stages of the seismic compression testing program, it was observed that significant compliance occurred in the shear direction during the cyclic loading phase. To remedy the issue, large external braces were fit to the equipment. The design of these braces prevents the cell from being used when the full
bracing is installed. However, the cell was unnecessary for either of testing programs described herein.

The second modification simply replaced one of the parts to which the top platen is mounted during testing. This part was resized to allow space for an internal normal pressure cell. This was necessary to perform constant-volume cyclic simple shear tests, as discussed in a subsequent section. Figure D.1 shows the two modifications in place for a test, and Figure D.2 shows the second modification in greater detail.

D.3 Specimen Preparation

For both testing programs, the cyclic simple shear specimens were prepared via dry pluviation. Pluviation mimics the natural deposition of sands and has been shown to provide a uniform fabric (Vaid and Negussey 1984: 1988). However, due to potential for grain-size segregation, pluviation is best used with poorly-graded sands only (Kuerbis and Vaid 1988).

Dry pluviation was performed by placing dry sand into a flask, attaching a stopper and funnel to the flask opening, and by gently swirling the flask as sand was poured through the funnel into the specimen mold. Figure D.3 shows the flask with stopper, funnel, and sand. For the seismic compression program, a specific mass of sand was placed in the flask, the sand was loosely poured into the mold, the surface of the sand was leveled, and the desired relative density was achieved by vibrating the specimen with the top platen in place. For the liquefaction triggering program, the mold was overfilled and the excess sand was removed using a straightedge (Figure D.4). In this case, the density of the sand was controlled by adjusting both the pour height and the diameter of the funnel opening.

D.4 Testing Procedure

The basic testing procedure for both programs involved three phases: specimen preparation, consolidation, and cyclic loading until failure. For both testing programs, dry specimens were used and drained conditions prevailed throughout the consolidation and cyclic loading phases. Consolidation was achieved by applying a normal stress of 50, 100, or 250 kPa (60, 100, 250 kPa for the liquefaction triggering program) to the top of the specimen until vertical strains ceased to accumulate. The void ratio and relative density at the end of consolidation are the values used in subsequent analyses. During consolidation and the cyclic loading phase, lateral deformations were prevented by the brass confining rings outside the specimen (shown in Figures D.1 and D.4).

For the cyclic loading phase of the seismic compression testing program, vertical stresses were held constant (at 50, 100, or 250 kPa) and vertical strains were allowed to occur while cyclic shear strains were applied to the base of the specimen (i.e. the seismic compression
tests were strain controlled). Because lateral deformations were prohibited by the con-
fining rings, vertical strains equaled volumetric strains. Cyclic loading was stopped after
volumetric strains exceeded one percent.

The liquefaction triggering program was conducted using constant-volume (C-V) tests
(Finn and Vaid 1977; Finn et al. 1979); vertical strains were minimized during cyclic
loading, and the vertical stress was allowed to change as cyclic loading progressed. For
constant-volume tests, a decrease in vertical stress corresponds to an increase in pore wa-
ter pressure; the excess pore water ratio reported from these tests is a simulated value.
Both stress- and strain-controlled tests were performed, with both sinusoidal and earth-
quake motions used as loading functions for the stress-controlled tests. The cyclic phase
continued until liquefaction had occurred as determined by a specific failure criterion. The
specific failure criterion depended on the type of loading and will be detailed in subsequent
sections.

D.5 Materials

Two different sands were used; a nondescript quartz sand was used in the seismic compres-
sion program, and Monterey 0/30 sand was used for the liquefaction triggering program.
Minimum and maximum void ratios were determined following ASTM (2000) specifica-
tions D4254 and D4253, respectively. Both sands are poorly-graded (see Figure D.5) and
suitable for use with the dry pluviation preparation method. Table D.1 summarizes some
of the index properties of each sand.

D.6 Results

A discussion on the results of the seismic compression program is given in Chapter 3; this
section will focus on the results of the liquefaction triggering program. As mentioned in
a previous section, stress-controlled tests were performed using sinusoidal and earthquake
loading functions, and strain-controlled tests were also performed using sinusoidal loading
functions. The results from each of these loading functions is given in this section, and
a comparison between the three is also given. Finally, the results from this study are
compared to those from two other studies.

D.6.1 Stress-Controlled Sinusoidal Tests

A number of stress-controlled sinusoidal-loading tests were performed on the Monterey
0/30 sand. The relative density of the test specimens ranged from approximately 30 to
80%, and overburden pressures of 60, 100, and 250 kPa were imposed for the entire range
of densities. A failure criterion of 3.75% single-amplitude shear strain was adopted (Vaid
Figures D.6 and D.7 show typical results for loose and dense specimens, respectively. From top to bottom, the figures show plots of the progression of normal and shear stresses, normal strain, and simulated pore pressure ratio ($r_u = u_{excess}/\sigma_v$ where $u_{excess}$ is defined here as $\sigma_{v0} - \sigma_v$). At the bottom is a plot of shear stress versus shear strain. Loose specimens experienced a “brittle” failure where large shear strains are observed in the last few cycles only. Dense specimens, on the other hand, experienced what might be termed a “ductile” failure with large shear strains for many cycles before failure. While an attempt was made to prevent any volumetric strain from occurring during the cyclic loading phase, some volumetric strain did occur with some tests exceeding 0.3% volumetric strain. For loose specimens, most of this volumetric strain occurred in the last few cycles only, but this was not the case for the dense specimens.

Figure D.8 shows a plot of cyclic stress ratio ($CSR$) versus the number of cycles to failure ($N_{liq}$). Contours of relative density are shown, and only four tests with relative densities greater than about 55% exceeded the shear strain failure criterion of 3.75%. The logarithm of $CSR$ was regressed as a function of relative density and the logarithm of $N_{liq}$, with a resulting $R^2_{adj.}$ value of 0.90.

As the purpose of this research was to incorporate dissipated energy into liquefaction evaluations, the dissipated energy to failure was calculated for each test. As discussed in Chapter 2, the dissipated energy per unit volume is estimated using the trapezoidal rule and the stress and strain time histories of each test. It was calculated up to the last data point of zero shear stress before the failure criterion was exceeded. This data point is illustrated by the green dot in Figures D.6 and D.7; the red dot corresponds to the data point at which the failure criterion is exceeded. The dissipated energy calculated in this manner is $\Delta W_{Effect.}$, the dissipated energy corresponding to an effective stress analysis.

Figure D.9 shows the normalized dissipated energy ($\Delta W_{Effect.}/\sigma'_{v0}$) versus relative density ($D_r$). The dissipated energy to liquefaction increases with increasing initial effective overburden stress, but the normalized dissipated energy is considered to be constant for a given relative density. Using the results of all the stress-controlled sinusoidal-loading tests, the logarithm of the normalized dissipated energy is regressed as a function of the square of the relative density with an $R^2$ value of 0.75. Judging by the $R^2$ values, the $CSR-N_{liq.-}D_r$ relationship is slightly stronger than the $\Delta W_{Effect.}/\sigma'_{v0}-D_r$ relationship. However, the former relationship corresponds to a stress-controlled sinusoidal loading, and the latter relationship should be insensitive to the loading function.

### D.6.2 Earthquake Loading Tests

A few stress-controlled tests were performed with earthquake-motion loading functions. The loading functions were obtained using equivalent-linear site response analyses, a simple sand profile, and a few earthquake motions from the NGA database (Chiou et al. 2008). The profile used in the equivalent-linear analyses is clean sand to bedrock at a depth of
30 meters and a shear wave velocity that increases from 74.6 m/s at the surface to 225.3 m/s at the layer just above the bedrock (Lee 2009). The shear stress motions used as the loading functions were taken from a depth of 5.1 m which corresponds to an overburden pressure of 100 kPa. These response shear stress motions were then scaled so that the CSR values of the tests ranged from 0.14 to 0.3.

Figure D.10 shows a typical test result, and Figure D.11 shows the normalized dissipated energy versus relative density for these tests. Of all the tests, only 24 exceeded the failure criterion of 3.75% shear strain, and all of these corresponded to a single input motion (NGA_no.87_SAD273). Relative densities of the tests were limited to less than 50%, and the trend of normalized dissipated energy to relative density is weak ($R^2 = 0.07$). However, the normalized dissipated energy required to cause liquefaction was fairly constant over all overburden stresses and cyclic stress ratios. The recorded motions used as input functions were not sufficiently long to cause liquefaction for dense specimens; this could be avoided in future testing by using artificial motions, by splicing together several motions, or by repeating a motion multiple times.

D.6.3 Strain-Controlled Tests

A few strain-controlled sinusoidal loading tests were performed to complement the stress-controlled tests. Figures D.12 and D.13 show typical results for loose and dense specimens, respectively. In a stress-controlled test, hysteresis loops increase in size as cyclic loading progresses, but in strain-controlled tests, the area bound by the hysteresis loops decreases as loading progresses. In other words, the shape of the dissipated-energy-accumulation path is different between the two types of tests. This is reflected in the paths of the pore pressure ratios, especially in loose specimens. At the last part of the test, pore pressure ratios increase sharply in a stress-controlled test, but flatten out in a strain-controlled test (see Figures D.6 and D.12). Altogether, comparing the results of stress- and strain-controlled tests provide a way to examine the efficacy of normalized dissipated energy as an indicator of liquefaction triggering.

Figure D.14 shows the single-amplitude shear strain ($\gamma$) versus the number of cycles to liquefaction ($N_{liq}$) for the strain-controlled tests. This is analogous to the CSR-$N_{liq}$ (Figure D.8) plot of stress-controlled tests. A failure criterion of $r_{u,static} = 0.98$ (i.e. $r_u \geq 0.98$ when the applied shear stress is equal to zero) was adopted for these strain-controlled tests, and 26 tests exceeded that threshold.

Figure D.14 also shows contours of relative density, and the logarithm of $\gamma$ was regressed as a function of $D_r$ and the logarithm of $N_{liq}$ with an $R^2_{adj}$ value of 0.36. Compared to the CSR-$N_{liq}$-$D_r$ relationship of the stress-controlled tests, the $\gamma$-$N_{liq}$-$D_r$ relationship of the strain-controlled tests is much weaker. However, Figure D.15 shows a strong trend ($R^2 = 0.82$) between the normalized dissipated energy and relative density. This $R^2$ value is greater than that given for the stress-controlled tests (0.75).
D.6.4 Comparison Between Stress- and Strain-Controlled Tests

Using the results of both the stress- and strain-controlled sinusoidal loading tests, additional regression coefficients were obtained via bootstrapping (Efron and Tibshirani 1994) for the following functional form:

\[
\frac{\Delta W_{\text{Effect}}}{\sigma'_{\text{v0}}} = \beta_0 + \beta_1 D_r^2 + \varepsilon \tag{D.1}
\]

where \( \Delta W_{\text{Effect}} / \sigma'_{\text{v0}} \) is the normalized dissipated energy per unit volume corresponding to effective stress analyses, \( D_r \) is the relative density in percent, \( \beta_0 \) and \( \beta_1 \) are regression coefficients, and \( \varepsilon \) is an error term. This is the same functional form presented in Figures D.9, D.11, and D.15. The regression coefficients presented in those figures were obtained using ordinary least squares regression. The bootstrapping method used in this section also implements ordinary least squares regression, but in a different manner:

1. From each dataset, 50 data points were randomly sampled with replacement (each dataset has less than 50 data points).
2. Using these 50 data points, ordinary least squares regression was performed to obtain the regression coefficients of \( \beta_0 \) and \( \beta_1 \).
3. Steps 1 and 2 were repeated for a total of 200 times, recording the regression coefficients for each iteration.

By using this bootstrapping method, the variability in each regression coefficient can be examined. In other words, the results of bootstrapping indicate how well each regression coefficient is constrained by the data. Table D.2 shows the mean and standard deviations of each regression coefficient for the two datasets and for a dataset that combined the two. For all three datasets (stress-controlled, strain-controlled, and combined), the mean and standard deviations of the regression coefficients are very similar. This is illustrated in Figure D.16 where the stress- and strain-controlled curves show good agreement; these curves use the non-bootstrapped regression coefficients.

In order to evaluate whether the regression coefficients are significantly close to be considered the same, two Welch’s (1947) t-tests were performed on the sets of regression coefficients from the bootstrapping. Welch’s t-test is used to test whether two populations have the same means, and it was chosen in this case (instead of the Student’s t-test) because Welch’s test does not assume that the samples have equal variances. For this t-test, the null hypothesis \( (H_0) \) and alternative hypothesis \( (H_a) \) are defined as:

- \( H_0 : \bar{\beta}_{0,\text{stress}} = \bar{\beta}_{0,\text{strain}} \) and \( \bar{\beta}_{1,\text{stress}} = \bar{\beta}_{1,\text{strain}} \)
- \( H_a : \bar{\beta}_{0,\text{stress}} \neq \bar{\beta}_{0,\text{strain}} \) and \( \bar{\beta}_{1,\text{stress}} \neq \bar{\beta}_{1,\text{strain}} \)
The Welch’s t-test returns a $t$ value and corresponding $p$-value. If the $p$-value is less than the level of significance, $\alpha$, then the null hypothesis is rejected. For this study, an $\alpha$ value of 0.05 was adopted. Table D.3 shows the results of the t-tests. For both the intercept ($\beta_0$) and slope ($\beta_1$) terms, the $p$-value is greater than $\alpha$ which indicates that the null hypothesis cannot be rejected based on this data. In other words, the differences between the stress-controlled and strain-controlled intercepts and slopes are not significantly different. It should be noted, however, that the intercept term is barely insignificant with a $p$-value of 0.0501. Also, as the number of bootstrap iterations increases, the $p$-values decrease and the null hypotheses will then be rejected.

**D.6.5 Comparison With Other Test Programs**

As part of his research in energy-based liquefaction evaluation, Green (2001) examined the results of a number of stress-controlled cyclic triaxial tests that were performed on Monterey and Yatesville sands. Figure D.17 shows the normalized dissipated energy calculated for each test on Monterey sand ($FC \leq 5\%$) as a function of relative density. The failure criterion used in these tests was $r_u = 1.0$ for the majority of the tests, and a double-amplitude axial strain ($\varepsilon_{DA}$) of 5% for a few cases. Also shown in Figure D.17 are the regression coefficients for the same $\Delta W_{\text{Effect.}}/\sigma'_{vo}D_r^2$ relationship. Compared to the regression coefficients of the fit to all the laboratory tests of this study (Figure D.18), the Green (2001) data shows a very similar trend.

Riemer et al. (1994) performed stress- and strain-controlled cyclic triaxial tests on Monterey #0 sand. The main purpose of their work was to study the effects of loading frequency on the liquefaction triggering of a clean sand. Accordingly, they performed their tests at frequencies of 0.1, 1, 10, 15, and 20 Hz. They also studied the accumulation of dissipated energy as loading progressed, and a plot of normalized dissipated energy versus relative density (Figure D.19) from their results is of interest here. Their tests were performed at relative densities of 40, 50, and 60%, and the trend with relative density is weaker than that of Green (2001) or that of this research.

Figure D.20 shows the data and trends from all three datasets: Green (2001), Riemer et al. (1994), and the results of all cyclic simple shear tests from the liquefaction triggering program. All three datasets have similar values of normalized dissipated energy at relative densities between 40 to 50%. At higher relative densities, the data from Green (2001) shows a trend of lower normalized dissipated energy when compared to the data from this study. At a relative density of 60%, the Riemer et al. (1994) data has a large spread of normalized dissipated energies; the trend lines from Green (2001) and this study fall within this spread.

Despite the fact that the three datasets were obtained from two different tests (cyclic triaxial and cyclic simple shear), two different sands (Monterey 0/30 and Monterey #0), and four different failure criteria ($r_u = 98\%$, $r_u = 100\%$, $\varepsilon_{DA} = 5\%$, and $\gamma = 3.75\%$), the resulting $\Delta W_{\text{Effect.}}/\sigma'_{vo}D_r^2$ relationships are remarkably similar between the datasets. This level of agreement is not possible with traditional relationships (e.g. $CSR-N_{\text{eq.}}-D_r$) because both stress- and strain-controlled test results are included here.
dissipated energy and relative density provide a robust liquefaction triggering criterion that merges the stress-based and strain-controlled laboratory testing results.

D.7 Summary

A number of cyclic simple shear tests were performed in support of the seismic compression and liquefaction triggering research. The test specimens were prepared via dry pluviation of quartz sand for seismic compression and Monterey 0/30 sand for liquefaction triggering.

Constant-volume cyclic simple shear tests were used in the liquefaction-triggering testing program, and the results show that normalized dissipated energy and relative density together are overall better predictors of initial liquefaction than $CSR$, $N_{liq}$, and $D_r$ or $\gamma$, $N_{liq}$, and $D_r$. This was illustrated with the results of stress-controlled sinusoidal loading tests and strain-controlled sinusoidal-loading tests. Due to a lack of results at high relative densities, the regressed $\Delta W_{Effect}/\sigma'_{vo}D^2_r$ curve from the earthquake loading data is poorly constrained. However, the regressed curves from the stress- and strain-controlled sinusoidal-loading tests give good agreement for the range of relative densities for which tests were performed ($\sim 30$ to $80\%$).

The results from this study were compared with those from Green (2001) and Riemer et al. (1994). Both Green (2001) and Riemer et al. (1994) performed cyclic triaxial tests. Despite the differences in laboratory test and failure criteria, all three sets of results show a similar trend of increasing normalized dissipated energy with relative density and similar magnitudes of normalized dissipated energy to liquefaction. The proposed $\Delta W_{Effect}/\sigma'_{vo}D^2_r$ relationship provides a good fit for all three datasets and merges the stress- and strain-controlled laboratory testing results.

D.8 References


Welch, B. L. (1947). “The generalization of”Student’s” problem when several different population variances are involved,” Biometrika, 34(1–2), 28–35.
Table D.1: Index Properties of the Sands Tested.

<table>
<thead>
<tr>
<th>Property</th>
<th>Quartz Sand</th>
<th>Monterey 0/30</th>
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<td>$e_{max}$</td>
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<td>0.845</td>
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<td>$G_s$ (assumed)</td>
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<td>$D_{50}$ (mm)</td>
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<td>0.59</td>
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<td>$C_u$</td>
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<tr>
<td>$\gamma_{d,max}$</td>
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Table D.2: Mean and Standard Deviations of Regression Coefficients for the $\Delta W_{Effect}/\sigma'_{ct}$-$D_r$ Relationship Obtained Via Bootstrapping

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<th>Test Type</th>
<th>$\bar{\beta}_0$</th>
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<th>$\bar{\beta}_1$</th>
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Table D.3: Results of Welch’s t-tests

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<tr>
<td>$\beta_1$</td>
<td>-0.446</td>
<td>0.656</td>
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</table>
D.10 Figures

Figure D.1: GCTS equipment with CSS specimen and modifications.
Figure D.2: Part of the top platen mount that has been modified. The silver-colored block is new; it replaces a larger (taller) block to allow room for the internal normal pressure cell (shown).
Figure D.3: Flask, funnel, and stopper used for dry pluviation.
Figure D.4: Removing excess sand from a liquefaction-evaluation specimen.
Figure D.5: Gradations of the sands used in cyclic simple shear testing.
Figure D.6: Typical results for a stress-controlled sinusoidal test on a loose specimen.

$D_t = 30.6\%$, $CSR = 0.11$, $N_{iq} = 12.0$, $\sigma_{v0}' = 100$ kPa
Figure D.7: Typical results for a stress-controlled sinusoidal test on a dense specimen.
Figure D.8: Cyclic stress ratio, CSR, versus number of cycles to liquefaction, $N_{\text{liq.}}$, for stress-controlled sinusoidal tests.
Figure D.9: Normalized dissipated energy, $\Delta W_{\text{Eff}}/\sigma_{v0}$, versus relative density, $D_r$, for stress-controlled sinusoidal tests.

\[
\frac{\Delta W_{\text{Eff}}}{\sigma_{v0}} = \exp\left(0.00049D_r^2 - 5.392\right)
\]

$R^2 = 0.75$
Figure D.10: Typical results for a stress-controlled earthquake-loading test.

\[ D_r = 31.0\%, \; CSR = 0.11, \; \sigma'_{a0} = 100 \text{ kPa} \]

- **Stress, \( \tau \) (kPa)**
- **Normal Strain, \( \varepsilon_n \) (%)**
- **Shear Stress, \( \tau_s \) (kPa)**
- **Shear Strain, \( \gamma \) (%)**
Figure D.11: Normalized dissipated energy, $\Delta W_{\text{Effect.}}/\sigma'_{v0}$, versus relative density, $D_r$, for stress-controlled earthquake-loading tests.
Figure D.12: Typical results for a strain-controlled sinusoidal test on a loose specimen.
Figure D.13: Typical results for a strain-controlled sinusoidal test on a dense specimen.

\[ \begin{align*}
D_t &= 83.0 \% \quad N_{liq} = 46.0 \, \text{cycles}, \quad \sigma'_{v_0} = 250 \text{ kPa}
\end{align*} \]
Figure D.14: Amplitude of cyclic shear strain, $\gamma$, versus number of cycles to liquefaction, $N_{liq}$, for strain-controlled sinusoidal tests.
Figure D.15: Normalized dissipated energy, $\Delta W_{\text{Effect.}}/\sigma_{v0}$, versus relative density, $D_r$, for strain-controlled sinusoidal tests.
Figure D.16: Normalized dissipated energy, $\Delta W_{\text{Effect.}}/\sigma_{v0}$, versus relative density, $D_r$, for all tests from this study.
Figure D.17: Normalized dissipated energy, $\Delta W_{\text{Effect.}} / \sigma'_{\alpha0}$, versus relative density, $D_r$, for cyclic triaxial tests performed on Monterey sand (from Green 2001).
Figure D.18: Normalized dissipated energy, $\Delta W_{\text{Effect.}}/\sigma'_{i0}$, versus relative density, $D_r$, for all tests performed as part of the liquefaction triggering program.
Figure D.19: Normalized dissipated energy, $\Delta W_{\text{Effect.}}/\sigma'_{10}$, versus relative density, $D_r$, for cyclic triaxial tests performed on Monterey #0 sand (Riemer et al. 1994).
Figure D.20: Normalized dissipated energy, $\Delta W_{\text{Effect.}}/\sigma'_{v0}$, versus relative density, $D_r$, for all laboratory testing (this study; Green 2001; Riemer et al. 1994).
D.11 Sinusoidal Loading Results

Table D.4 summarizes the results of the stress-controlled sinusoidal tests. In the table heading, $D_r$ is the relative density of the sample (in percent) at the beginning of the cyclic phase of testing, $CSR$ is the cyclic stress ratio of the loading, $\sigma'_{v0}$ is the effective overburden stress felt by the sample at the beginning of the cyclic phase in kPa, $N_{liq.}$ is the number of cycles to ‘liquefaction’ defined as 3.75% single amplitude shear strain, $\Delta W_{\text{Effect.}}$ is the dissipated energy up to initial liquefaction in kPa (calculated from effective stress analyses), and $\Delta W_{\text{Total}}$ is the dissipated energy up to liquefaction corrected to remove effects of softening (i.e. corresponding to total stress analyses; see Green 2001$^1$).

Table D.4: Results of stress-controlled sinusoidal CV-CSS tests.

<table>
<thead>
<tr>
<th>No.</th>
<th>$D_r$</th>
<th>$CSR$</th>
<th>$\sigma'_{v0}$</th>
<th>$N_{liq.}$</th>
<th>$\Delta W_{\text{Effect.}}$</th>
<th>$\Delta W_{\text{Total}}$</th>
<th>Name</th>
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<td>1</td>
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D.12 Earthquake Loading Results

Table D.5 summarizes the results of stress-controlled tests that use earthquake motions as the loading function. The stress time history used as the loading function was obtained by applying an earthquake acceleration time history at the base of a simple sand profile (30 m thick) and performing an equivalent-linear site response analysis. The stress time history is the response at an effective overburden stress of 100 kPa. The columns of Table D.5 are defined as follows: $D_r$ is relative density of the specimen at the beginning of the cyclic phase (%), $CSR$ is defined as $0.65 \cdot \frac{\tau_{\text{max}}}{\sigma'_{v,i}}$ of the recorded stress, $\sigma'_{v,0}$ is the initial effective overburden stress, $\Delta W_{\text{Effect.}}$ is the dissipated energy up to initial liquefaction in kPa, $\Delta W_{\text{Total}}$ is the dissipated energy up to liquefaction corrected to remove effects of softening (kPa) (i.e. corresponding to total stress analyses), $r_{u,\text{final}}$ is the ‘synthetic’ excess pore pressure ratio at failure obtained from the effective overburden stress ($r_u = (\sigma'_{v,0} - \sigma'_{v,i})/\sigma'_{v,0}$), and ‘Motion’ is the name of the input time history. If the motion name ends in ‘inv’, the stress time history was multiplied by -1, i.e. it was inverted. For these results, failure or initial liquefaction was considered to have occurred when the single-amplitude shear strain exceeded 3.75 percent. Thus, $r_{u,\text{final}}$ is not equal to one in all cases.

Table D.5: Results of Stress-Controlled Earthquake-Loading Constant Volume Cyclic Simple Shear Tests

<table>
<thead>
<tr>
<th>No.</th>
<th>$D_r$</th>
<th>$CSR$</th>
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D.13 Strain-Controlled Sinusoidal Loading Results

Table D.6 summarizes the results of strain-controlled sinusoidal constant volume cyclic simple shear tests. Failure or initial liquefaction was determined as the static excess pore pressure ratio exceeded 98% ($r_u \geq 0.98$ when $\tau_{cyclic} = 0$). The cutoff of 0.98% was chosen because loose specimens tended to reach $r_u = 1$ without a problem, but denser specimens had trouble reaching $r_u = 1$ despite very low shear stress response. The columns of Table D.6 are defined as follows: $D_r$ is relative density of the specimen at the beginning of the cyclic phase (%), $\gamma$ is the single-amplitude shear strain of the loading (%), $\sigma'_{v0}$ is the initial effective overburden stress (kPa), $\Delta W_{Effect}$ is the dissipated energy up to initial liquefaction (kPa) corresponding to effective stress analyses. The dissipated energy values of strain-controlled tests do not need to be adjusted to account for softening of the soil as stress-controlled tests do.

Table D.6: Results of Strain-Controlled CV-CSS Tests

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Appendix E

Soil Profiles of the Equivalent-Linear Analyses

Fifty profiles from Cetin (2000)\textsuperscript{1} were used for equivalent-linear site response analyses. These profiles were collected from case histories of a number of different earth-quake events. The shear wave velocity of the bedrock layers were increased for use with central-eastern United States (CEUS) motions. For more information, see Chapter 4.

E.1 Profile000 - Balboa Boulevard-Northridge Earthquake (1994)

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Figure E.1: Shear wave velocities of Profile000
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Figure E.3: Shear wave velocities of Profile002
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Prieta Earthquake (1989)

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Figure E.5: Shear wave velocities of Profile004
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Loma Prieta Earthquake (1989)

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Figure E.6: Shear wave velocities of Profile005
## E.7 Profile006 - Treasure Island-Loma Prieta Earthquake (1989)

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Figure E.7: Shear wave velocities of Profile006
# E.8 Profile007 - SFOBB-1-Loma Prieta Earthquake (1989)

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Figure E.8: Shear wave velocities of Profile007
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Figure E.9: Shear wave velocities of Profile008
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Figure E.10: Shear wave velocities of Profile009
## E.11 Profile010 - POO7-3-Loma Prieta Earthquake (1989)

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Figure E.11: Shear wave velocities of Profile010
### E.12 Profile011 - Woodward Marine UC-B4-
Loma Prieta Earthquake (1989)

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Figure E.12: Shear wave velocities of Profile011

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Figure E.13: Shear wave velocities of Profile012
## E.14 Profile013 - Moss Landing UC-B2-
Loma Prieta Earthquake (1989)

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Figure E.16: Shear wave velocities of Profile015
### E.17 Profile016 - Miller Farm CMF 3-Loma Prieta Earthquake (1989)

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Figure E.17: Shear wave velocities of Profile016
## E.18 Profile017 - Miller Farm CMF 5-Loma Prieta Earthquake (1989)

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Figure E.18: Shear wave velocities of Profile017
# E.19 Profile018 - Miller Farm CMF 8-Loma Prieta Earthquake (1989)

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Figure E.19: Shear wave velocities of Profile018
### Profile019 - Miller Farm CMF 10-Loma

**Prieta Earthquake (1989)**

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Figure E.20: Shear wave velocities of Profile019
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Figure E.21: Shear wave velocities of Profile020
### E.22 Profile021 - Port of Richmond POR-2-
Loma Prieta Earthquake (1989)

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Figure E.22: Shear wave velocities of Profile021
E.23  Profile022 - Port of Richmond POR-3-
Loma Prieta Earthquake (1989)

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Figure E.23: Shear wave velocities of Profile022
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Loma Prieta Earthquake (1989)

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Figure E.24: Shear wave velocities of Profile023
## E.25 Profile024 - Miller Farm-Loma Prieta Earthquake (1989)

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Figure E.25: Shear wave velocities of Profile024
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Figure E.26: Shear wave velocities of Profile025
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Figure E.27: Shear wave velocities of Profile026
E.28 Profile027 - Wildlife Site-Superstition Hills (1987)

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Figure E.28: Shear wave velocities of Profile027

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Figure E.29: Shear wave velocities of Profile028
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Figure E.30: Shear wave velocities of Profile029

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Figure E.31: Shear wave velocities of Profile030
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Figure E.32: Shear wave velocities of Profile031
### E.33 Profile032 - River Park A & C - Superstition Hills (1987)

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Figure E.33: Shear wave velocities of Profile032

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Figure E.34: Shear wave velocities of Profile033
### E.35 Profile034 - Heber Road A2-Superstition Hills (1987)

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Figure E.35: Shear wave velocities of Profile034
**E.36 Profile035 - Heber Road A3-Superstition Hills (1987)**

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Figure E.36: Shear wave velocities of Profile035
## Profile036 - Kornbloom-Westmorland (1981)

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Figure E.37: Shear wave velocities of Profile036
## E.38 Profile037 - McKim Ranch-Westmorland (1981)

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Figure E.38: Shear wave velocities of Profile037

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Figure E.40: Shear wave velocities of Profile039
### E.41 Profile040 - River Park A & C-Westmorland (1981)

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Figure E.41: Shear wave velocities of Profile040
### E.42 Profile041 - Wildlife-Westmorland (1981)

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Figure E.42: Shear wave velocities of Profile041
### E.43 Profile042 - Heber Road A1-Imperial Valley (1979)

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Figure E.46: Shear wave velocities of Profile045
### E.47 Profile046 - Radio Tower B1-Imperial Valley (1979)

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Figure E.48: Shear wave velocities of Profile047
### E.49 Profile048 - River Park A & C-Imperial Valley (1979)

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Figure E.49: Shear wave velocities of Profile048
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Figure E.50: Shear wave velocities of Profile049
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Appendix F

Earthquake Motions

F.1 NGA Earthquake Database

The following figures show the WUS earthquake motions used in the equivalent-linear site response analyses. More details on each motion are given in the electronic supplements of Chapters 4 and 5.
Figure F.1: WUS 1: 1011_WON095 and 1011_WON185.

Figure F.2: WUS 2: 1012_LA0000 and 1012_LA0090.
Figure F.3: WUS 3: \textit{1021\_L04000} and \textit{1021\_L04090}.

Figure F.4: WUS 4: \textit{1023\_L09090} and \textit{1023\_L09000}.
Figure F.5: WUS 5: 1027_LV1000 and 1027_LV1090.

Figure F.6: WUS 6: 1029_LV3000 and 1029_LV3090.

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Figure F.7: WUS 7: 1033_LIT090 and 1033_LIT180.

Figure F.8: WUS 8: 1041_MTW000 and 1041_MTW090.
Figure F.9: WUS 9: 1050_PAC265 and 1050_PAC175.

Figure F.10: WUS 10: 1051_PUL104 and 1051_PUL194.
Figure F.11: WUS 11: 1060_CUC090 and 1060_CUC180.

Figure F.12: WUS 12: 1074_SAN090 and 1074_SAN180.
Figure F.13: WUS 13: $1078.5108-090$ and $1078.5108-360$.

Figure F.14: WUS 14: $1091.VAS000$ and $1091.VAS090$. 
Figure F.15: WUS 15: `1096_WWJ090` and `1096_WWJ180`.
Figure F.16: WUS 16: 1142_IZ1090 and 1142_IZ1000.
Figure F.17: WUS 17: 1154_BRS090 and 1154_BRS180.

Figure F.18: WUS 18: 1159_ERG090 and 1159_ERG180.
Figure F.19: WUS 19: 1165_IZT090 and 1165_IZT180.

Figure F.20: WUS 20: 1168_MNS000 and 1168_MNS090.
Figure F.21: WUS 21: \textit{1169.MSK000} and \textit{1169.MSK090}.

Figure F.22: WUS 22: \textit{1172.TKR090} and \textit{1172.TKR180}.

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Figure F.23: WUS 23: 124_A-FLT000 and 124_A-FLT270.

Figure F.24: WUS 24: 1257_HWA003-W and 1257_HWA003-N.
Figure F.25: WUS 25: 126\_GAZ000 and 126\_GAZ090.

Figure F.26: WUS 26: 133\_B-SRO000 and 133\_B-SRO270.
Figure F.27: WUS 27: 1347_ILA063-N and 1347_ILA063-W.

Figure F.28: WUS 28: 1352_KAU003-N and 1352_KAU003-W.
Figure F.29: WUS 29: 139\_DAY-LN and 139\_DAY-TR.

Figure F.30: WUS 30: 143\_TAB-LN and 143\_TAB-TR.
Figure F.31: WUS 31: 1440_TAP065-E and 1440_TAP065-N.
Figure F.32: WUS 32: 1446_TAP077-N and 1446_TAP077-W.

Figure F.33: WUS 33: 146_G01230 and 146_G01320.
Figure F.34: WUS 34: 150_G06230 and 150_G06320.

Figure F.35: WUS 35: 1518_TCU085-E and 1518_TCU085-N.
Figure F.36: WUS 36: 1529_TCU102-E and 1529_TCU102-N.

Figure F.37: WUS 37: 155_F-BEV-EW and 155_F-BEV-NS.
Figure F.38: WUS 38: 1551_TCU138-N and 1551_TCU138-W.

Figure F.39: WUS 39: 156_F-CSC-EW and 156_F-CSC-NS.
Figure F.40: WUS 40: 1577_TTN025-E and 1577_TTN025-N.

Figure F.41: WUS 41: 1585_TTN040-N and 1585_TTN040-W.
Figure F.42: WUS 42: 1587_TTN042-N and 1587_TTN042-W.

Figure F.43: WUS 43: 1613_1060-E and 1613_1060-N.
Figure F.44: WUS 44: 1618_531-E and 1618_531-N.

Figure F.45: WUS 45: 1619_MDR000 and 1619_MDR090.
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Figure F.193: WUS 193: 957_HOW060 and 957_HOW330.
Figure F.194: WUS 194: 989\textunderscore CHL070 and 989\textunderscore CHL160.

Figure F.195: WUS 195: 994\textunderscore 0141-270 and 994\textunderscore 0141-360.
F.2 McGuire et al. (2001) Earthquake Motions (CEUS)

The following figures show the CEUS earthquake motions (McGuire et al. 2001\(^1\)) used in the equivalent-linear site response analyses. More details on each motion are given in the electronic supplements of Chapters 4 and 5.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{ceus-motions.png}
\caption{CEUS 1: 1125A54E and 1125A54N.}
\end{figure}

Figure F.197: CEUS 2: 1125A61E and 1125A61N.

Figure F.198: CEUS 3: 1125A64E and 1125A64N.
Figure F.199: CEUS 4: 1125S08L and 1125S08T.

Figure F.200: CEUS 5: 1125S16L and 1125S16T.
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Figure F.221: CEUS 26: B-KOD180 and B-KOD270.
Figure F.222: CEUS 27: BOL000 and BOL090.

Figure F.223: CEUS 28: BRN000 and BRN090.
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Figure F.229: CEUS 34: CAD250 and CAD340.

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Figure F.231: CEUS 36: CLS000 and CLS090.

Figure F.232: CEUS 37: CLS000 and CLS090.
Figure F.233: CEUS 38: CLS220 and CLS310.

Figure F.234: CEUS 39: CPE045 and CPE315.
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Figure F.236: CEUS 41: CSM095 and CSM185.
Figure F.237: CEUS 42: *CSM095* and *CSM185*.

Figure F.238: CEUS 43: *CUC090* and *CUC180*.
Figure F.239: CEUS 44: *CUC090* and *CUC180*.

Figure F.240: CEUS 45: *CYC195* and *CYC285*. 
Figure F.241: CEUS 46: $D$-OLC270 and $D$-OLC360.
Figure F.242: CEUS 47: $D$-PLM270 and $D$-PLM360.

Figure F.243: CEUS 48: DAY-LN and DAY-TR.
Figure F.244: CEUS 49: \textit{DCF090} and \textit{DCF180}.

Figure F.245: CEUS 50: \textit{FER-L1} and \textit{FER-T1}.
Figure F.246: CEUS 51: \textit{FSD172} and \textit{FSD262}.

Figure F.247: CEUS 52: \textit{G06000} and \textit{G06090}.

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Figure F.248: CEUS 53: \textit{G06000} and \textit{G06090}.

Figure F.249: CEUS 54: \textit{GAZ000} and \textit{GAZ090}.
Figure F.250: CEUS 55: GAZ000 and GAZ090.

Figure F.251: CEUS 56: GBZ000 and GBZ270.
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Figure F.253: CEUS 58: GRN180 and GRN270.
Figure F.254: CEUS 59: *GYN000* and *GYN090*.

Figure F.255: CEUS 60: *H-PG3000* and *H-PG3090*.
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Figure F.257: CEUS 62: $H$-$TM2000$ and $H$-$TM2090$.

Figure F.258: CEUS 63: $H$-$VC4000$ and $H$-$VC4090$. 
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Figure F.260: CEUS 65: \textit{H-Z11000} and \textit{H-Z11090}.
Figure F.261: CEUS 66: \( H01000 \) and \( H01090 \).

Figure F.262: CEUS 67: \( HCP045 \) and \( HCP135 \).
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Figure F.264: CEUS 69: \textit{HWA026-N} and \textit{HWA026-W}.
Figure F.265: CEUS 70: *HWA056-N* and *HWA056-W*.

Figure F.266: CEUS 71: *ILA031-N* and *ILA031-W*.
Figure F.267: CEUS 72: *ILA051-N* and *ILA051-W*.

Figure F.268: CEUS 73: *ILA063-N* and *ILA063-W*.
Figure F.269: CEUS 74: ISD014 and ISD284.

Figure F.270: CEUS 75: IZN180 and IZN090.
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Figure F.272: CEUS 77: *KAU078-N* and *KAU078-W*.

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Figure F.275: CEUS 80: KJM000 and KJM090.
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Figure F.277: CEUS 82: L-BPL070 and L-BPL160.
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Figure F.279: CEUS 84: *LCN260* and *LCN345*.
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Figure F.281: CEUS 86: \textit{LGP000} and \textit{LGP090}.

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Figure F.282: CEUS 87: *LMR162* and *LMR252*.

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Figure F.284: CEUS 89: MA2130 and MA2220.

Figure F.285: CEUS 90: MA3130 and MA3220.
Figure F.286: CEUS 91: $MCD000$ and $MCD090$. 

$MCD000$ and $MCD090$. 

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Figure F.287: CEUS 92: MDR000 and MDR090.

Figure F.288: CEUS 93: MEL090 and MEL180.
Figure F.289: CEUS 94: MEL090 and MEL180.

Figure F.290: CEUS 95: MEL090 and MEL180.
Figure F.291: CEUS 96: NSK-E and NSK-N.

Figure F.292: CEUS 97: PAC175 and PAC265.
Figure F.293: CEUS 98: PKC090 and PKC360.

Figure F.294: CEUS 99: PLC000 and PLC090.
Figure F.295: CEUS 100: \textit{PLC258} and \textit{PLC348}.

Figure F.296: CEUS 101: \textit{PNG-E} and \textit{PNG-N}.
Figure F.297: CEUS 102: PUL104 and PUL194.

Figure F.298: CEUS 103: RAN000 and RAN090.
Figure F.299: CEUS 104: \textit{RAN000} and \textit{RAN090}.

Figure F.300: CEUS 105: \textit{RIV180} and \textit{RIV270}.
Figure F.301: CEUS 106: \textit{RIV180} and \textit{RIV270}. 

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{CEUS 106: \textit{RIV180} and \textit{RIV270}.}
\end{figure}
Figure F.302: CEUS 107: *RIV180* and *RIV270*.

Figure F.303: CEUS 108: *S1010* and *S1280*. 
Figure F.304: CEUS 109: S3270 and S3360.

Figure F.305: CEUS 110: SER000 and SER270.
Figure F.306: CEUS 111: *SER000* and *SER270*.

Figure F.307: CEUS 112: *SER000* and *SER270*. 
Figure F.308: CEUS 113: SHL000 and SHL090.

Figure F.309: CEUS 114: SIL000 and SIL090.
Figure F.310: CEUS 115: $SKR_{180}$ and $SKR_{090}$.

Figure F.311: CEUS 116: $SLO_{234}$ and $SLO_{324}$.
Figure F.312: CEUS 117: SLO234 and SLO324.

Figure F.313: CEUS 118: SOD015 and SOD285.
Figure F.314: CEUS 119: *SOD015* and *SOD285*.

Figure F.315: CEUS 120: *SON033* and *SON303*. 

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Figure F.316: CEUS 121: SOR225 and SOR315.
Figure F.317: CEUS 122: SOR225 and SOR315.

Figure F.318: CEUS 123: SRO-NS and SRO-WE.
Figure F.319: CEUS 124: SUL230 and SUL320.

Figure F.320: CEUS 125: TAP035-N and TAP035-W.
Figure F.321: CEUS 126: TAP036-N and TAP036-W.

Figure F.322: CEUS 127: TAP059-N and TAP059-W.
Figure F.323: CEUS 128: *TAP060-N* and *TAP060-W*.

Figure F.324: CEUS 129: *TAP067-N* and *TAP067-W*. 668
Figure F.325: CEUS 130: *TAP069-N* and *TAP069-W*.

Figure F.326: CEUS 131: *TAP072-N* and *TAP072-W*.
Figure F.327: CEUS 132: TAP075-N and TAP075-W.

Figure F.328: CEUS 133: TAP078-N and TAP078-W.
Figure F.329: CEUS 134: \textit{TCU015-N} and \textit{TCU015-W}.

Figure F.330: CEUS 135: \textit{TCU025-N} and \textit{TCU025-W}.
Figure F.331: CEUS 136: TCU046-N and TCU046-W.
Figure F.332: CEUS 137: TCU047-N and TCU047-W.

Figure F.333: CEUS 138: TCU087-N and TCU087-W.
Figure F.334: CEUS 139: TCU089-N and TCU089-W.

Figure F.335: CEUS 140: TCU095-N and TCU095-W.
Figure F.336: CEUS 141: TCU120-N and TCU120-W.

Figure F.337: CEUS 142: TCU128-N and TCU128-W.
Figure F.338: CEUS 143: *TCU136-E* and *TCU136-N*.

Figure F.339: CEUS 144: *TFS000* and *TFS090*. 

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Figure F.340: CEUS 145: *TMB205* and *TMB295*.

Figure F.341: CEUS 146: *VIR200* and *VIR290*.  

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Figure F.342: CEUS 147: *WTW115* and *WTW205*.

Figure F.343: CEUS 148: *WWJ090* and *WWJ180*. 

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Figure F.344: CEUS 149: WWJ090 and WWJ180.
G.1 Introduction

This manual is meant as a guide to aid the new student/researcher in the use of the GCTS equipment for cyclic direct simple shear testing at Virginia Tech. A separate manual should be available for cyclic triaxial testing. This treatment of the subject is by no means exhaustive; pertinent external literature should be reviewed as well as the manuals provided by GCTS.

A general overview of the equipment and setup are given herein. Additionally, best practices for sample preparation and equipment operation are discussed. In this manual, dry pluviation is presented as the method of sample preparation. However, with slight changes, other preparation methods can be easily implemented. Finally, discussion of data reduction is presented. The GCTS equipment has very high potential for academic research, however, it has its share of quirks. The over-arching purpose of this manual is to help the reader avoid the issues that prevent a successful test in the hope that proficiency can be gained in less time than that of the author.

G.1.1 Physical Setup

The GCTS equipment is located in Lab 15 of the W.C. English Geotechnical Lab at 260 Inventive Lane (previously 104 Plantation Road). Facing the equipment, the components of the equipment are, from left to right:

- **Hydraulic Pump**: This gray-colored tank with valves, pipes, and gauges provides the force to the hydraulic-operated normal and shear actuators. The oil level,
temperature, and condition should be periodically checked.

- **Load Frame and Pressure Cell Components**- This is where samples are prepared and tested.

- **PCP-200 Pressure Control Panel or Pressure Panel**- This panel contains a vacuum and a pressure gauge, vacuum and pressure controls, burettes, valves, and switches for the Top Back Pressure lines, Bottom Back Pressure lines, and the Cell Pressure lines.

- **APC UPS**- This black box provides power in case of a power outage. During a test it should give the user about 10 minutes to shutdown the controller and PC, preventing data loss. Note: the hydraulic pump is not connected to the UPS, so if the power goes out, your test it over anyway. The UPS should also prevent power surges, etc. Documentation (registration info, manual, etc) for this device should be found on one of the shelves with other documents.

- **SCON-200 Digital System Controller or SCON or controller**- This blue cube controls the entire system and collects all data. The firmware of the controller was updated to version 1.96 in the summer of 2013.

- **ULT-100 Ultrasonic Interface**- This gray box on top of the the SCON controls and receives information from the bender-element platens.

- **Lab PC**- This PC and associated software provide an interface to the SCON controller, and, thus, the rest of the equipment.

- **Welch Duoseal Vacuum Pump 1402**- Located on the counter behind the SCON, this vacuum pump, with the Nold DeAerator, deaerates water for use in saturated samples. The oil in the vacuum pump should be changed about once a year (which never really happens) or anytime contaminants can be seen in the oil. A manual for this particular pump can be found online without too much effort. Effort should be made to prevent the introduction of any contaminants, even water. A valve on the back of the pump allows for ‘gas ballast.’ Operating the pump with the gas ballast (with the valve open) prevents the condensation of water vapor within the pump at the slight sacrifice of vacuum pressure (see the manual for more information).

- **Geokon Nold DeAerator Model 2100**- On the wall above the vacuum pump, the deaerator removes the dissolved air from water to aid in saturation of samples. Only distilled water should be used in the deaerator. To prevent water from being pulled into the vacuum pump, the deaerator tank should be filled only to three-fourths of the tank capacity. Water is deaerated by running the impeller while a vacuum is applied. Ten or 15 minutes should remove most of the air; see the manual for more information.

Figure G.1 shows some of these components and their approximate layout in the lab.
G.1.2 The Cell

The cell is composed of many parts that fit together to allow the specimen to be pressurized (i.e., cell pressures greater than ambient air pressure). We will not be using several parts of the cell for cyclic simple shear testing, but I will introduce them all, anyways. These parts include:

Base The base of the cell is short, stainless steel cylinder mounted below the normal load frame (Figure G.2). On the front are valves and poke-throughs for the top back pressure lines, bottom back pressure lines, and the cell drain line. To the sides are poke-through ports for internal sensors. Attached at the rear is the ball bushing guide for the shear actuator piston.

Columns The columns support the cell top cap. See Figure G.3.

Cell Wall This acrylic plastic shell fits over the columns and top cap and onto the base of the cell.

Top Cap The top cap mounts onto the top of the columns and contains a ball bushing guide for the normal piston and poke-through ports for internal sensors.

Top Ring The top ring seals the cell assembly.

If filled with water, the maximum cell pressure is 1000 kPa. If the cell is air-filled, the maximum pressure is 500 kPa.

G.1.3 The Pressure Panel

The pressure panel contains valves and regulators to used to apply pressures (including vacuums) to the sample specimens. See Figure G.4. These pressures can be piped via
Figure G.2: The base of the cell with the shear carriage installed and two posts removed. Notice the back pressure sensor mounted at the front.
Figure G.3: Other parts of the cell. Clockwise from bottom left: the top cap, two of the four columns, the cell wall, and the top ring.
the cell lines, the bottom back pressure lines, and the top back pressure lines. At the top
of the panel are the manual pressure regulators. Below these are the selector switches so
that each line can be individually set to manual pressure control, vacuum control, vent,
or servo pressure control. Below the selector switches are the burettes that show the level
of water in each column, and below the burettes are valves for each line. To the left side
of the panel is the vacuum pressure regulator, the vacuum port, the dial gauge, and the
dial gauge selector switch. Note that the back pore pressure sensor has been moved from
the back of the pressure panel to the front of the base of the cell.

G.1.4 Other Parts

A few other items are needed to perform a successful cyclic simple shear test. Figures
G.5-G.7 show some of the items. They include:

- Top and bottom platens (plain or with bender elements)
- O-rings
- Brass confining rings (or a reinforced membrane)
- Flask with stopper and spout
- The internal LVDT assembly, brackets, and reaction plates (somewhat optional)
- Normal piston
- Shaft-locking collars
- The normal actuator contact plate
- Two normal-movement guides
- Cell-stiffening plate and reaction arms
- Top platen-to-normal-piston block

G.2 The Testing Cycle

This section covers the steps that need to be taken to perform a test in its entirety. It
includes setup, sample preparation, equipment assembly, and cyclic loading.

G.2.1 Sample Preparation

Placement of Bottom Platen, Membrane, and Mold

1. Mount the bottom platen onto the shear carriage using the four appropriate bolts.
Figure G.4: The pressure panel.
Figure G.5: Clockwise from left: top platen, flask with stopper and spout, brass confining rings, membrane, o-rings, and, at center, bottom platen.

Figure G.6: Clockwise from the top left: the internal LVDT assembly, the internal shear LVDT reaction plate and bracket, the normal piston, large and small shaft-locking collars, and the normal actuator contact plate. In the center is the top-platen-to-normal-piston block.
Either the bender-element or non-bender element platens may be used. I like to put an old piece of membrane under the platen to keep sand off of the carriage tracks (see Figure G.8). I also find it useful to remove the front two cell columns before I start, but depending on your preparation method, it may not be necessary.

2. Place the membrane on the bottom platen and secure it with two o-rings (Figure G.9).

I find it useful to use the mold as an o-ring stretcher (Figure G.10); I place the o-rings on the top of the mold and thread the unattached end of the membrane through the mold until the top of the mold fits around the bottom platen. The o-rings can then be rolled off onto the bottom platen.

3. Place the confining rings with their base on the bottom platen, taking care not to put a fold in the membrane.

4. Attach the vacuum hose to the side of the confining ring base and apply a small vacuum (probably no more than 2 or 3 inches of mercury).

5. Gently pull the free end of membrane up and around the outside of the confining rings. Make sure there are no wrinkles in the membrane inside the confining rings.
Figure G.8: Mounting the bottom platen onto the shear carriage.

Figure G.9: Membrane attached to the bottom platen.
and that the membrane is pulled tight to the inside of the rings by the vacuum. See Figure G.11.

At this point I like to clamp a plastic ‘fence’ around the outside of the rings, as shown in Figure G.12. It keeps me from spilling a lot of sand into the bottom of the cell. This ‘fence’ is cut from a dollar-store cutting board.
Dry Pluviation

Wet pluviation mimics the natural fluvian and lacustrine deposition of soils (Vaid and Negussey, 1984, 1988), and works best for poorly-graded materials that are less likely to experience particle segregation. However, dry pluviation is, in many ways, easier to perform and doesn’t allow the segregation of particles by size as much as wet pluviation. Because we won’t need to saturate our specimens, dry pluviation is the method presented here.

The dry (or air) pluviation procedure outlined here closely follows that of Vaid and Negussey (1988).

If your material is fine-grained, well-graded, or cannot be dried, another method of sample preparation is warranted. Moist tamping and slurry deposition are popular alternatives (see Bradshaw and Baxter (2007); Wang et al. (2011)).

1. Place a generous amount of dry sand into a flask. The flask should have an accompanying stopper and funnel (see Figure G.13).

2. With a gentle swirling motion, pour sand from the flask, through the stopper and funnel, into the confining rings. Slightly overfill the rings so that the sand is heaped above the top of the rings (Figure G.14).

   The density of the sand can be controlled by the pour height and the size of the funnel. Some experimentation may be needed to get the correct densities.
Figure G.13: Flask with sand, stopper, and funnel.
3. Using a straight edge and as few strokes as possible, scrape the extra sand from the top of the rings, leaving the sand level flush with the top of the rings (see Figure G.15).

I use a mini-vacuum to clean up the excess sand from both the top of the rings and around the base of the cell (Figure G.16. I created this particular vacuum by attaching a small, thin cloth bag to one end of a T. The opposite side of the T has air pressure coming in. The remaining part of the T has the vacuum nozzle attached to it. It works as a crude venturi vacuum.

4. Replace the cell columns, if they were removed previously. Place the top of the cell onto the columns (no need to bolt it on).

5. Attach the top-platen-to-normal-piston block onto the top platen. Place this assembly on a beam resting on the confining rings. Figure G.17 shows how it should look.

When attaching the top-platen-to-normal-piston block to the top platen, it needs to be tightened very little. Otherwise you will disturb the top surface of the specimen when you try to remove it.

6. Lower the normal actuator piston through the cell top cap and screw it onto the top-platen-to-normal-piston block. Lift the entire assembly, remove the beam, and gently lower the top platen onto the top of the specimen. Make sure the top platen is straight before you place it. You may need move the shear carriage forward or
Figure G.15: Scraping the excess sand off of the top of the confining rings.

Figure G.16: The mini-vacuum that I use to clean up sand.
Figure G.17: The top platen with the top-platen-to-normal-piston block on top of the specimen-in-preparation
backward so that the top platen is centered inside the confining rings. Tighten the shear piston locking collar.

As I lower the top platen, I place the beam in between the columns and the top platen, as shown in Figure G.18. This helps me place the top platen straight.

Figure G.18: Using the beam to straighten the orientation of the top platen.

7. Turn off the vacuum and remove the vacuum hose from the side of the confining rings. Roll the membrane up and onto the top platen. Place the o-ring(s) onto the top platen to hold the membrane in place.

8. At this point, vibrate or otherwise densify the specimen, if needed or wanted.

I like to lightly tap the top of the normal actuator with a rubber mallet. It slightly densifies my sample and makes me feel confident that the top platen interfaces well with the specimen.

9. Apply a vacuum to the specimen (20-30 kPa) and remove the normal piston, the top-platen-to-normal-piston block, and the cell top cap.

10. Measure and record the height of the specimen.

G.2.2 Assembly of Equipment

In this section, I list the order in which I assemble the GCTS equipment for a cyclic simple shear test. Some of the orderings are important; others are not. However, I will not take the time to tell you which is which. Good luck!
1. Attach the internal shear LVDT reaction plate and bracket to the right side of the shear carriage.

2. Place the internal LVDT assembly on top of the top platen (includes the internal shear LVDT bracket, the internal normal LVDT reaction plate, and the horizontal plate that holds both).

3. Place both of the black normal-movement guides on the cell columns. (They can be seen in Figure G.19.)

   I try to place these as far apart as possible. The lower one I put just above the internal LVDT assembly, the upper one just below the aluminum cell stiffener plate. It works best to only tighten one corner until all three pieces (i.e. the two black normal-movement guides and the stiffener plate) are in place.

4. Place the aluminum-colored cell stiffener plate onto the cell columns. Insert and tighten all bolts (the bolts that connect the stiffener plate to the arms, those on the black guides, and the rest on the cell stiffener plate). Figure G.19 shows how it should look up to this point.

5. Gently lower the normal track assembly (Figure G.7) onto the LVDT assembly and top platen. Bolt the normal track assembly to the top platen (Figure G.20).

6. Place the small locking collar onto the mini normal load cell.

7. Set the top of the cell onto the support columns. Start screwing in the corresponding bolts into the columns, but do not completely tighten them down.

8. Insert the normal piston into the top cap; screw it onto the mini normal load cell. Do not screw it tight; leave a small gap between the normal piston and the LVDT. If it is tightened, it will cause the measured load values to go awry.

9. Cautiously tighten the top cap bolts and the set screws center the normal track assembly. (There are four set screws, two in each of the black normal-movement guides.) Make sure that no moments are applied to the mini normal load cell.

10. Place the large locking collar around the normal piston and screw the normal actuator contact plate into the end of the piston. Zero out the mini normal load cell to the appropriate value (17.13 lbs for the non-bender-element platens).

11. Install and zero the internal LVDTs.

12. With the vacuum still applied to the specimen, place some weights onto the normal piston to double-check the mini normal load cell calibration. Calibrate the load cell, if needed.

13. Bring the normal loading frame into its vertical position.

14. Turn on the pump.

15. Open the Outputs Function Window. Switch the output to Shear Actuator and the Feedback to ‘T-Shear Stress’ or ‘Shear Load.’ In the PID window, make sure the corresponding ‘P’ value is fairly low. Make sure the value is set at zero, and turn on the shear actuator.
Figure G.19: Partial assembly of the internal cell components including the black normal-movement guides, the silver-colored stiffener plate, and the internal LVDT reaction plates and other parts.
Figure G.20: Bolting the normal track assembly onto the top platen.
16. Cautiously pull on the end of the external shear load cell to cause the shear actuator to move into position. Allow it to make contact with the piston going into the cell, and firmly attach the two parts of the shear piston by screwing on the mating collar.

17. Set the Feedback to 'Shear Displacement'. Unlock the piston at the collar, remove the shear pins in the confining ring set, and, using the Inputs Offset tool, set the shear displacement equal to that of the Internal Shear LVDT.

18. In the Outputs Function window, set the Output to Normal Actuator. Since we are using the internal mini load cell, I manually lower the normal actuator. To do so, set the Feedback to ‘Normal Displacement.’ Turn on the actuator and move it until contact is made.

   If you know the displacement at which the two piston parts meet, type in a distance about 5 mm from contact. For example, a previous test set the distance to contact at 0 mm, so I type in -5 mm and turn on the normal actuator in the software. Once the actuator has arrived within about 5 mm, I click the down arrow of the Set-Point scrollbar until the distance is down below about 0.5 mm. Then I click the ‘Fine Adj’ checkbox and continue to lower the actuator until I see the normal load increase.

19. At this point, I change the Feedback to ‘Sn - Normal Stress.’ Next, use the Inputs Offset tool to set the normal displacement value to that of the internal normal LVDT value.

20. Remove the applied vacuum, and open the back pressure lines to the sample. You are now ready to initiate a test.

G.2.3 GCTS Control of Testing

This section will guide you through the actual running of the test in which the GCTS system controls the specimen and collects data.

It is assumed that a suitable test file already exists. If not, you need to create one. See the GCTS manuals and section G.4.1 in this manual. This section will walk you through starting and running a test with a consolidation and cyclic loading phase.

1. Click on the ‘P/S/S’ (or ‘Projects’) button to open the ‘Projects/Samples/Specimen’ window. Select the appropriate project and sample, or create new ones.

2. Click ‘New’ to create a new specimen. Give an appropriate ‘ID’ (and description, if desired). Fill in the boxes for the measurements of height and diameter. On the next tab, change the specific gravity \((G_s)\) as needed. When ready, click ‘Ok.’

3. Select the correct test. Click on the ‘Edit’ button if you need to make changes. When finished, click ‘Ok.’
4. A screen will ask you if you want to apply a 5 kPa axial stress difference. If your normal actuator is already in contact, click ‘Skip.’ (I’ve had problems with this step in the past, so I always skip it. Your mileage may vary.)

5. A screen may come up asking you if you want to correct the specimen dimensions. Choose how you deem prudent and continue.

Now the test window should have come up. The test window shows the status of the test including the stage and phase of the test. It also has buttons at the top to stop and pause the test. If you have chosen the correct test file to run, the normal stress should increase until it reaches the predefined effective consolidation pressure. This is the consolidation phase. You should allow your specimen to consolidate for a minute or two, at least. I generally let it sit for 5 minutes during the consolidation phase, for consistency.

6. When normal displacements have steadied, tighten the shaft-locking collars around the normal actuator.

I start with the largest collar, at the top. Then I continue to the attached collar (on the top of the normal piston bushing), and, finally, I finish with the smallest collar under the top cap. If you are not careful, you may disturb the sample while tightening the collars, so tighten slowly! If the normal actuator begins to have a high frequency response, your P value is probably too high.

7. In the test window, click ‘Next’ to go to the cyclic loading phase. If you are sure, click ‘Ok.’

8. Behold the cyclic loading phase! Depending on your settings in the test setup, you may need to end the test manually by clicking on the ‘Stop’ button. Otherwise, let the test run its course.

From the PID window, I like to open the ‘Tune Chart.’ If the feedback doesn’t match the command of the normal actuator, you may need to adjust the P-I-D values. Usually, I only have to adjust the P values.

9. Wait for the GCTS system to transfer the test file from the SCON to the PC.

G.2.4 Cleanup/Tear Down

After the test file has transferred from the SCON to the PC, you can regain control of the GCTS system. A few final steps are needed before we are finished.

1. Unscrew the mating collar from the shear actuator.


3. Change the ‘Output’ to the Shear Actuator.
4. Change the shear stress to zero. Push the shear actuator until it moves all the way back.

5. In the ‘Outputs Function’ window, turn off the shear actuator.

   At this point, I like to change the feedback to ‘Shear Load’ so that it is ready for the next test.

6. Again in the ‘Outputs Function’ window, switch the ‘Output’ to Normal Actuator.

7. With the feedback set to ‘Normal Displacement,’ change the set point to -25 mm in order to lift the normal actuator out of the way.

8. Once the normal actuator has finished moving, turn off the normal actuator in the Outputs Function window. Turn off the pump in the ‘Hydraulic Tool’ window.

9. Tilt the normal load frame back.

10. Disassemble the equipment. You can mix up the order however you want, but here is a recommended order:

    (a) Loosen the internal shear LVDT.
    (b) Remove the internal shear LVDT reaction plate and bracket.
    (c) Remove the internal normal LVDT.
    (d) Loosen the set screws in the normal movement guide (that center the normal track assembly).
    (e) Remove the normal actuator contact plate from the end of the normal piston.
    (f) Loosen and remove the large shaft-locking collar.
    (g) Loosen the shaft-locking collar attached to the normal piston bushing.
    (h) Loosen the small shaft-locking collar.
    (i) Unscrew and remove the normal piston.
    (j) Remove the top cap by first removing the bolts holding it down.
    (k) Remove the small shaft-locking collar.
    (l) Remove the normal track assembly.
    (m) Remove the cell-stiffener plate and the two normal movement guides. I find it works best to first loosen all of the small bolts on the sides of both the cell-stiffener plate and the normal guides before trying to lift off any of the pieces.
    (n) Remove the internal shear LVDT from the internal LVDT assembly and remove this assembly.
    (o) Unscrew and remove the two front columns.

11. Remove the top o-ring(s).
12. Remove the top platen and brush the sand off of it into a bowl.
13. Remove the confining rings and put the pins back in.
14. Remove the screws holding down the bottom plate.
15. Dump the specimen into the same bowl as before. Brush off the the membrane and bottom platen.
16. Place the bowl into the oven and allow the specimen to dry for approximately 24 hours.
17. When the specimen has dried, mass the specimen and record. This is needed to calculate the relative density of the specimen.
G.3 Data Reduction

The data reduction can be performed using most data processing software. Before beginning data reduction, it is first necessary to obtain the output file from the GCTS software.

1. Open the ‘P/S/S’ window in the GCTS CATS software. Navigate through the projects and samples to the specimen you would like to examine.
2. Select the specimen of interest.
3. In the toolbar at the top of the ‘P/S/S’ window, click on the ‘Edit’ button. Click ‘Ok’ to dismiss the popup.
4. Find the appropriate space and enter the dry mass of the specimen. Click ‘Ok’ when done.
5. In the toolbar at the top of the ‘P/S/S’ window, click on the ‘Export’ button.
6. In the new dialog window, select an output format and the data that you would like to export. I prefer the .csv format and I select all data to be exported.
7. When finished, click ‘Ok’ and pick a folder to which you would like to export the data file.

For cyclic tests, several values must be calculated from the output file. These include the void ratio and relative density of the sample, the cyclic stress ratio, the number of cycles to liquefaction, and the dissipated energy to liquefaction.

G.3.1 Void Ratio and Relative Density

The void ratio ($e$) is calculated using the total specimen volume and the volume of solids ($V_s$) in the specimen. The volume of solids is calculated as

$$V_s = \frac{m_{\text{specimen}}}{G_s \rho_{\text{water}}} \tag{G.1}$$

where $m_{\text{specimen}}$ is the mass of the specimen, $G_s$ is the specific gravity of the sample, and $\rho_{\text{water}}$ is the density of water. The void ratio is

$$e = \frac{V_{\text{specimen}} - V_s}{V_s} = \frac{V_v}{V_s} \tag{G.2}$$

where $V_{\text{specimen}}$ is the volume of the entire specimen and $V_v$ is the volume of voids in the specimen.

The relative density ($D_r$) is calculated as

$$D_r = \frac{e_{\text{max}} - e}{e_{\text{max}} - e_{\text{min}}} \times 100\% \tag{G.3}$$

where $e_{\text{max}}$ and $e_{\text{min}}$ are the maximum and minimum void ratios of the sample, respectively.
G.3.2 Number of Cycles to Liquefaction

There are several methods used to determine the point of liquefaction during cyclic loading. Wu et al. (2004) discusses many of these methods. The most common methods define the onset of initial liquefaction as either the point at which the pore pressure ratio \( r_u \) is equal to unity, or point at which a certain strain is reached. You will have to decide the correct criteria for your laboratory testing needs.

G.3.3 Calculation of Dissipated Energy

Dissipated energy is defined as the area bound by the hysteresis loops of a stress-strain plot (see Figure G.21). For a simple shear test, it can be calculated by using the trapezoidal rule:

\[
\Delta W = \frac{1}{2} \sum_{i=1}^{n-1} (\tau_{i+1} + \tau_i)(\gamma_{i+1} - \gamma_i)
\]

where \( \Delta W \) is dissipated energy in units of stress, \( n \) is the number of data points in the stress and strain time histories, \( \tau \) is the shear stress, and \( \gamma \) is the shear strain.

![Figure G.21: The hysteresis loops of a stress versus strain plot.](image)

G.3.4 Plotting Results

Plotting results is an important part of data reduction. Plots can help you diagnose poor tests and discover new results. You should plot both results from a single test, and the
results for multiple tests. Plots for the results of a single test may be a plot showing stress versus strain, a stress time history, a strain time history, a pore pressure time history, etc. Plots of multiple test results might include CSR versus number of cycles to liquefaction (on log-log scales, the trend should be linear), and dissipated energy versus effective consolidation pressure or versus relative density. Figure G.22 shows an example of a diagnostic output plot.

![Figure G.22: An example of an output plot.](image_url)
G.4 Maintenance/Preparation

G.4.1 Creating a Cyclic Simple Shear Test File

A cyclic simple shear test consists of three stages: a ramp up to confining pressure, consolidation, and cyclic loading. Additionally, you may wish to add a final phase to move the normal actuator out of the way at the end of the test. This would allow you to disassemble the equipment while the data file transfers. In this section, only the ramp, consolidation, and cyclic loading stages will be created. You are left to your own devices to add any other stages.

I refer to stages here, but, strictly speaking and according to the GCTS system, we will be creating three separate phases of a ‘Universal’ stage.

1. Open the ‘Test Setup’ window (Figure G.23), and select ‘New.’

![Figure G.23: The ‘Test Setup’ dialog box.](image)

2. In the ‘Simple Shear Program Definition’ dialog box (Figure G.24), type in the appropriate information into the ‘ID’ and ‘Description’ boxes. Click on the ‘Save Objects’ button.

3. In the ‘Test Data Save Options’ dialog box (Figure G.25), select the inputs and analog outputs that you are interested in saving. I generally select them all. Close this dialog when you are finished.

4. Once again in the ‘Simple Shear Program Definition’ dialog box, click on the ‘New’ button to create a new stage. In this dialog box (Figure G.26), select ‘Universal’ and ‘Ok.’

5. In the ‘Simple Shear Program Stage [1]: Universal’ dialog box (Figure G.27), click the desired strain-handling boxes and then choose ‘New’ to create a new universal program.
Figure G.24: The ‘Simple Shear Program Definition’ dialog box.

Figure G.25: The ‘Test Data Save Options’ dialog box.
I like to ‘Update [the] Specimen Dimensions’ at the beginning of this stage, but you should make sure that it is taking care of your strains as you wish. Click ‘Ok’ when you are done.

6. Give the new universal program an ‘ID’ and ‘Description’ (Figure G.28), and create a new phase.

7. **Ramp Phase** In this phase dialog box, we will create the ramp phase. In the Duration tab (Figure G.29), set an appropriate duration. In this case, it depends on how long we take to ramp to the consolidation pressure.

8. In the ‘Data Acquisition’ tab (Figure G.30), select the type of data acquisition that you would like. I like to have timed increments. Pick an increment that will give you a good idea of the loading function without creating too big of a data file. You shouldn’t need many data points in this phase.

9. Still in the Ramp phase dialog box, double-click on the ‘A0-2: Normal Actuator - Not Defined’ line at the bottom of the dialog. This opens another dialog box (Figure G.31); make the following changes:

   - Select ‘Sn - Normal Stress’ from the feedback drop-down list.
   - Select the ‘Ramp’ waveform.
   - Change the ‘Ramp Control Parameters’ so that the normal stress ramps up to some value at a rate (or in the time) that you want.
Figure G.27: The universal program selector dialog box.

Figure G.28: The universal programs dialog box.
Figure G.29: The duration tab of the Ramp phase dialog box.

Figure G.30: The data acquisition tab of the Ramp phase dialog box.
Figure G.31: The normal actuator definition dialog box for the Ramp phase.
Generally, I use the ‘E & R’ (end value and rate), but you could make it work with any of those options. ‘D’ is for duration.

- Click ‘Ok’ when you are done.

10. Back in the Ramp phase dialog box, double click on the ‘A0-1: Shear Actuator - Not Defined’ line at the bottom. This opens another dialog box (Figure G.32); make the following changes:

   ![Image of shear actuator definition dialog box](image)

   Figure G.32: The shear actuator definition dialog box for the Ramp phase.

   - Select ‘Shear Displacement’ from the feedback drop-down list. This will hold the shear displacement to be the same as when the phase started.

   Alternately, you could select ‘Shear Stress’ from the feedback and have it set at a constant value of zero. The benefit of this is that this input is ready to go for the cyclic phase, and, thus, is less likely to do something weird when the cyclic phase starts. On the other hand, your shear actuator would be more likely to misbehave during the ramp and consolidation phases. But your mileage may vary.

   - When you are finished here, click ‘Ok.’
11. Now we are back again in the Ramp phase dialog box. We don’t need to define the Back or Cell Pressure inputs, so if everything looks ok, click ‘Ok.’

12. Returning to the Universal Program Definition dialog, click ‘New’ to create the consolidation phase.

13. **Consolidation Phase** In the ‘Duration’ tab of this dialog box (Figure G.33), set the phase duration to a time that is well above that needed for consolidation. We manually proceed from this phase, so we don’t have to worry about getting the duration perfectly.

![Figure G.33: The dialog box for the Consolidation phase.](image)

14. In the ‘Data Acquisition’ tab, choose a timed scheme that won’t collect too much data. Every 5 seconds might be enough.

15. Double click on the ‘A0-1 Shear Actuator - Not Defined’ line to set the controls for the shear actuator (Figure G.34).
   - Choose the feedback to be the same as the previous phase. In our case, it should be ‘Shear Displacement.’
   - Set the waveform to ‘Constant’ with ‘Relative/Current’ as control value.
   - Click ‘Ok’ when done.

16. Double click on the ‘A0-2 Normal Actuator - Not Defined’ line to set the output for the normal actuator (Figure G.35).
   - Set the feedback to ‘Sn - Normal Stress.’
Figure G.34: The shear actuator definition dialog box for the Consolidation phase.
Figure G.35: The normal actuator definition dialog box for the Consolidation phase.
• Set the waveform to ‘Constant’ and the control value to ‘Relative/Current.’
• Click ‘Ok’ when finished.

17. Back in the Consolidation phase definition dialog, double-check everything and click ‘Ok’ when finished.

18. Now back to the Universal Program Definition dialog (Figure G.26), you should see the ramp and consolidation phases. Click ‘New’ to create the third and final phase, the cyclic phase.

19. **Cyclic Phase** In the Duration tab of the Cyclic phase dialog (Figure G.36), set an appropriate duration. Since we want to run the test until failure, I do NOT set a timed duration. I like my tests to stop when a failing strain occurs or when I am about to reach the limits of the machine. Make sure to set this as needed. In this case, the internal shear LVDT has a stroke of $\pm 1.25$ mm. I set the duration of the test as ‘Until A1-9 Internal Shear LVDT $\geq 1.2$ mm.’

![Figure G.36: The duration tab for the Cyclic phase.](image)

20. In the Data Acquisition tab of this dialog, set the acquisition to something appropriate to your testing. I prefer to use only timed increments, making sure to get several data points for each cycle. Choose what is best for your testing conditions.

21. Double click on the ‘A0-1: Shear Actuator - Not Defined’ line to set the controls of the shear actuator during the cyclic phase (Figure G.37).

• Set the feedback to ‘T - Shear Stress.’
• Set the waveform to ‘Sine.’ Change the delay and phase shift, if desired.

717
Figure G.37: The shear actuator definition dialog box for the Cyclic phase.
• Make sure it is set to a ‘Mean’ control value of 0. (If you are performing a test with some static shear stress value, you would have to change this setting to something other than 0 kPa.)

• On the ‘Amplitude’ tab at the bottom, type in the appropriate value. For a simple shear test, \( \text{Amplitude (P-P)} = 2 \cdot CSR \cdot \sigma_v' \). The factor of 2 is to change from single-amplitude to double-amplitude (P-P). In this equation, \( \sigma_v' \) is your normal consolidation stress.

• On the ‘Frequency’ tab, input the frequency of the sinusoidal loading. I normally choose 0.25 Hz, but it seems like a lot of literature cite a frequency of 0.1 Hz (e.g. Wu et al. (2004)). (Alternately, you can adjust the period instead of the frequency.)

• Click ‘Ok’ when you are finished.

22. Now double-click on the ‘A0-2 Normal Actuator - Not Defined’ line. In the new dialog box:

• Set the feedback to ‘Normal Displacement.’ (It’s a constant-volume test.)

• Set the waveform to ‘Constant’ and the control value set to ‘Relative/Current.’

• Click ‘Ok’ when finished.

23. When finished with the Cyclic phase definition, click ‘Ok.’ Continue to click ‘Ok’ in all the open test definition windows. You are finished creating a new test.
Arbitrary (Earthquake) Loading

An earthquake loading test is created in the same way as a normal sinusoidal test, except instead of choosing a sine waveform in the cyclic phase definition, ‘User Defined’ should be chosen as the waveform. Once ‘User Defined’ is chosen as the waveform, an input file can be chosen. You have to create the input file yourself. Section UNI 3.6.2.8 of the CATS Advanced and Universal Manual (v.1.96) contains details about how to use the ‘User Defined’ waveform.

The code snippet below shows how I have created the input file using Python. Since this is only a snippet, it is important to know that name is the name of the entry in repofile where I have stored several stress and strain time histories. The variable tm0 contains the stress time history in this case.

```python
# extract the data node from the aggregate file
data = repofile.getNode('/TimeHistoriesProfileN05/{}').format(name))
# extract the variables I need from data
profile = data.col('profile')[0]
depth = data.col('depth')[0]
tm0 = data.col('taugam')[0][i,motind] # This is the stress time history
dt = data.col('dt')[0]
maxval0 = np.max(np.abs(tm0))

# Normalize the time histories so that they all have max values of 1.
tm = tm0 / maxval0

# Limit: 4096 data points for each input file
# See CATS Advanced and Universal Manual, pg 273
if len(tm) > 4096:
    if (len(tm) % 4096) > 0:
        no_files = len(tm0) // 4096 + 1
    else:
        no_files = 1

filepath = './Figures/ProfileN05/GCTSfiles/{}.format(name)
f2 = open(filepath + '-info.txt', 'w')

# Create a file for each 4096 data points in my time history
for i in xrange(no_files):
    f = open(filepath + '-{}{}.txt'.format(i+1,no_files), 'w')
    f.write('0
')
    if no_files > 1:
        if i < no_files-1:
            f.write(1)\r\n'.format(4096))
        else:
            f.write(1)\r\n'.format(len(tm) % 4096))
        else:
            f.write(1)\r\n'.format(len(tm))

    temptm = tm[i * 4096:(i+1)*4096] # Create a temporary time hist var
    maxval = np.max(temptm)
    minval = np.min(temptm)
```

720
meanval = (maxval + minval) / 2.
valrange = maxval - minval
Peak2Peak = valrange

# Now write out the temp time history for this file.
for j, val in enumerate(temptm):
    f.write('{}
'.format(val))

f.close()

# To help myself with the data needed for the GCTS software, I also create an
# additional file:
if i == 0:
    f2.write('{}
'.format(name) +
              'This is a {} time history in units of kPa '.format(motiontype) +
              'for cyclic simple shear tests. \n' +
              'The motion is from a depth of {:.2f} m'.format(depth) +
              ' from {}.
'.format(profile) +
              'No. of files: {}\n'.format(no_files) +
              'To get original amplitudes, multiply by {}'.format(maxval0) +
    )
else:
    f2.write(  
        'End Control Value: Given value: {}'.format(  
            temptm[0] / 0.65) +
        ' * CSR * sig\’v (in kPa)\n\n' +
        'For file # {}:\n'.format(i+1) +
        'Mean Control Value: {} * NewScaleFactor \n'.format(meanval) +
        ' / 0.65) +
        'Amplitude (P-P): {} * NewScaleFactor \n'.format(Peak2Peak) +
        ' / (0.65) +
        'NewScaleFactor = < ------------------------ >\n' +
        ' \n0.65 / \n' +
        'Duration: {} points\n'.format(len(temptm)) +
        'Time Step: {:.4f}\n'.format(dt))
    f2.write('End Control Value: Last Value \n')
f2.close()

G.4.2 Friction Baseline Tests

The GCTS equipment is not frictionless. This is especially apparent for dynamic/cyclic
testing. To get a handle on the amount of extra load due to friction that the load sensors
pick up (and the sample doesn’t feel), a friction baseline test may be useful.

A friction baseline test is performed by running a strain-controlled test on an air- or water-
filled sample. You may think of a better way to do it, but one way is to create a test in the
GCTS software with a sinusoidal strain-controlled loading function at the same frequency
as your normal testing regime. I begin the loading at very small strains but increase the
amplitude during loading so that the final cycles of the baseline test have as large of strains as I would expect from my soil test.

The results of this baseline test can be used to subtract friction from a regular soil test. The extra load due to friction is not always insignificant. For simple shear tests, I have found the friction to be a function of the displacement and load history (hysteresis loops are formed at large displacements), but I invite you to look closely at your own data. Figure G.38 shows some results from one baseline test on a sample of air.

![Figure G.38: Results of an air friction baseline test. The relationship between friction load and displacement can be approximated with a bi-linear fit. The points on this plot are each from the peaks of the sinusoidal loading.](image)

**G.4.3 Sensor Calibration**

The calibration of the sensors should be checked periodically. Eventually, the sensors will need to be calibrated. To do so:
1. Select Analog from the System → Inputs menu.

2. In the ‘Analog Inputs’ window (Figure G.39), choose the appropriate sensor.

3. In the ‘Editing Analog Inputs...’ window (Figure G.40), double-check that the ‘Attached Sensor’ is correct. If so, click on ‘Calibrate.’

4. You are given three choices on how to calibrate your sensor (Figure G.41). I generally use either the two-point method (Figure G.42) repeated a few times, or the multi-point method (Figure G.43).

5. Whatever method of calibration, apply the forcing or loadings to the sensor, as needed, and put the known values of these forcing into the dialog window.

**Load Cells**

For the calibration of load cells, I suggest using one of two methods to apply variable loads: free weights or a calibration ring.

If you are using free weights, contact the lab supervisor to get a frame onto which you can apply the weights. These look like a triaxial cell without the acrylic plastic shell. You place the load cell of interest between the bottom of the frame and a vertical piston arm. This piston arm leads through the top cap of the frame to a plate onto which you can place consolidation weights. You can mass the piston arm and consolidation plates before beginning. This is how you obtain your known loading.
Figure G.40: The ‘Editing Analog Inputs …’ window for the normal load cell.

Figure G.41: Dialog box for choosing the calibration method.
Figure G.42: The 2 point calibration method dialog.
Figure G.43: The multiple point calibration method dialog.
There is a calibration ring in the lab, somewhere. If you use it, put the ring in the place of the triaxial sample with the normal piston attached to the normal actuator and the load frame tilted forward. Use the GCTS’ normal actuator to apply incremental loadings to the ring. Measure the deflection of the ring and calculate the applied load from the deflection.

If you choose to use the calibration ring, you may need to calibrate the ring. At the very least, make sure it performs linearly. If it does, you can simply zero out your sensor when you are done with the calibration. It should be noted that the calibration ring will probably not work well for the shear load cells unless you mount them on the normal actuator.

**Pressure Sensors**

For calibration of the pressure sensors, find a pressure gauge that you trust. The pressure panel gauge has heretofore been accurate, so it might be a good place to start. If you don’t trust it, one of the lab supervisors can help you find a better gauge.

### G.4.4 Pore Pressure Servo Calibration

The back pore pressure servo may need to be calibrated, especially if you intend to perform automatic back pressure saturation. (Obviously this doesn’t apply to constant-volume simple shear tests. For information about back pressure saturation, see the companion manual on triaxial testing.) To do so, consult the document *(PCP-200) Back Pressure E-P Valve setup procedure.pdf*. It was written by GCTS and should be with the other digital documents. To summarize:

1. Close the back pressure lines so that there is no flow out of the system and the back pressure sensors can get a pressure reading.
2. Open the ‘Outputs Function’ window. Change the ‘Output’ to ‘Back Pressure’ and the ‘Feedback’ to ‘None - Open Loop.’
3. Change the Set-Point value to 5 pfs (percent full scale) and turn on the control.
4. Adjust the ‘ZERO’ screw on the back pressure servo (also known as the E-P valve; one of the black boxes mounted on the top back of the pressure panel) until the pore pressure sensor reads close to 50 kPa.
5. Turn off the back pressure control. Change the Set-Point value to 50 pfs. Turn the control back on.
6. Adjust the ‘SPAN’ screw on the back pressure servo until the pore pressure sensor reads close to 500 kPa. (House pressure is ~ 1000 kPa. Fifty percent full scale then is 50%/100% * 1000kPa = 500kPa.)
7. Turn off the back pressure control.
8. Repeat steps 3 to 7 until convergence.
G.4.5 Loading & Saving Configuration Files

In the GCTS software, configuration files save information about the current configuration of the system. This data includes the default height and diameter of the samples, the calibration of the sensors, which load cells are being used, and the PID values of each control-feedback loop. When switching between simple shear and triaxial tests, it is more convenient to load the required configuration file than to make all the changes by hand. Additionally, it is helpful to be able to go back to a known working configuration.

After making changes to the system configuration and every few months, it is a good idea to create a new configuration file. This is done by going to the System → Configuration menu and selecting Save As. Likewise, to load a previously-saved configuration, go to the System → Configuration menu and select Load. Finally, you can export the configuration to a text file by selecting Export from that same menu.
Bibliography


Appendix H

Cyclic Triaxial Testing Manual

H.1 Introduction

This manual is meant as a guide to aid the new student/researcher in the use of the GCTS equipment for cyclic triaxial testing. A separate manual should be available for cyclic simple shear testing. The treatment of the subject is by no means exhaustive; pertinent external literature should be reviewed as well as the manuals provided by GCTS.

A general overview of the equipment and setup are given. Additionally, best practices for sample preparation and equipment operation are discussed. In this manual, wet pluviation is presented as the method of sample preparation. However, with slight changes, other preparation methods can be easily implemented. Finally, discussion of data reduction is presented. The GCTS equipment has very high potential for academic research; however, it has its share of quirks. The over-arching purpose of this manual is to help the reader avoid the issues that prevent a successful test in the hope that proficiency can be gained in less time than that of the author.

H.2 Setup and Equipment

H.2.1 Physical Setup

The GCTS equipment is located in Lab 15 of the W.C. English Geotechnical Lab at 260 Inventive Lane (previously 104 Plantation Road). Facing the equipment, the components of the equipment are, from left to right:

- **Hydraulic Pump** - This gray-colored tank with valves, pipes, and gauges provides the force to the hydraulic-operated normal and shear actuators. The oil level,
temperature, and condition should be periodically checked.

- **Load Frame and Pressure Cell Components** - This is where samples are prepared and tested.

- **PCP-200 Pressure Control Panel** or **Pressure Panel** - This panel contains a vacuum and a pressure gauge, vacuum and pressure controls, burettes, valves, and switches for the Top Back Pressure lines, Bottom Back Pressure lines, and the Cell Pressure lines.

- **APC UPS** - This black box provides power in case of a power outage. During a test it should give the user about 10 minutes to shutdown the controller and PC, preventing data loss. Note: the hydraulic pump is not connected to the UPS, so if the power goes out, your test it over anyway. The UPS should also prevent power surges, etc. Documentation (registration info, manual, etc) for this device should be found on one of the shelves with other documents.

- **SCON-200 Digital System Controller** or **SCON or controller** - This blue cube controls the entire system and collects all data. The firmware of the controller was updated to version 1.96 in the summer of 2013.

- **ULT-100 Ultrasonic Interface** - This gray box on top of the SCON controls and receives information from the bender-element platens.

- **Lab PC** - This PC and associated software provide an interface to the SCON controller, and, thus, the rest of the equipment.

- **Welch Duoseal Vacuum Pump 1402** - Located on the counter behind the SCON, this vacuum pump, with the Nold DeAerator, deaerates water for use in saturated samples. The oil in the vacuum pump should be changed about once a year (which never really happens) or anytime contaminants can be seen in the oil. A manual for this particular pump can be found online without too much effort. Effort should be made to prevent the introduction of any contaminants, even water. A valve on the back of the pump allows for ‘gas ballast.’ Operating the pump with the gas ballast (with the valve open) prevents the condensation of water vapor within the pump at the slight sacrifice of vacuum pressure (see the manual for more information).

- **Geokon Nold DeAerator Model 2100** - On the wall above the vacuum pump, the deaerator removes the dissolved air from water to aid in saturation of samples. Only distilled water should be used in the deaerator. To prevent water from being pulled into the vacuum pump, the deaerator tank should be filled only to three-fourths of the tank capacity. Water is deaerated by running the impeller while a vacuum is applied. Ten or 15 minutes should remove most of the air; see the manual for more information.

Figure H.1 shows some of these components and their approximate layout in the lab.
The cell is composed of many parts that fit together to allow the specimen to be pressurized (i.e. cell pressures greater than ambient air pressure). These parts include:

**Base**  The base of the cell is short, stainless steel cylinder mounted below the normal load frame (Figure H.2). On the front are valves and poke-throughs for the top back pressure lines, bottom back pressure lines, and the cell drain line. To the sides are poke-through ports for internal sensors. Attached at the rear is the ball bushing guide for the shear actuator piston.

**Columns**  The columns support the cell top cap. See Figure H.3.

**Cell Wall**  This acrylic plastic shell fits over the columns and top cap and onto the base of the cell.

**Top Cap**  The top cap mounts onto the top of the columns and contains a ball bushing guide for the normal piston and poke-through ports for internal sensors.

**Top Ring**  The top ring seals the cell assembly.

If filled with water, the maximum cell pressure is 1000 kPa. If the cell is air-filled, the maximum pressure is 500 kPa.

**H.2.3 The Pressure Panel**

The pressure panel contains valves and regulators to used to apply pressures (including vacuums) to the sample specimens. See Figure H.4. These pressures can be piped via the cell lines, the bottom back pressure lines, and the top back pressure lines. At the top
Figure H.2: The base of the cell with the shear carriage installed and two posts removed. Notice the back pressure sensor mounted at the front.
Figure H.3: Other parts of the cell. Clockwise from bottom left: the top cap, two of the four columns, the cell wall, and the top ring.
of the panel are the manual pressure regulators. Below these are the selector switches so that each line can be individually set to manual pressure control, vacuum control, vent, or servo pressure control. Below the selector switches are the burettes that show the level of water in each column, and below the burettes are valves for each line. To the left side of the panel is the vacuum pressure regulator, the vacuum port, the dial gauge, and the dial gauge selector switch. Note that the back pore pressure sensor has been moved from the back of the pressure panel to the front of the base of the cell.

H.2.4 Other Parts

A few other items are needed for a successful triaxial test. Figure H.5 shows some of them. They include:

- A soil sample
- A flask with stopper and spout
- A mold
- O-rings
- A latex membrane
- Top and bottom platens
- Pedestals to situate the specimen at the appropriate height.
- Filter paper
- A pi tape and a ruler
- The normal piston
- The mating collar and load-bearing piece for the normal actuator
- A mold extender.

H.2.5 The GCTS Software

The GCTS software on the lab PC provides the gateway to the GCTS system. On the PC, two GCTS programs have been installed, the CATS program and the ultrasonics program. The ultrasonics program is used in conjunction with the bender elements to measure the shear wave velocity of a specimen. This same functionality can be found in the CATS program, so the ultrasonics program will not be discussed here.

The GCTS CATS software is started by double-clicking the 'CATS(2)' shortcut on the desktop of the PC, or by finding the 'CATS' entry in the start menu. Before starting the software, the SCON controller (and the ULT-100 controller if you will use it) should be
Figure H.4: The pressure panel.
Figure H.5: Assorted other parts used in a triaxial test. Clockwise from the left: sand-filled flask with spout, 2.8-inch triaxial mold, o-rings, black triaxial pedestal, additional pedestal for 2.8-inch specimens, the top and bottom platens, a latex membrane, a piece of filter paper, the normal piston, a pi tape, the normal actuator contact plate and mating collar, and a mold extender.
on. It may take a few moments for the software to connect with the SCON. Once it has done so, you will be prompted to login.

Two accounts are available in the CATS software: 'Administrator' and 'operator.' The operator account should be used for most day-to-day testing; the Administrator account is needed to change some sensitive settings. Log into either account using the password of gcts.

There are some settings that cannot be changed with the regular Administrator account, e.g., changing the polarity of the internal LVDTs. To change these settings, you need to log in using the license number. To do so:

1. Log in as the Administrator.
2. In the System menu, select Setup.
3. From this system setup window, copy down the license number. It should end in D0L0. (Those are zeros, not o’s.)
4. Log out from the administrator account, and log back into the administrator account using the license number as the password. Don’t include the dashes and remember to capitalize the letters.

Obviously, you should only log in like this when you need to, and be careful what you change.

Once the software logs in, you are left with a mostly blank window with a menubar at the top, a toolbar below the menubar, and another toolbar to the right. The right toolbar contains dials, gauges, graphs, and other readouts that will help you follow the progress of your test (see Figure H.6). Once you set up a layout that you like, you can save it under the Views → Save Layouts menu.

The top toolbar (Figure H.7) contains the tools you need to interact with the GCTS system. From left to right, these tools are:

- **Test Setup** This tool allows you to create new ‘tests’ or instructions to run a test. You can add, rearrange, or edit stages of a test. See Figure H.8. Also see the ‘Creating a Triaxial Test’ section of this manual.
- **Projects** The Projects tool gives you access to test results and allows you to run new tests. See Figure H.9.
- **Inputs Offset** This tool allows you to set any sensor to any arbitrary value (in other words, zero-out your sensors). See Figure H.10.
- **PID** The PID tool (Figure H.11) adjusts the settings of the proportional-integral-derivative control loop feedback mechanism. In other words, the PID settings affect the way the equipment controls itself based on the feedback it receives. The settings tell the equipment how much adjustment to make so that the actual
Figure H.6: The right toolbar in the GCTS main screen allows access to various sensor readouts.

Figure H.7: The top toolbar in the GCTS main screen contains the tools needed to interact with the GCTS system.

Figure H.8: The Test Setup dialog/window allows you to create and edit test instructions.
Figure H.9: The Projects dialog/window allows you to create and view test results.

Figure H.10: The Inputs Offset dialog/window allows you to set the values of the sensors.
Figure H.11: The PID dialog/window allows you to set the sensitivity of the feedback mechanisms. The response matches the expected response. Wikipedia has a good article on it (search ‘PID Controller’). Also see the GCTS manuals that came with the equipment.

**Outputs Function** This tool allows you to control the normal and shear actuators and the back and cell pressures. See Figure H.12.

**Signal Analysis Chart** This tool allows you to inspect a signal in time or frequency domain.

**Digital Outputs** The Digital Outputs tool allows you to turn the servos and digital controls on or off. It is most often used to turn on the Tilt control and turn off (or open) the automatic ball valve. See Figure H.13.

**Hydraulic** This tool gives you access to the hydraulic pump controls. See Figure H.14.

**VCD Status** Not implemented in our setup.

**PVC Status** Not implemented in our setup.

**Flushing Status** Not implemented in our setup.

**Ultrasonics** This tool gives you access to the ultrasonics/bender element equipment.
Figure H.12: The Outputs Offset dialog/window allows you to control the actuators and cell and back pressures.

Figure H.13: The Digital Outputs dialog/window allows you to turn the servos on or off.
Figure H.14: The Hydraulic dialog/window allows you to turn the hydraulic pump on and off.
H.3 The Test Cycle

This section covers the steps that need to be taken to perform a test in its entirety. It includes setup, sample preparation, saturation, and cyclic loading.

H.3.1 Setup

Several preliminary steps need to be taken before preparing the sample:

1. Fill the deaerator and begin to deaerate a tankful of water. For a 2.8”-diameter sample, one tank should be enough.
   
   (a) On the orange-colored panel, make sure the rightmost valve (‘Vent’) is closed. The middle valve should be open (‘To Deaerator’), and the leftmost valve should be closed (pointed to the left).
   
   (b) Turn on the vacuum pump. The vacuum should build fairly quickly. If not, one of your valves is open or something is broken.
   
   (c) Connect the intake tube with a container of distilled water. Switch the leftmost valve to ‘From Bottle.’ The Nold Deaerator tank should begin filling.
   
   (d) Switch out containers of distilled water, if needed, by closing the leftmost valve, moving the intake tube, and opening the leftmost valve again.
   
   (e) When the Nold tank is full, close the leftmost valve.
   
   (f) With the vacuum pump still on, turn on the Nold Deaerator. Allow these two to run for about 20 minutes. Consult the Nold manual for more accurate information.
   
   (g) After sufficient time, turn off the Nold and the vacuum pump.
   
   (h) Slowly switch the rightmost valve to ‘Vent’ to release the vacuum.
   
   (i) Switch the leftmost valve ‘To GCTS.’

   Remember, the Nold Deaerator should only be filled three-quarters full. Also, never turn on the deaerator without a few inches of water in the tank. This height of water is needed to lubricate the inner bearings.

2. In the ‘Inputs Offset’ tool, zero-out the load cell by hanging the normal piston, top platen, and two o-rings from the normal load cell.

3. Run an air or water ‘friction baseline’ test, if desired. See the subsection under the Maintenance/Preparation section.

4. Optional: Clean the top and bottom platens (or the stones alone, if they come out) in the ultrasonic cleaner.
I find this step helps with the saturation of the sample. After cleaning the platens, I keep the platens in a bowl of water flushed from the lines (next step) until I need them.

5. Thoroughly flush the top and bottom back pressure lines.

I like to open the BYPASS 2 value on the panel and fill both back pressure burettes at once. I then empty both burettes together, twice for the top lines, and twice for the bottom lines.

H.3.2 Sample Preparation

Placement of Bottom Platen, Membrane, and Mold

1. Mount the bottom platen onto the required pedestals.

   For a 2.8-inch-diameter specimen, the black cylinder pedestal and another silver-colored pedestal are needed. For a 4-inch-diameter specimen, only the black pedestal is needed.

2. Place the top cap of the cell onto the columns, and, using the normal piston and the top platen, mark the desired height of the specimen onto the normal piston. I use a rubber dummy specimen between the two platens and mark the intersection of the top platen and the normal piston with a permanent marker.

3. Place the membrane on the bottom platen and secure it with two o-rings.

   I find it useful to use the mold as an o-ring stretcher; I place the o-rings on the top of the mold and thread the unattached end of the membrane through the mold until the top of the mold fits around the bottom platen. The o-rings can then be rolled off onto the bottom platen.

4. Place the un-tightened mold onto the the bottom platen, taking care not to bunch or pinch the membrane. Tighten the mold band.

5. Place a piece of filter paper in the annulus between the mold and the membrane.

   Without the filter paper, the membrane is not pulled tight against the inside of the mold in all places.

6. Place the mold extender on top of the mold.

   The mold extender is held together using a single o-ring. At this time, I like to have the last remaining o-ring on the top of the mold, before placing the mold extender. The mold extender was made to allow some freeboard during wet pluviation, allowing the sand grains to approach terminal velocity, even for the very top of the specimen. The mold extender may not be needed for other sample preparation techniques.
7. Place an old section of membrane over the gap between the mold and the mold extender. This piece of membrane should be about 4 inches long. It both centers the mold extender and seals the gap for vacuuming the membrane.

8. Apply a vacuum to the mold, and gently pull the top edge of the membrane up and over the upper lip of the mold extender. Make sure that the membrane is pulled tightly against the inside of the mold and that there are no wrinkles in the membrane inside the mold.

9. Fill the mold with distilled, de-aired water.

As currently plumbed, you should be able to open the leftmost bottom back pressure valve located at the base of the cell. After a couple of inches of water are in the mold, I like to use the baster to squirt water into the annulus between the mold and the bottom platen, expelling any bubbles there. I also like to make sure there are no bubbles on the sides of the mold.

**Wet Pluviation**

Wet pluviation mimics the natural fluvian and lacustrine deposition of soils (Vaid and Negussey, 1984, 1988). However, wet pluviation works best for poorly-graded materials that are less likely to experience particle segregation. Additionally, materials with fines require long settlement times. If your material meets these conditions, another method of sample preparation is warranted. Moist tamping and slurry deposition are popular alternatives (see Bradshaw and Baxter (2007); Wang et al. (2011). The wet pluviation procedure outlined here closely follows that of Vaid and Negussey (1988).

1. Place an appropriate amount of soil into a glass flask. The appropriate amount can be determined with the following equation:

\[
m = \frac{G_s \rho_w V_T}{e + 1}
\]

where \(m\) is the mass in grams, \(G_s\) is the specific gravity of the material, \(\rho_w\) is the mass density of water (1 g/cm\(^3\)), \(V_T\) is the total target volume of the specimen in cubic meters, and \(e\) is the target void ratio of the specimen. For completeness, \(e\) can be calculated from the relative density \((D_r)\) as follows:

\[
e = \epsilon_{\text{max}} - \frac{D_r}{100} (\epsilon_{\text{max}} - \epsilon_{\text{min}})
\]

where \(\epsilon_{\text{max}}\) and \(\epsilon_{\text{min}}\) are the maximum and minimum void ratios of the material.

2. Fill the flask with distilled water and place it on a heat source. Allow it to boil for at least 20 minutes, and allow it to cool for some time after boiling.
Instead of boiling the soil and water mixture, you could try to add de-aired water to the flask or simply apply a vacuum to the flask instead of boiling. I find I get best saturation results when boiling. Saturation also seems to be better when the sand grains are still warm when pluviated.

3. Fill the flask to the brim with de-aired water, place the stopper and spout firmly into the flask, and fill the spout with de-aired water.

   I find that the boiling causes some particle segregation in the flask. Now is a good time to put your finger over the spout and shake/mix/desegregate the sand particles.

4. Pour the soil slurry from the flask into the mold. If the spout is kept under the surface of the water, none of the slurry should spill. Vaid and Negussey (1988) call this ‘mutual displacement of sand and water under gravitational influence.’ Gently level the surface of the sand after you have emptied the flask.

5. Place the top of the cell on the vertical columns and bolt it down. Insert the normal actuator piston through the top of the cell and screw it onto the top platen.

6. Slowly lower the top platen through the mold extender until it no longer moves under its own weight. The tubing to the top platen should not yet be attached.

7. Fill both back pressure burettes with distilled water. Leave the 'Bypass 2' valve open. Open all valves in the bottom back pressure lines so that water passes through the sample and begins to come out of the top platen port. Open the valves of the top back pressure lines, clearing the unattached top platen tubing of air bubbles. Attach the top platen tubing to the port of the top platen.

8. While applying moderate pressure on the normal piston apply vibrations to the side of the sample until the desired (and premarked) height is reached.

   I originally used a blunt-tipped engraver tool applied to the side of the mold to cause densification, but lately a few decent taps with a rubber mallet has been my preferred method.

9. Tighten the shaft lock to prevent movement (optional).

10. Place the mating collar around the normal piston and screw the normal actuator contact plate onto the end of the normal piston.

11. Turn off the vacuum applied to the mold, and close the vacuum port valve.

12. Place the membrane onto the top platen with two o-rings to secure it.

   (a) Pull the top of the membrane up and off of the mold extender and onto the top platen.

   (b) Pull the small membrane from the mold extender to down around the mold.

   (c) Roll the o-ring from the mold extender to above the top platen.

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(d) Remove the mold extender.

(e) Roll the other o-ring from the mold to the top platen and place the previous o-ring on the platen, as well.

(f) Now pull the small piece of membrane (the one that was used to seal the mold extender) up and out of the way. You can’t remove it entirely because it is around the normal actuator, but at least move it so it isn’t touching the specimen at all (i.e. around the top platen or around the piston).

(g) Ensure that the o-rings are well placed on the platen and that there are not any wrinkles in the membrane or sand in the annulus between the membrane and the platen.

The pool filter sand we originally used would often get stuck in that annulus. This often caused leaks. I had a few methods to deal with it. First, I added some tape to the inside of the mold extender so that the annulus is small. Second, if the top platen is lowered into position very slowly, the exiting water doesn’t have the velocity to pick up particles. Third, you can spray a stream of water into the annulus before pulling the membrane off of the mold extender and onto the top platen.

13. Close the ‘Bypass 2’ valve, valve ‘B’, and the bottom back pressure valve at the cell. Switch the top pore pressure line to ‘vacuum.’ Slowly apply a vacuum to the sample, looking for leaks. You should see the level in the top back pressure burette rise slightly then stop. You may also see a bubble or two in the top pressure line coming out of the top platen. If the bubbles continues to move, you have a leak, obviously.

   It may not be necessary to close both the valve ‘B’ and the bottom back pressure valve at the cell, but I once thought that the valve at the cell was leaking, and I also like to isolate the lines as much as possible, out of habit.

14. If you don’t have a leak, remove the mold from around the specimen. Adjust the top and bottom o-rings, if necessary.

   If you do have a leak, you need to find it. It could be a hole in a membrane, a leak or wrinkle at the interface between the membrane and the platens, or it could simply be a piece of tubing that hasn’t been completely inserted into a connection. If you have some vacuum applied to the specimen, you can remove the mold and try to find leaks in the membrane. If it is a slow leak, sometimes filling the cell and applying a cell pressure will clear up the issue enough for a test. Otherwise, you may need to prepare a new sample.

15. Measure and record the height and diameter of the sample.

   I measure the diameter in three places and take the average. The best way to measure the diameter is using a π tape. Remember to account for the thickness of the membrane when putting the diameter into the software. Neglecting to
subtract the thickness of the membrane can significantly change your calculated relative density.

H.3.3 Assembly of Equipment

After preparing the sample and placing it under vacuum, the cell needs to be assembled to continue. It is done as follows:

1. Make sure the top of the cell is firmly attached to the posts.
2. Place the acrylic cell wall over the sample, columns, and top of cell and onto the base of the cell. Make sure the o-ring on the top of the base of the cell is in its channel and lightly greased.
3. Place the top ring onto the top of the cell and securely bolt it on. Take the time now to make sure that all the parts of the cell are fitting well together.
4. Use a piece of tubing to connect the faucet to the drain valve at the base of the cell. Both the drain valve and the valve at the top of the cell should be open.
5. Slowly turn on the water at the faucet and fill the cell with tap water. An approximately one-centimeter gap of air should be left at the top of the cell. This is to prevent the dynamic motion of the normal actuator from increasing and decreasing the cell pressure during the cyclic phase of the test.
6. Once the cell is full of tap water, turn off the tap, close the bottom cell valve, and attach a piece of tubing from the top of the cell to the cell pressure port on the pressure panel.
7. Manually increase the cell pressure while decreasing the vacuum. I like to keep the effective stress between 15 and 30 kPa. A slight vacuum can be left on the sample; we will be using it soon.

Normal Actuator Connection

At this point, the cell should be completely assembled, and, before continuing, I like to place the normal actuator into contact with the normal piston. You could wait to do this until after the manual saturation section, but I prefer to do it now. To save time, I often connect the normal actuator and piston while the cell is filling with water.

1. In the software, open the Digital Outputs window (1 ⇔ 0, 0 ⇔ 1) and make sure the Tilt output control is on (green).
2. Flip the tilt switch (mounted to the right of the cell base) to the FORWARD position. As the load frame arms swing up, make sure that everything is clear, including the normal actuator and piston.
3. Turn on the hydraulic pump to low pressure by opening the Hydraulic Tool pump window and clicking on the ‘Low P’ button.


5. If the readings in the windows on the left and right side of the Output Function window do not match, click on the Reset button to make them equal.

6. Open the PID window, and find the Normal Actuator and Axial Stress Difference options. Change the P value for Axial Stress Difference so that it falls around 1. Remember the old value because we will change it back in a minute.

   If the P value is too high, the software will have trouble coping with the sudden contact between the normal actuator and the normal piston. Usually, this causes the actuator to lose control and go into high frequency oscillations, perhaps prematurely liquefying your specimen.

7. In the Output Functions window, turn on the Axial Stress Difference controls. The normal actuator may move upward at this point. If it moves downward, turn it off immediately and decrease the Axial Stress Difference and turn it back on.

   If you haven’t caught on yet, the Set Point control values can be changed by either typing a value into the left box (and pressing enter), dragging the left scrollbar, or by clicking on the up and down arrows at the ends of the scroll bar. For example, if I want to increase the axial stress difference, I would click on the down arrow (or the up arrow if the inverse bar box is selected).

8. Pull down on the normal actuator below the load cell. The actuator should begin to move in the direction pulled. Make sure to keep your person out from in-between the actuator and the normal piston head! Allow the actuator to make contact with the piston head. You may have to slow it down as it arrives.

9. Screw the collar onto the actuator until the two parts (actuator and piston) are tightly mated.

10. Zero the normal displacement in the software using the inputs offset tool.

11. Turn off the normal actuator in the Outputs Function window, and turn off the pump.

12. Change the P value of the Axial Stress Difference back to what it was before.

**H.3.4 Saturation**

Most tests require that the sample is saturated. Accurate pore pressure and volume change measurements are very difficult without a saturated sample. If you know that you are studying the response of unsaturated or partially saturated samples, feel free to skip this section. Otherwise, you will need to saturate your sample specimen.
Flushing the Specimen

We took care to prepare our sample so that it would be as saturated as possible: we flushed the lines before starting, we boiled our sample, and we filled the mold with de-aired water. Despite our best efforts, however, the B value of our specimen (Skempton, 1954) is probably less than 80% at this point. Most testing regimes will require the saturation (as measured by the B value) to be upwards of 95%. Frankly, the higher saturation, the better. One way to increase our saturation before back pressure saturation is to flush the sample (and lines, equipment, etc.) with de-aired water. Physically, there are several different ways that this flushing may be performed, and the researcher should feel free to try whatever they deem prudent. However, I have found the following method to give the best saturation values:

1. Make sure you have at least half a tank of de-aired water in the Nold deaerator (more may be needed).
2. With a slight vacuum on the top pore pressure lines and the selector switch of the bottom pore pressure lines set to vent, open all pore pressure valves (A, B, E, and the pore pressure valves at the cell).
3. Allow the column of water in the bottom pore pressure burette to move into the sample and into the top pore pressure burette.
4. When the top pore pressure burette is full or the bottom pore pressure burette is nearly empty, close both the bottom and top pore pressure valves at the cell.

The purpose of flushing the sample is to remove as many air bubbles as possible from the sample specimen and equipment before beginning the back-pressure saturation. If the water level in the burettes is allowed to completely exit the bottom of the burette, air bubbles will be trapped in the piping when the burette is refilled. Additionally, the water levels should not be allowed to overflow the top of the burettes; the pressure regulators work best and last longest if they remain dry. In other words, keep the water levels in the top and bottom back pressure burettes where you can see them.

5. Change the top back pressure selection switch to ‘Vent’ and the bottom back pressure selection switch to ‘Vacuum.’
6. At the cell, unplug the top back pressure line and allow the water to drain from the top back pressure burette (but not completely!).

Once the water has been through the sample once, we consider it waste water and do not want it to enter the sample again. In order to facilitate the previous step, I keep a bowl under the cell connection. I do not close the top back pressure valve at the panel (valve E), but unplug and replug the tubing at the cell connection. I allow the bowl to fill up as I continue to flush; it provides me a way to gauge how much water has been flushed through the sample specimen.

7. Refill the top back pressure burette by opening the fill switch that resides to the lower left of the top pore pressure burette. (Again, don’t let it overfill!)
8. Transfer the water from the top pore pressure burette to the bottom back pressure burette by opening valve C. Close valve C when finished.

9. Switch the top back pressure selection valve to ‘Vacuum’ and the bottom back pressure selection valve to ‘Vent.’

10. Repeat steps 2 to 9 until a few pore volumes of water have been flushed. Generally, I use the rest of the water in the deaerator tank, or about two small bowlfuls of water.

On writing this section, I tried to find the paper that discusses flushing and how much. I couldn’t find the paper. If I remember correctly, it said to flush two pore volumes. In any case, flushing isn’t absolutely necessary, and you may not be able to flush fine-grained samples. However, for sand specimens, the longer I have flushed the specimen, the greater success I have had at achieving high B values at low confining pressures.

Manual Back-Pressure Saturation

Once the sample has been flushed, you are ready to begin back pressure saturation. The GCTS equipment can perform automatic back pressure saturation, but I prefer to manually back pressure saturate. Before beginning the following steps, make sure that you have cell pressure and back pressure selection valves set to ‘Manual Pressure,’ and valves A, B, and C on the pressure panel should be open. The bottom back pressure and cell pressure valves at the cell should also be open. Bypass valves 1 and 2, valve E, and the top pore pressure valve at the cell should all be closed. A few inches of water should remain in the back pressure burette.

This is a good point to zero and bleed the pore pressure sensor.

1. Change the bottom back pressure selector valve to ‘Vent.’

2. Measure the approximate height of the midpoint of the specimen, and mark the corresponding height on the bottom back pressure burette. (It should be somewhere around the 120 point of the burette for a 2.8-inch-diameter specimen.)

3. Make sure the water level in the burette is a few inches higher than the point we just marked.

4. Remove the bleed screw from the pore pressure transducer, allowing water to bleed out. Once the burette level arrives at the mark from step 2, replace and secure the bleed screw.

5. Open the Inputs Offset window in the software. Zero the ‘Back/Pore Pressure’ reading. (We want it to be zero at the center of the specimen.)

6. Change the bottom back pressure selector valve back to ‘Manual Pressure.’
In this section, several very specific pressures will be given, but there is no need for exact and specific values to be used. In back pressure saturation and the measurement of the B value, the relative cell and back pressures are what matter. In all cases, the cell pressure should be greater than the back pressure. I like the effective stress \((\sigma' c = \sigma_c - u)\) to be somewhere between 10 and 40 kPa. It should remain below about 40 kPa so that I don’t consolidate my sample during this saturation stage. The effective stress should be greater than about 10 kPa so that the specimen retains some stiffness.

Also, within this manual back pressure saturation section, when I refer to changing pressures, it is always using the manual pressure regulators at the top of the pressure panel. Additionally, when I refer to changing the pore pressures, it is always the bottom back pressure regulator to which I refer.

1. With the cell pressure around 20 kPa, increase the bottom back pressure to around 10 kPa.
2. Close the bottom back pressure valve at the cell (assuming the pore pressure sensor is still mounted at the cell). (I generally also close valve B, but this is not absolutely necessary.)
3. Gently raise the cell pressure by some amount. You should see the back pressure also rise. I like to increase the cell pressure each time by 20 kPa. It is a nice round number, and it makes calculating the B value easy.
4. Calculate the B value of the specimen.

   The B value is the change in back pressure divided by the change in the cell pressure \((B = \frac{\Delta u}{\Delta \sigma_c})\). A B value of 1 corresponds to a fully-saturated specimen. We would like our B value to be greater than 0.95.
5. Manually increase the back pore pressure at the pressure panel until it equals the back pressure felt by the sample. You will need to use the pressure gauge on the pressure panel in conjunction with the software readout of back pressure. (We want to equalize the pressure on both sides of the closed back pressure valve before we open it so that we don’t overconsolidate or otherwise disturb our specimen.)
6. Open the bottom back pressure valve (and valve B, if you closed it earlier).
7. Continue to increase the back pressure until you have reached your target effective stress (maybe 20 kPa).
8. Wait for about 20 to 30 minutes to allow the internal pressure differences to dissipate throughout the specimen and to allow the air to go into solution.
9. Repeat steps 2 to 8 until the target B value has been reached.

I generally move quickly up to about 100 kPa before I wait in between iterations. Also, for sands, 20 to 30 minutes of waiting may be overkill; you might achieve 80% of the increase in saturation by waiting only 5 or 10 minutes. However, your mileage may vary.
Switching From Manual to Servo Pressure Control

This is a slightly delicate procedure; I have several times lost a sample by accidentally removing all effective strength. Be sure to read through the directions before beginning these steps.

In preparation for cyclic loading, the control of the cell and back pressure must be switched from manual to servo.

1. Isolate the sample by closing the cell and pore pressure valves at the cell.
2. Open the Outputs Function window in the GCTS software, and select ‘Cell Pressure’ at the ‘Outputs:’ drop-down list. The ‘Feedback:’ drop-down list should read ‘Cell Pressure,’ as well.
3. Manually lower the cell pressure at the pressure panel until there is none applied.
4. Switch the cell pressure selector switch to ‘Servo.’
5. In the Outputs Function window, turn on the servo-controlled cell pressure. The cell pressure should automatically increase to its previous value. If it doesn’t, type the correct value into the small window on the left side of the Outputs Function window.
6. Once the cell pressure has stabilized, open the cell pressure valve at the cell for a few moments and close it again. This ensures that the cell pressure within the cell is really what we think it is before we continue.
7. In the Outputs Function window, select ‘Back Pressure’ from the ‘Outputs:’ drop-down list. Select ‘Back/Pore Pressure’ from the ‘Feedback:’ drop-down list. Once the back pressure reading shows up on the Outputs Function windows, switch the ‘Feedback:’ to ‘None-Open Loop.’

Because I moved the pore pressure sensor from the back of the pressure panel to the front of the cell, it is necessary to use the Open Loop feedback. ‘Open Loop’ simply means that the system guesses the correct pressure, but does not correct the guessed pressure; i.e. there is no feedback. If we tried to set the pore pressure with the servo control with the feedback set to back/pore pressure and the back pressure valve at the cell closed, the intended pressure and the pore pressure read from the sensor would not agree exactly. The system would then open or close a servo regulator to adjust the pressure. When this adjustment made no difference (because the sensor is behind the closed valve), it would open or close the servo regulator to a greater degree. Eventually, the pressures on the servo side will be as high or as small as possible and the system will abort. Feel free to try it yourself, just make sure to have your sample isolated, or you will waste several hours of preparation and saturation.
8. With the feedback set to ‘None-Open Loop,’ manually remove back pressure until there is none applied.
9. Change both the bottom back pressure and top back pressure selector switches to servo. Open both bypass valves. (The servo pressure port for the top back pressure selector valve is plugged; we can control both top and bottom back pressures by opening the bypass valves.)

10. In the Outputs Function window, turn on the Back Pressure control. (Feedback should still be ‘None - Open Loop.’) The pore pressures in the panel should rise (see the gauge on the pressure panel).

11. In the Outputs Function window, adjust the pore pressure (as read from the pressure panel gauge) until it matches the pressure given by the sensor. (The ‘pfs’ units in the Outputs Function window under open loop stands for percent full scale. Full scale pressure should be around 1000 kPa. So if your back pressure is, say, 350 kPa, the pfs value should be around 35 (350/1000 * 100% = 35).

12. Make sure the locking collar on the normal actuator is firmly locked.


14. Turn on the pump.

I am assuming that the normal actuator is in contact with the normal piston, as I described in section H.3.3. If the normal actuator and piston are not currently connected, go back and follow the directions in that section first, then come back here.

15. Turn on the normal actuator in the Outputs Function window (still set to displacement controlled). Ensure that the command and response values in the Outputs Function window match before you turn it on.

I like to turn on the normal actuator when it is set to displacement controlled because the actuator is less likely to move unexpectedly when it is displacement controlled (versus stress-controlled).

16. Now switch the normal actuator feedback to ‘Axial Stress Difference.’ Change the control value so that the axial stress difference it equal to zero.

If you forget to change the axial stress difference to zero, it will carry the same value through the consolidation phase. Be careful changing this value, however, because if it is a big change, the change in normal displacement may be significant.

17. Gently unlock the normal actuator locking collar.

18. Once the normal actuator settles down, slowly open all top and bottom back pressure valves. I suggest starting with the bottom back pressure valves first.

19. Once the pore pressures have stabilized, return to the Outputs Function window. Switch the output to Back Pressure. Now change the feedback from ‘None - Open Loop’ to ‘Back/Pore Pressure.’
20. Open all valves in the cell pressure lines. Now all valves in the pressure panel and at the cell (except the cell drain valve) should be open. Double check that these are all open! If you forget to open one of these, you will ruin your specimen and your day!

Your specimen should now be entirely under the SCON control: normal actuator, cell pressure, top and bottom back pressure. Again, make sure all valves are open and the normal actuator locking collar is loose. I had you turn on the normal actuator in the middle of switching from manual to servo pressure control. In reality, you could turn on the normal actuator at any time during saturation or after switching to servo-controlled pressure. I like to turn it on at this point, however, so that my specimen is still isolated. On multiple occasions I have turned on the normal actuator to immediately have a normal actuator control error and subsequent abort. When this occurs, control of the pressures is also lost, and, likely, your specimen will also be lost. Having the cell and pore pressure valves closed for these steps gives me an extra safeguard.

Automatic Back-Pressure Saturation

As mentioned, the GCTS software can perform automatic back-pressure saturation as another phase of testing. For several reasons, I stopped using this feature. First, the back-pressure saturation phase increases the time that the pump must be running, and I dislike the noise of the pump. Also, if the back pressure servo-regulator is not well calibrated (this seems to always be the case, despite my efforts), the specimen is often overconsolidated or allowed to soften as the effective stresses stray from the intended values.

Of course, you may find the auto-saturation phase to be helpful; feel free to experiment. It is pretty straightforward to add the phase at the beginning of your test.

H.3.5 GCTS Control of Testing

This section will guide you through the actual running of the test in which the GCTS system controls the specimen and collects data.

It is assumed that a suitable test file already exists. If not, you need to create one. See the GCTS manuals and section H.5.1 in this manual. This section will walk you through starting and running a test with a consolidation and cyclic loading phase.

1. Before starting, note the height of the water column in the pore pressure burettes.
2. Click on the ‘P/S/S’ (or ‘Projects’) button to open the ‘Projects/Samples/Specimen’ window. Select the appropriate project and sample, or create new ones.
3. Click ‘New’ to create a new specimen. Give an appropriate ‘ID’ (and description, if desired). Fill in the boxes for the measurements of height and diameter. On the next tab, change the specific gravity \( G_s \) as needed. When ready, click ‘Ok.’
4. Select the correct test. Click on the ‘Edit’ button if you need to make changes. When finished, click ‘Ok.’

5. A screen will ask you if you want to apply a 5 kPa axial stress difference. If your normal actuator is already in contact, click ‘Skip.’ (I’ve had problems with this step in the past, so I always skip it. Your mileage may vary.)

6. A screen may come up asking you if you want to correct the specimen dimensions. Choose how you deem prudent and continue.

    Now the test window should have come up. The test window shows the status of the test including the stage and phase of the test. It also has buttons at the top to stop and pause the test. If you have chosen the correct triaxial test, the cell pressure should increase until it reaches the predefined effective consolidation pressure. This is the consolidation phase. You should allow your specimen to consolidate for a minute or two, at least.

7. When normal displacements have steadied, make a note of the height of the water column in the pore pressure burettes. The difference in height from before is the amount of volume change that occurred during the consolidation phase. Each tick mark is equal to 0.25 mL.

8. When ready to proceed, close all back/pore pressure valves going into the cell. We want a cyclic test with no drainage.

9. In the test window, click ‘Next’ to go to the cyclic loading phase. If you are sure, click ‘Ok.’

10. Behold the cyclic loading phase! Depending on your settings in the test setup, you may need to end the test manually by clicking on the ‘Stop’ button. Otherwise, let the test run its course.

    From the PID window, I like to open the ‘Tune Chart.’ If the feedback doesn’t match the command of the normal actuator, you may need to adjust the P-I-D values. Usually, I only have to adjust the P values.

11. Wait for the GCTS system to transfer the test file from the SCON to the PC.

H.3.6 Cleanup/Tear Down

After the test file has transferred from the SCON to the PC, you can regain control of the GCTS system. A few final steps are needed before we are finished.

1. Lock the collar around the normal actuator.

3. With the top and bottom pore pressure valves still closed, select ‘Cell Pressure’ from outputs drop-down list. Lower the cell pressure to around 20 kPa.
   I like to lower the cell pressure by degrees, making sure that my back pressure is lowering at the same time.

4. In the ‘Outputs Function’ window, turn off the cell pressure control as well as the back pressure. When both cell and back pressure are turned off, change the ‘Output’ to Normal Actuator.

5. Change the axial stress difference to zero. Take off the normal actuator mating collar and gently push up the normal actuator until it is completely clear.

6. In the ‘Outputs Function’ window, turn off the normal actuator. Turn off the pump.

7. Tilt the load frame back and, on the pressure panel, switch all pressure selector switches to ‘Vent.’

8. In the software, open the ‘Digital Outputs’ dialog and turn off the ‘Automatic Ball Valve.’

9. Gently open the pore pressure valves to release any remaining pressure in the specimen. Watch the back pressure burettes to make sure they don’t overflow.

10. Open the cell drain valve and allow the cell to drain.
   I am usually impatient, so I manually add a cell pressure to the top of the cell to speed drainage.

11. Once the cell has drained, disassemble the cell. Unscrew the normal actuator from the top platen.

12. Remove the bolts holding the bottom platen.

13. Remove the top platen o-rings and the top platen. Using a laboratory water bottle, rinse off the sand from the top platen into a clean bowl.

14. Dump the specimen into the same bowl. Rinse off the the membrane and bottom platen.

15. Place the bowl into the oven and allow the specimen to dry for approximately 24 hours.

16. When the specimen has dried, mass the specimen and record. This is needed to calculate the relative density of the specimen.
H.4 Data Reduction

The data reduction can be performed using most data processing software. Before beginning data reduction, it is first necessary to obtain the output file from the GCTS software.

1. Open the ‘P/S/S’ window in the GCTS CATS software. Navigate through the projects and samples to the specimen you would like to examine.
2. Select the specimen of interest.
3. In the toolbar at the top of the ‘P/S/S’ window, click on the ‘Edit’ button. Click ‘Ok’ to dismiss the popup.
4. Find the appropriate space and enter the dry mass of the specimen. Click ‘Ok’ when done.
5. In the toolbar at the top of the ‘P/S/S’ window, click on the ‘Export’ button.
6. In the new dialog window, select an output format and the data that you would like to export. I prefer the .csv format and I select all data to be exported.
7. When finished, click ‘Ok’ and pick a folder to which you would like to export the data file.

For cyclic tests, several values must be calculated from the output file. These include the void ratio and relative density of the sample, the cyclic stress ratio, the number of cycles to liquefaction, and the dissipated energy to liquefaction.

H.4.1 Void Ratio and Relative Density

The void ratio ($e$) is calculated using the total specimen volume and the volume of solids ($V_s$) in the specimen. The volume of solids is calculated as

$$V_s = \frac{m_{\text{specimen}}}{G_s \rho_{\text{water}}} \quad \text{(H.3)}$$

where $m_{\text{specimen}}$ is the mass of the specimen, $G_s$ is the specific gravity of the sample, and $\rho_{\text{water}}$ is the density of water. The void ratio is

$$e = \frac{V_{\text{specimen}} - V_s}{V_s} = \frac{V_v}{V_s} \quad \text{(H.4)}$$

where $V_{\text{specimen}}$ is the volume of the entire specimen and $V_v$ is the volume of voids in the specimen.

The relative density ($D_r$) is calculated as

$$D_r = \frac{e_{\text{max}} - e}{e_{\text{max}} - e_{\text{min}}} \times 100\% \quad \text{(H.5)}$$

where $e_{\text{max}}$ and $e_{\text{min}}$ are the maximum and minimum void ratios of the sample, respectively.
H.4.2 Number of Cycles to Liquefaction

There are several methods used to determine the point of liquefaction during cyclic loading. Wu et al. (2004) discusses many of these methods. The most common methods define the onset of initial liquefaction as either the point at which the pore pressure ratio \((r_u)\) is equal to unity, or point at which a certain strain is reached. You will have to decide the correct criteria for your laboratory testing needs.

H.4.3 Calculation of Dissipated Energy

Dissipated energy is defined as the area bound by the hysteresis loops of a stress-strain plot (see Figure H.15). For a triaxial test, it can be calculated by using the trapezoidal rule:

\[
\Delta W = \frac{1}{2} \sum_{i=1}^{n-1} (\sigma_{d,i+1} + \sigma_{d,i})(\varepsilon_{a,i+1} - \varepsilon_{a,i})
\]  

(H.6)

where \(\Delta W\) is dissipated energy in units of stress, \(n\) is the number of data points in the stress and strain time histories, \(\sigma_d\) is the deviator stress (axial stress difference), and \(\varepsilon_a\) is the axial strain.

Figure H.15: The hysteresis loops of a stress versus strain plot.
H.4.4 Plotting Results

Plotting results is an important part of data reduction. Plots can help you diagnose poor tests and discover new results. You should plot both results from a single test, and the results for multiple tests. Plots for the results of a single test may be a plot showing stress versus strain, a stress time history, a strain time history, a pore pressure time history, etc. Plots of multiple test results might include CSR versus number of cycles to liquefaction (on log-log scales, the trend should be linear), and dissipated energy versus effective consolidation pressure or versus relative density. Figure H.16 shows an example of a diagnostic output plot.

Figure H.16: An example of an output plot.
H.5 Maintenance/Preparation

H.5.1 Creating a Triaxial Test File

A cyclic triaxial test consists of two or three stages: auto-saturation (optional), consolidation, and cyclic loading. Additionally, you may wish to add a final phase to ramp down pressures and move the normal actuator out of the way. In this section, only the consolidation and cyclic loading stages will be created. You are left to your own devices to add any other stages.

1. Open the ‘Test Setup’ window (Figure H.17), and select ‘New.’

2. In the ‘Simple Shear Program Definition’ dialog box (Figure H.18), type in the appropriate information into the ‘ID’ and ‘Description’ boxes. Click on the ‘Save Objects’ button.

3. In the ‘Test Data Save Options’ dialog box (Figure H.19), select the inputs and analog outputs that you are interested in saving. I generally select them all. Close this dialog when you are finished.

4. Once again in the ‘Simple Shear Program Definition’ dialog box, click on the ‘New’ button to create a new stage. In this dialog box (Figure H.20), select ‘Consolidation’ and ‘Ok.’

5. In the consolidation dialog box (Figure H.21), set values as you need for your test. I like to ‘Update [the] Specimen Dimensions’ at the beginning of this stage, but you should make sure that it is taking care of your strains as you wish. Click ‘Ok’ when you are done.

6. Back to the ‘Simple Shear Program Definition’ dialog box, click on ‘New’ again, and in the next dialog box, select ‘Universal’ before ‘Ok.’
Figure H.18: The ‘Simple Shear Program Definition’ dialog box.

Figure H.19: The ‘Test Data Save Options’ dialog box.
Figure H.20: The new stage dialog box.

Figure H.21: The consolidation stage dialog box.
7. In the universal stage dialog box, create a new universal program (Figure H.22). Give the new universal program an ‘ID’ and ‘Description’ (Figure H.23), and create a new phase.

![Figure H.22: The universal programs dialog box.](image)

8. In the phase dialog box, in the Duration tab (Figure H.24), set an appropriate duration. I like my tests to stop when a failing strain occurs or when I am about to reach the limits of the machine. Make sure to set this as needed.

9. In the ‘Data Acquisition’ tab (Figure H.25), select the type of data acquisition that you would like. I like to have timed increments. Pick an increment that will give you a good idea of the loading function without creating too big of a data file. The other options may be useful in addition to the timed increments.

10. Still in the phase dialog box, double-click on the ‘A0-2: Normal Actuator...’ in the bottom of the box. This opens another dialog box (Figure H.26); make the following changes:

- Select ‘Sd - Axial Stress Difference’ from the feedback drop-down list.
- Select the ‘Sine’ waveform. (Or whatever wave form you want. Change the delay or phase shift options if for some reason you need it.)
- Select ‘Mean’ control value and make sure it reads ‘Absolute/Change to 0 kPa.’ (If you are performing a test with loading oscillating around some static shear stress value, you would have to change this setting to something other than 0 kPa.)
Figure H.23: Creating a new universal program.

Figure H.24: The duration tab of the phase dialog box.
Figure H.25: The data acquisition tab of the phase dialog box.

Figure H.26: The normal actuator definition dialog box.
On the ‘Amplitude’ tab at the bottom, type in the appropriate value. (For an isotropically consolidated triaxial test, Amplitude \( (P-P) = 2 \cdot 2 \cdot CSR \cdot \sigma'_c \). One 2 is to change from single-amplitude to double-amplitude (P-P), and the other is needed for the calculation of \( CSR \) for triaxial tests.)

On the ‘Frequency’ tab, input the frequency of the sinusoidal loading. I normally choose 0.25 Hz, but it seems like a lot of literature cite a frequency of 0.1 Hz (e.g. Wu et al. (2004)). (Alternately, you can adjust the period instead of the frequency.)

Click ‘Ok’ when you are finished.

11. Now double-click on the ‘A0-3 Cell Pressure ...’ line. In the new dialog box (Figure H.27), make sure the feedback is cell pressure and the waveform is constant. Click ‘Ok’ when finished.

12. Now double-click on the ‘A0-4 Back Pressure ...’ line. In the new dialog box (Figure H.28), make sure the feedback is ‘None - Open Loop’ and the waveform is constant. Click ‘Ok’ when finished.

13. Back in the phase dialog box, click on the ‘Digital Outputs Control’ check box at the bottom of the window. In the new part (Figure H.29) of the window, change
Figure H.28: The back pressure definition dialog box.
the automatic ball valve control to ‘On’. This will close a valve in the bottom back pressure line in the pressure panel at the beginning of this phase. For our liquefaction tests, we assume the samples are undrained during loading, and this makes sure no drainage can occur via the bottom back pressure lines. However, if you have the top back pressure selector switch set to ‘Servo’ and your top back pressure and bypass 1 & 2 valves open, it really doesn’t matter if you have this set to on or off.

Figure H.29: The digit outputs section of the phase dialog box.

14. When finished, click ‘Ok’ in all the open test definition windows. You are finished creating a new test.
Arbitrary (Earthquake) Loading

An earthquake loading test is created in the same way as a normal sinusoidal test, except instead of choosing a sine waveform, ‘User Defined’ should be chosen as the waveform. Once ‘User Defined’ is chosen as the waveform, an input file can be chosen. You have to create the input file yourself. Section UNI 3.6.2.8 of the CATS Advanced and Universal Manual (v.1.96) contains details about how to use the ‘User Defined’ waveform.

The code snippet below shows how I have created the input file using Python. Since this is only a snippet, it is important to know that name is the name of the entry in reinfo file where I have stored several stress and strain time histories. The variable tm0 contains the stress time history in this case.

```python
# extract the data node from the aggregate file
data = repofile.getNode('/TimeHistoriesProfileN05/{}'.format(name))
# extract the variables I need from data
profile = data.col('profile')[0]
depth = data.col('depth')[0]
TM0 = data.col('taugam')[0][:, motind] # This is the stress time history
dt = data.col('dt')[:, 0]
maxval0 = np.max(np.abs(tm0))

# Normalize the time histories so that they all have max values of 1.
tm = tm0 / maxval0

# Limit: 4096 data points for each input file
# See CATS Advanced and Universal Manual, pg 273
if len(tm) > 4096:
    if (len(tm) % 4096) > 0:
        no_files = len(tm0) // 4096 + 1
    else:
        no_files = 1

filepath = './Figures/ProfileN05/GCTSfiles/{}.format(name)
f2 = open(filepath + '-{}-info.txt'.format(name))

# Create a file for each 4096 data points in my time history
for i in xrange(no_files):
    f = open(filepath + '-{}-{}-{}.txt'.format(i, no_files, name))
    # First line in the file is the number of data points
    if no_files > 1:
        if i < no_files-1:
            f.write('{}
'.format(4096))
        else:
            f.write('{}
'.format(len(tm) % 4096))
    else:
        f.write('{}
'.format(len(tm)))

    temptm = tm[i * 4096:((i+1) * 4096)] # Create a temporary time hist var
    maxval = np.max(temptm)
    minval = np.min(temptm)
    meanval = (maxval + minval) / 2.
```

771
valrange = maxval - minval
Peak2Peak = valrange

# Now write out the temp time history for this file.
for j, val in enumerate(temptm):
    f.write('{}
'.format(val))
f.close()

# To help myself with the data needed for the GCTS software, I also create an additional file:
if i == 0:
    f2.write('{}
'.format(name) +
    'This is a {} time history in units of kPa '.format(motiontype) +
    'for cyclic simple shear tests. \r\n' +
    'The motion is from a depth of {:.2f} m'.format(depth) +
    'from \r\n\r\n'.format(profile) +
    'No. of files: {}\r\n'.format(no_files) +
    'To get original amplitudes, multiply by \r\n\r\n'.format(maxval0))
else:
    f2.write(
        'End Control Value: Given value: {}'.format(temptm[0] / 0.65) +
        ' * CSR * sig\'v (in kPa)\r\n\r\n')
    f2.write(
        'For file # {}: \r\n'.format(i+1) +
        'Mean Control Value: {} * NewScaleFactor \r\n'.format(meanval) +
        ' = {} * CSR * sig\'v \r\n'.format(meanval / (0.65)) +
        'Amplitude (P-P): {} * NewScaleFactor \r\n'.format(Peak2Peak) +
        ' = {} * CSR * sig\'v \r\n'.format(Peak2Peak / 0.65) +
        'NewScaleFactor = \r\n\r\n')
f2.write('End Control Value: Last Value \r\n')
f2.close()

H.5.2 Friction Baseline Tests

The GCTS equipment is not frictionless. This is especially apparent for dynamic/cyclic testing. To get a handle on the amount of extra load due to friction that the load sensors pick up (and the sample doesn't feel), a friction baseline test may be useful.

A friction baseline test is performed by running a strain-controlled test on an air- or water-filled sample. You may think of a better way to do it, but one way is to create a test in the GCTS software with a sinusoidal strain-controlled loading function at the same frequency as your normal testing regime. I begin the loading at very small strains but increase the amplitude during loading so that the final cycles of the baseline test have as large of strains
as I would expect from my soil test.

The results of this baseline test can be used to subtract friction from a regular soil test. The extra load due to friction is not always insignificant. For triaxial tests, I have found the friction to be a function of the velocity of the normal actuator, but I invite you to look closely at your own data. Figure H.30 shows some results from one baseline test on a sample of air.

Figure H.30: Results of an air friction baseline test. The relationship between friction load and velocity can be approximated with a tri-linear fit.

**H.5.3 Sensor Calibration**

The calibration of the sensors should be checked periodically. Eventually, the sensors will need to be calibrated. To do so:

1. Select *Analog* from the *System → Inputs* menu.
2. In the ‘Analog Inputs’ window (Figure H.31), choose the appropriate sensor.

3. In the ‘Editing Analog Inputs…’ window (Figure H.32), double-check that the ‘Attached Sensor’ is correct. If so, click on ‘Calibrate.’

4. You are given three choices on how to calibrate your sensor (Figure H.33). I generally use either the two-point method (Figure H.34) repeated a few times, or the multi-point method (Figure H.35).

5. Whatever method of calibration, apply the forcing or loadings to the sensor, as needed, and put the known values of these forcing into the dialog window.

Load Cells

For the calibration of load cells, I suggest using one of two methods to apply variable loads: free weights or a calibration ring.

If you are using free weights, contact the lab supervisor to get a frame onto which you can apply the weights. These look like a triaxial cell without the acrylic plastic shell. You place the load cell of interest between the bottom of the frame and a vertical piston arm. This piston arm leads through the top cap of the frame to a plate onto which you can place consolidation weights. You can mass the piston arm and consolidation plates before beginning. This is how you obtain your known loading.

There is a calibration ring in the lab, somewhere. If you use it, put the ring in the place of the triaxial sample with the normal piston attached to the normal actuator and the
Figure H.32: The ‘Editing Analog Inputs …’ window for the normal load cell.

Figure H.33: Dialog box for choosing the calibration method.
Figure H.34: The 2 point calibration method dialog.
Figure H.35: The multiple point calibration method dialog.
load frame tilted forward. Use the GCTS’ normal actuator to apply incremental loadings to the ring. Measure the deflection of the ring and calculate the applied load from the deflection. If you choose to use the calibration ring, you may need to calibrate the ring. At the very least, make sure it performs linearly. If it does, you can simple zero out your sensor when you are done with the calibration.

**Pressure Sensors**

For calibration of the pressure sensors, find a pressure gauge that you trust. The pressure panel gauge has heretofore been accurate, so it might be a good place to start. If you don’t trust it, one of the lab supervisors can help you find a better gauge.

**H.5.4 Pore Pressure Servo Calibration**

The back pore pressure servo may need to be calibrated, especially if you intend to perform automatic back pressure saturation. To do so, consult the document *(PCP-200) Back Pressure E-P Valve setup procedure.pdf*. It was written by GCTS and should be with the other digital documents. To summarize:

1. Close the back pressure lines so that there is no flow out of the system and the back pressure sensors can get a pressure reading.
2. Open the ‘Outputs Function’ window. Change the ‘Output’ to ‘Back Pressure’ and the ‘Feedback’ to ‘None - Open Loop.’
3. Change the Set-Point value to 5 pfs (percent full scale) and turn on the control.
4. Adjust the ‘ZERO’ screw on the back pressure servo (also known as the E-P valve; one of the black boxes mounted on the top back of the pressure panel) until the pore pressure sensor reads close to 50 kPa.
5. Turn off the back pressure control. Change the Set-Point value to 50 pfs. Turn the control back on.
6. Adjust the ‘SPAN’ screw on the back pressure servo until the pore pressure sensor reads close to 500 kPa. (House pressure is \(\sim 1000\) kPa. Fifty percent full scale then is \(50\% / 100\% \times 1000kPa = 500kPa\).)
7. Turn off the back pressure control.
8. Repeat steps 3 to 7 until convergence.

**H.5.5 Loading & Saving Configuration Files**

In the GCTS software, configuration files save information about the current configuration of the system. This data includes the default height and diameter of the samples, the
calibration of the sensors, which load cells are being used, and the PID values of each control-feedback loop. When switching between simple shear and triaxial tests, it is more convenient to load the required configuration file than to make all the changes by hand. Additionally, it is helpful to be able to go back to a known working configuration. After making changes to the system configuration and every few months, it is a good idea to create a new configuration file. This is done by going to the System → Configuration menu and selecting Save As. Likewise, to load a previously-saved configuration, go to the System → Configuration menu and select Load. Finally, you can export the configuration to a text file by selecting Export from that same menu.
Bibliography


Appendix I

Conference Paper: Verification of ShakeVT2
COMPARISON OF EQUIVALENT-LINEAR SITE RESPONSE ANALYSIS SOFTWARE

S.J. Lasley¹, R.A. Green² and A. Rodriguez-Marek³

ABSTRACT

The objective of the study presented herein is to compare equivalent-linear site response analysis software. Ground motions recorded at soft soil sites can be drastically different from those recorded at rock sites. Site-specific response analyses provide an important way to predict surface ground motions from bedrock ground motions. Of all methods of site response analysis, the equivalent-linear method is, perhaps, the most popular. It has become an important method of site response analysis since first proposed by Schnabel et al. (1972) and has been shown to give a good approximation for many scenarios. In the years since the algorithm was released, several software programs that implement the equivalent-linear procedure have been written and made available to the engineering community. As part of ongoing research at Virginia Tech, a new equivalent-linear site response program, ShakeVT2, has been written in the Python programming language. In an effort to verify the implementation of the equivalent linear algorithm, extensive comparisons were made between ShakeVT2 and other equivalent-linear codes (i.e., SHAKE91, SHAKEVT, Strata, and DEEPSOIL). It was found that these implementations give similar results when supplied the same inputs. However, the choice of complex shear modulus and effective strain ratio have an impact on the results, especially for motions that contain a lot of energy at high frequencies. Additionally, it has been shown that when using DEEPSOIL, SHAKE91, SHAKEVT91 the discretization of the profile may obscure peaks when plotting the maximum shear strain, shear stress, or acceleration with depth. Finally, SHAKE91 and SHAKEVT suffer from a bug that gives incorrect results when the input motion file has an odd number of columns.

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Comparison of Equivalent-Linear Site Response Analysis Software

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The objective of the study presented herein is to compare equivalent-linear site response analysis software. Ground motions recorded at soft soil sites can be drastically different from those recorded at rock sites. Site-specific response analyses provide an important way to predict surface ground motions from bedrock ground motions. Of all methods of site response analysis, the equivalent-linear method is, perhaps, the most popular. It has become an important method of site response analysis since first proposed by Schnabel et al. (1972) and has been shown to give a good approximation for many scenarios. In the years since the algorithm was released, several software programs that implement the equivalent-linear procedure have been written and made available to the engineering community. As part of ongoing research at Virginia Tech, a new equivalent-linear site response program, ShakeVT2, has been written in the Python programming language. In an effort to verify the implementation of the equivalent linear algorithm, extensive comparisons were made between ShakeVT2 and other equivalent-linear codes (i.e., SHAKE91, SHAKEVT, Strata, and DEEPSOIL). It was found that these implementations give similar results when supplied the same inputs. However, the choice of complex shear modulus and effective strain ratio have an impact on the results, especially for motions that contain a lot of energy at high frequencies. Additionally, it has been shown that when using DEEPSOIL, SHAKEVT, or SHAKE91 the discretization of the profile may obscure peaks when plotting the maximum shear strain, shear stress, or acceleration with depth. Finally, SHAKE91 and SHAKEVT suffer from a bug that gives incorrect results when the input motion file has an odd number of columns.

Introduction

Soft soil profiles can greatly affect the amplitude of incoming earthquake motions. This fact was drastically demonstrated in various earthquakes, including the 1989 Loma Prieta earthquake [1]. Consequently, modern building codes (e.g. [2]) apply a factor to modify motions from rock profiles to those for soil profiles. Moreover, under some conditions, codes require that site-specific response analyses are performed. The equivalent-linear procedure is a popular method of site response analyses because, in part, it is easy to perform compared to other non-linear site response analyses.

Ongoing research at Virginia Tech on liquefaction assessment includes the calculation of dissipated energy from site response analyses of multiple soil profiles and earthquake motions. To aid the research, it was decided to re-implement the equivalent-linear algorithm [3][4] instead of using existing codes (e.g. SHAKE91, SHAKEVT, Strata, DEEPSOIL). This paper gives an
overview and comparison of the existing implementations of the equivalent linear algorithm.

**Equivalent-Linear Site Response Analysis**

The 1-D equivalent-linear site response analysis first introduced by Schnabel et al. in 1972 [3][4] is a well-known and well-used method. It is used to estimate the transformation of earthquake motions as they propagate upward through a soil profile. It assumes the vertical propagation of shear waves from a uniform half-space through horizontal layers of a soil profile modeled as visco-elastic material having a constant damping ratio across all frequencies [5]. These calculations are performed in the frequency domain, greatly increasing the speed and numerical stability of the calculations. However, in order to model the non-linear response of soil in the frequency domain, an iterative procedure is required.

For each layer in a soil profile, the equivalent-linear procedure approximates the non-linear stress-strain behavior using shear modulus reduction and damping curves. Fig. 1 shows examples of these curves for a range of overburden pressures. An iterative procedure is used to determine the degraded soil properties due to strain induced nonlinearities. For the first iteration of the algorithm, the response of the soil profile is calculated using small-strain values of shear modulus and damping.

Using the initial shear modulus and damping values, a shear strain time history response is calculated, wherein the soil properties are held constant from the beginning to the end of the earthquake motion. From this time history response of each layer, a representative shear strain, $\gamma_{eff}$, is chosen. This representative strain is used to determine the degraded values of shear modulus and damping that are used in the next iteration of the analysis (see Fig. 1), and the process repeats until modulus and damping values reasonably converge to the specified degradation curves. Historically, various methods and values have been used to calculate the effective shear strain ($\gamma_{eff}$). An effective strain value of 65% of the maximum shear strain is most commonly used today.

Figure 1. Shear modulus and damping degradation curves [6].
Implementation of the Equivalent-Linear Algorithm

Several sources were consulted ([3][4][5][7][8][9][10][11][12]) in order to code the core of the equivalent-linear algorithm. As mentioned, the equivalent-linear algorithm requires iteration until the assumed shear modulus and damping from the beginning of the iteration agree with the shear modulus and damping from the calculated effective strain. Both Kramer [7] and the EERA manual [8] give the equation for the time-domain shear strain within a layer for a harmonic motion. However, the frequency-domain equation for shear strain in a layer for non-harmonic motions is not explicitly defined in these references. To clarify, the equation for strain in the frequency domain is given by:

\[
\gamma_j(z_j, \omega) = ik_j^* A_j(\omega) \exp(ik_j^* z_j) - B_j(\omega) \exp(-ik_j^* z_j) \tag{1}
\]

where \(z_j\) is the depth from the top of layer \(j\); \(\omega\) is an array of discrete angular frequencies defined by the Fourier transform and of length \(N_{FFT}\); \(A_j(\omega)\) and \(B_j(\omega)\) are arrays of amplitudes of the up-going and down-going harmonic shear waves of layer \(j\); \(i\) is the complex number; and \(k_j^*\) is the complex wave number of the layer \((\omega \sqrt{\rho / G_j^*})\). Similarly, the frequency-domain shear stress in a layer is given by:

\[
\tau_j(z_j, \omega) = ik_j^* G_j^* A_j(\omega) \exp(ik_j^* z_j) - B_j(\omega) \exp(-ik_j^* z_j) \tag{2}
\]

where \(G_j^*\) is the complex shear modulus of the layer. Regarding Eq. 2, some software may use \(G\), the shear modulus of the layer, instead of \(G^*\), the complex shear modulus. When this is done, the stress-strain curve (in time-domain) becomes a straight line with a slope of \(G\) instead of a series of hysteresis loops. Using \(G\) in lieu of \(G^*\) is inconsequential for computing acceleration time histories and response spectra, but use of \(G^*\) is essential for computing dissipated energy, which is was the motivation for this study.

Comparison of Existing Software

SHAKE91

The original SHAKE program, written by Per B. Schnabel et al. 1972 [13], was the first well-known equivalent-linear code. It has undergone several updates, and SHAKE91 [5] is a direct descendant of the original. SHAKE91 is the de facto standard equivalent-linear code, and several subsequent codes either directly use its code or are based on it. SHAKEVT [14] added the option to output dissipated energies for each layer and increased the maximum length of the input motion, among other modifications. SHAKE2000 is a pre- and post-processor for SHAKE91 [15]. WESHAKE is a modification and expansion of the SHAKE program [16]. Although the EduSHAKE and ProSHAKE programs are a rewrite of the SHAKE code, they are based on SHAKE, as well [17].

SHAKE91 continues to be a standard because it is such a simple program. Its input and output are simple text files and its executable is a slight 500 kB. Where EduSHAKE and ProSHAKE require an XP emulator to run in Windows 7 (or newer versions), SHAKE91’s
Fortran executable still runs on most platforms without problems. However, SHAKE91 lacks a graphical user interface, a batch mode, and a catalog of degradation curves. It also has a few limitations that additionally hamper its utility. For example, the recommended limit to the number of points in the input motion is 3800. This was fine when most motions were discretized at intervals of 0.01 seconds. However, many motions are now discretized at 0.005 second intervals, and thus, SHAKE91 will not run with these motions. Additionally, a maximum of 13 distinct shear modulus and damping degradation curves can be used, limiting the discretization of the soil profile to some extent.

Additionally, SHAKE91 has an implementation bug: if the input motion has an odd number of columns, the motion is interpreted incorrectly by the program [18]. For example, if the input motion has 5 columns (the standard PEER database format), every sixth data point of the ground motion is interpreted as a zero by SHAKE91. This causes a frequency shift in the motion and cuts off the tail of the motion. This is caused by the way SHAKE91 stores the input motion (line 171, MAIN.FOR). In an apparent effort to save memory, SHAKE91 splits the real input motion and stores it in the real and imaginary parts of a variable. For odd-columned input motion formats, the last data point of the column goes into the real part and zero is assumed for the imaginary part.

DEEPSOIL

DEEPSOIL was first developed in 1998 under the direction of Youssef M.A. Hashash at the University of Illinois at Urbana-Champaign [12]. The program has several features in addition to those of SHAKE91: it has a graphical user interface, it contains a catalog of shear modulus and damping degradation curves, it can output data and plots to Microsoft Excel format, and it has a batch mode for handling multiple input motions. Additionally, both time domain non-linear and frequency domain equivalent-linear analyses are supported; only the frequency domain equivalent-linear analyses were evaluated here. One minor issue was encountered: the output shear stress time history is calculated using shear modulus (i.e., \(G\)) instead of the complex shear modulus (i.e., \(G^*\)); thus, it cannot be used to calculate dissipated energy without additional post-processing.

Strata

Strata was written by Albert Kottke and Ellen M. Rathje at the University of Texas at Austin [10]. It has a graphical user interface, an extensive and customizable catalog of shear modulus and damping degradation curves, an option to use Random Vibration Theory (RVT), and options to randomize the profile properties. It also has an extensive set of output options (including dissipated energy), outputs to universal comma-separated value (.csv) format, and multiple input motion batch support. The source code of Strata is completely open and can be compiled on virtual any desktop operating system. (Windows binaries are available precompiled.) In contrast with other implementations of the equivalent-linear algorithm, Strata has an option to auto-discretize the layers of a soil profile, splitting each soil type into smaller sub-layers for analysis. For the comparisons in this paper, auto-discretization of the layers was turned off. Strata is currently under development, but the most recent version (399) is stable enough for most analyses.
ShakeVT2

ShakeVT2 was written in the Python language. Python is an object-oriented, interpreted language that excels at readability and portability of the code [19]. It was chosen for use in this research because it is easy to learn, free to use and distribute, and a large number of scientific libraries are readily available to extend the base language. At the time of this writing, a graphical user interface is not available for ShakeVT2. However, ShakeVT2 well performs the functions for which it was designed: calculating dissipated energy and the number of equivalent cycles for multiple profiles and motions using the low cycle fatigue implementation of the Palmgren-Miner hypothesis outlined in Green and Terri (2005) [20]. Because ShakeVT2 is written in a high-level language (compared to Strata’s C++ or SHAKE91’s Fortran), the core equivalent-linear algorithm of ShakeVT2 is much slower than those of Strata, DEEPSOIL, and SHAKE91. In most cases, however, the difference in the speed of the core algorithm is not an issue.

Comparison of Computation Results

In order to adequately compare the performance of the above-mentioned implementations of the equivalent-linear algorithm, a comparison of their results is presented herein. The Treasure Island E-W ground motion (TRI090) from the 1989 Loma Prieta earthquake is compared with the Yerba Buena Island E-W motion (YBI090) applied at the base of the Treasure Island soil profile (after [21]). Table 1 summarizes the profile.

Figure 2 shows the Fourier amplitude spectrum of the accelerations at the top of the profile after convergence of the equivalent-linear algorithms. The various algorithms show agreement within the accuracy of floating-point numbers for this profile and motion. Although not shown in this figure, discrepancies between SHAKE91/VT and the other software exist at amplitudes below about 10e-4 g/s. This is due to SHAKE’s lack of precision.

Table 1. Treasure Island soil profile used in the analysis (after [21]).

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (m)</th>
<th>Unit Weight (kN/m³)</th>
<th>Shear Wave Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (Fill)</td>
<td>2.9</td>
<td>19.7</td>
<td>270</td>
</tr>
<tr>
<td>Sand (Fill)</td>
<td>5.5</td>
<td>19.7</td>
<td>142.4</td>
</tr>
<tr>
<td>Sand (Fill)</td>
<td>5</td>
<td>19.7</td>
<td>175</td>
</tr>
<tr>
<td>Young Bay Mud</td>
<td>8.1</td>
<td>16.6</td>
<td>179</td>
</tr>
<tr>
<td>Young Bay Mud</td>
<td>8.2</td>
<td>16.6</td>
<td>179</td>
</tr>
<tr>
<td>Sand</td>
<td>5.2</td>
<td>20.4</td>
<td>320</td>
</tr>
<tr>
<td>Sand</td>
<td>6.6</td>
<td>20.4</td>
<td>320</td>
</tr>
<tr>
<td>Old Bay Mud</td>
<td>17.6</td>
<td>19.5</td>
<td>270</td>
</tr>
<tr>
<td>Old Bay Mud</td>
<td>17.6</td>
<td>19.5</td>
<td>270</td>
</tr>
<tr>
<td>Old Bay Mud</td>
<td>12.5</td>
<td>19.5</td>
<td>390</td>
</tr>
<tr>
<td>Weathered Rock</td>
<td>11.9</td>
<td>21</td>
<td>660</td>
</tr>
<tr>
<td>Bedrock</td>
<td>-</td>
<td>22</td>
<td>1072</td>
</tr>
</tbody>
</table>

In this and the subsequent plots, SHAKE91 and SHAKEVT are plotted as the same line.
since they gave identical results for motions with less than 4096 data points. And, because the Yerba Buena Island motion had more than 4096 points, SHAKE91 could not be used and it is assumed that SHAKE91 and SHAKEVT would yield the same results. There are several different normalization formats commonly used for Fourier amplitude spectrum (FAS). The FAS format used by SHAKE91/VT is different from that used by Strata and DEEPSOIL. As a result, to compare the FAS computed by the different codes, the SHAKE91/VT FAS was normalized using Eq. 3:

\[
FAS_{\text{Strata}} = FAS_{\text{DEEPSOIL}} = 0.5 \cdot N_{\text{FFT}} \cdot \Delta t \cdot FAS_{\text{SHAKE91}}
\]

where \(N_{\text{FFT}}\) is the number of points used in the FFT, and \(\Delta t\) is the time step of the input motion.

Figure 2. Comparison of the calculated Fourier amplitude spectra. Note that Strata smooths the FAS but that functionality was removed to aid in comparison.

The maximum shear strain profiles computed by the various codes differed (see Figure 3). By requesting the maximum shear strain at 1 meter depth intervals, ShakeVT2 shows that the peak value of shear strain occurs at approximately 15 meters. In comparison, Strata also outputs the maximum shear strains at relatively small depth increments but the output values are not as high as those of ShakeVT2. However, this disparity relates to how Strata outputs its maximum shear strain profile and is not due to differences in the algorithms used to compute the maximum shear strains at a given depth. Strata calculates the maximum shear strains at the center of each layer and interpolates between these depths in plotting the shear strain profile. However, the shear strain time histories computed by ShakeVT2 and Strata at a given depth are identical. SHAKE91/VT and DEEPSOIL also output the maximum shear strains at only at one depth per layer, at the top and center of each layer, respectively. As a result, the soil profile would need to be discretized by more/thinner layers in order to improve the accuracy of the computed strain profiles.
Comparing the Effects of the Method to Calculate Response Spectrum

Several methods are available to calculate the response spectra from an acceleration time history. DEEPSOIL [10] allows the user to select from one of three methods to compute response spectra: ‘Frequency Domain’, ‘Duhamel Integral’, or ‘Newmark’. These respectively refer to a method that uses the FAS to calculate the response spectra, Nigam and Jennings’ piecewise-exact method [22], and the Newmark $\beta$ method. Using the same soil profile and motion, the 5% damping response spectra at the surface of the profile was computed for each option. Fig. 4 shows that for this profile and ground motion, the choice of method to calculate response spectra makes little difference.

Comparing the Effects of the Complex Shear Modulus

Historically, several different equations have been used to calculate the complex shear modulus, $G^*$. SHAKE91/VT (lines 421-422 of B1.FOR) calculates the complex shear modulus of a layer using Eq. 4:

Figure 3. Maximum shear strain profile for the YBI090 motion.

Figure 4. Comparison of methods to compute the response spectrum.
where $G$ is the shear modulus ($\tau/\gamma$) of the layer and $\xi$ is the viscous damping ratio of the layer (as a decimal). Strata [9] uses the complex shear modulus calculated from Eq. 5. Both DEEPSOIL and ShakeVT2 allow the user to choose Eqs. 4, 5, or 6, but default to Eq. 6. All equations give similar results when damping is small.

$$G^* = G(1 - 2\xi^2 + i2\xi\sqrt{1 - \xi^2})$$  \hspace{1cm} (4)

$$G^* = G(1 - \xi^2 + i2\xi)$$  \hspace{1cm} (5)

$$G^* = G(1 + i2\xi)$$  \hspace{1cm} (6)

Fig. 5 illustrates how the choice of complex shear modulus affects the FAS at the surface and the maximum acceleration profile. The FASs are very similar below a frequency of about 0.3 Hz, but the values diverge above that frequency. This translates into a difference in maximum acceleration at several depths in this soil profile.

**Comparison of Effective Strain Ratios**

All of the software mentioned in this paper allow the user to choose a ratio of effective shear strain to the maximum shear strain. The default value in Strata, DEEPSOIL, and ShakeVT2 is 0.65. The SHAKE91 manual [5] suggests using values between 0.4 and 0.75 “depending on the input motion and which magnitude earthquake it is intended to represent.” Using ShakeVT2 and values of 0.5, 0.65, and 0.8 for the effective strain ratio, the response of the soil profile was calculated. Fig. 6 shows the resulting Fourier amplitude spectra and maximum acceleration profiles. Once again, the Fourier amplitude spectra diverge most at high frequencies and the maximum acceleration profiles are significantly different at several depths. This is not a surprise because effective strain ratio directly affects the stiffness and damping of a profile, and, thus, its capacity to amplify the incoming ground motion.

**Conclusions**

The equivalent-linear procedure, since its introduction with SHAKE in 1972, continues to be a useful method to estimate site response. Five implementations of the equivalent-linear algorithm have been compared for a single profile and ground motion. It has been shown that these implementations give similar results when supplied the same inputs. However, the choice of complex shear modulus and effective strain ratio have an impact on the results, especially for motions that contain a lot of energy at high frequencies. Additionally, it has been shown that when using DEEPSOIL, SHAKEVT, or SHAKE91 the discretization of the profile may obscure peaks when plotting the maximum shear strain with depth. Finally, SHAKE91 and SHAKEVT suffer from an implementation bug that gives incorrect results when the input motion file has an odd number of columns.
Figure 5. Differences in the Fourier amplitude spectrum and the max acceleration profile caused by using different equations for shear modulus.

Figure 6. Fourier amplitude spectra and maximum acceleration profiles as affected by the effective shear strain ratio.

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not necessarily reflect the views of the National Science Foundation.

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Appendix J

Code

J.1 License

Copyright (C) 2015 Samuel J. Lasley, Russell A. Green, and Adrian Rodriguez-Marek

Permission is hereby granted, free of charge, to any person obtaining a copy of this software and associated documentation files (the ”Software”), to deal in the Software without restriction, including without limitation the rights to use, copy, modify, merge, publish, distribute, sublicense, and/or sell copies of the Software, and to permit persons to whom the Software is furnished to do so, subject to the following conditions:

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J.2 Equivalent-Linear: ShakeVT2

The file `EquivLin.py` performs equivalent-linear site response analysis and calculates the number of cycles based on dissipated energy, \( n_{eq} \).

```python
try:
    import ipdb as pdb
except:
    import pdb
import csv
import numpy as np
# import numexpr as ne
from scipy.interpolate import interp1d
# import guiqwt.pyplot as plt
import matplotlib.pyplot as plt
import degrcurv as dc

try:
    xrange
except NameError:
    xrange = range

class SoilProfile(object):
    '''
    This object acts as a container for the Soil Profile and subsequent
calculations.
    Example:
    SoilProfileObject = SoilProfile(profile_name, Unit_Wt, Vs, t, **kwargs)
The functions 'inputread' and 'input_soil_profile' automatically call this
object. Alternately, the required values can be given manually.

    Inputs:
    profile_name = a name for the profile
    Unit_Wt = an array of unit weights of the layers of the profile.
    Vs = an array of shear wave velocities of the layers of the profile.
    t = tan array of the thicknesses of each layer of the profile.
    Keyword Arguments: Definition/Default:
    filename filename of the input profile
    ko The ratio of vertical over horizontal shear
    stresses (array). This is used to calculate
    the degradation curves.
    phi The friction angle (array). Also used to calculate
degradation curves. Used if the ko array
    is zero.
    '''
```
N160  Corrected SPT blowcounts (array). Only used if ko and phi are zero. If an N160 value is not given, ko is assumed to be 0.5.

gwt  The depth of the ground water table. If not given, it is assumed to be at the surface.

g  Acceleration due to gravity. Assumed to be 9.81 m/s^2.

layerno  An array of integers numbering the layers. Assumed to be counted from the surface starting at 1.

layername  An array of names describing the layers.

scalefactor  A factor by which ground motions can be amplified or deamplified. Assumed to be 1.

strainratio  Ratio of equivalent uniform strain divided by the maximum strain. Default is 0.65. This value is the default when calling the Dynamics.iterations method.

loc_mot  Layer at which the motion is input into the profile, given as an integer. When using this value, the Dynamics.calcWaves method counts the layers from the surface, starting at 1, irrespective of the layerno array values. Default is the bottom layer (bedrock).

outcrop_mot  0 signifies that the input motion is an outcrop motion, 1 otherwise. This can be overridden by the Dynamics object call if the 'outcrop_mot' keyword is used.

OCR  An array giving the Over Consolidation Ratio for each layer. This is used only for the Darendeli and Stokoe (2001) Degradation Curves.

DS_soil  Soil number for Darendeli and Stokoe Degrad Curves. The soil type indicator:
0 for a general set of curves
(Table S.12 from Darendeli's Dissertation)
1 for clean sand
2 for sands with high fines contents
3 for silts
4 for clays

DS_N  Number of cycles for the Darendeli and Stokoe (2001) Degradation Curves. Default is 10 for all layers.


ACCTHo6  an array indicating if the acceleration time history should be
output for the center of each layer. 1 will output, 0 will suppress output.

AccThOutcrop6 Specifies if the motion from the above is an outcrop motion (O) or within (1) [default]

AccThType6 Specifies if the above timehistories should be the entire time history (1), or the max value only (0) [default]

TauTh7a An array specifying if the stress time histories of the corresponding layers should be output. 1 will output, 0 will suppress output.

GamTh7b An array specifying if the stress time histories of the corresponding layers should be output. 1 will output, 0 will suppress output.

RespSpec9 An array specifying if the response spectrum should be calculated and output: 0 for no [default], 1 for outcrop, 2 for within

There should be additional options that I need to code.

The following 'data attributes' or variables are created by __init__:

```
def __init__(self, profile_name, unit_wt, Vs, t, **kwargs):
    self.profile_name = profile_name
    self.unit_wt = unit_wt
    self.Vs = Vs
    self.t = t
    self.ks = kwargs.get('ks', np.zeros(len(t),))
    self.ks = kwargs.get('phi', np.zeros(len(t),))
    self.PI = kwargs.get('PI', np.zeros(len(t),))
    self.N160 = kwargs.get('N160', np.zeros(len(t),))
    self.gwt = kwargs.get('gwt', 0)
    self.g = kwargs.get('g', 9.81)
    self.layerno = kwargs.get('layerno', np.arange(len(t),)+1)
    self.layername = kwargs.get('layername')
    self.scalefactor = kwargs.get('scalefactor',1.)
```
self.strainratio = kwargs.get('strainratio', 0.65)
self.loc_mot = kwargs.get('loc_mot', 0)
self.outcrop_mot = kwargs.get('outcrop_mot', 0)

# self.AccTHo6 = kwargs.get('AccTHo6', np.zeros(len(t),))
# self.AccTHoutcrop6 = kwargs.get('AccTHoutcrop6', np.ones(len(t),))
# self.AccTHotype6 = kwargs.get('AccTHotype6', np.zeros(len(t),))
# self.TauTH7a = kwargs.get('TauTH7a', np.zeros(len(t),))
# self.GamTH7b = kwargs.get('GamTH7b', np.zeros(len(t),))
self.RespSpec9 = kwargs.get('RespSpec9', np.zeros(len(t),))

self.OCR = kwargs.get('OCR', None)
self.DS_soil = kwargs.get('DS_soil', None)
self.DS_N = kwargs.get('DS_N', None)
self.DS_freq = kwargs.get('DS_freq', None)
self.filename = kwargs.get('filename')

self._calcInsituStress()}

def _calcInsituStress(self):
    """
    Calculates the mid-depth of each layer, the vertical stress,
    the effective stresses, and the mean effective stresses.
    
    This method is automatically called by the soil profile
    object __init__. For an external call, use SoilProfile.calcInsituStress.
    
    Notice that if ko is not given, it is calculated from phi. If
    phi is not given, it is calculated from N160. If none of ko, phi, or
    N160 are given, the ko value is assumed to be 0.5. This is important
    because ko is used to calculate the mean effective stress which is
    used, in some cases, to calculate the degradation curves.
    
    Each of the inputs should be an array with the [0] value being the
    value of the layer at the surface:
    
    t = thickness of the layer
    unit_wt = the unit weight of the layer
    gwt = depth of the ground water table from the surface (positive value-
    not an array)
    ko = at rest earth pressure coefficient
    phi = effective friction angle. Used to calc the ko if ko is given as
    zero.
    N160 = the overburden- and energy-corrected SPT blowcount. Used to
    calc the ko if ko and phi are zero.
    
    If N160, phi and ko are all zero for a layer, Ko is assumed to
    be 0.5
    
    The following 'data attributes' or variables are created:
    self.t_mid
    self.sigv
    self.sigveff
    self.sigmef
    """
t = self.t
unit_wt = self.unit_wt
gwt = self.gwt
t_mid = np.zeros(len(t))
sigv = np.zeros(len(t))
sigveff = np.zeros(len(t))
for i in xrange(len(t_mid)):
    if i == 0:
        t_mid[i] = (t[i] / 2)
        sigv[i] = (t_mid[i] * unit_wt[i])
    else:
        t_mid[i] = (t_mid[i - 1] + t[i - 1] / 2 + t[i] / 2)
        sigv[i] = (sigv[i - 1] + t[i - 1] / 2 * unit_wt[i - 1] + 
                   t[i] / 2 * unit_wt[i])
    if t_mid[i] > gwt:
        sigveff[i] = (sigv[i] - 9.81 * (t_mid[i] - gwt))
    else:
        sigveff[i] = (sigv[i])
    if ko[i] == 0:
        if phi[i] != 0:
            ko[i] = 1 - np.sin(phi[i] * np.pi / 180.) # Using phi to calc ko
        elif N160[i] != 0:
            phi[i] = (20 * N160[i]) ** 0.5 + 20 # Jaky, 1944, using N160 to calc phi
            and ko
            ko[i] = 1 - np.sin(phi[i] * np.pi / 180.)
            # Hatanae and Uchida, 1996
        else:
            ko[i] = 0.5 # making an assumption
    sigmeff = sigveff * (1. + 2. * ko[:len(sigveff)]) / 3.
self.t_mid, self.sigv = t_mid, sigv
self.sigveff, self.sigmeff = sigveff, sigmeff

def calcInsituStress(self, *args, **kwargs):
    
    This small function calculates the stresses at new depths
    Positional Arguments:
    Depths at which the insitu stresses should be calculated.
    If specified, the keyword argument "depths" is ignored.
    If neither the positional or keyword arguments are used,
    the mid-depth of each layer is used.
    
    Keyword Arguments:
    out = 'total': the total vertical stress is output,
    Example:
        sigv = self.calcInsituStress([0.5,5.2], out='total')
    out = 'all': the total, effective and mean effective stresses are output,
    Example:
        sigv, sigveff, sigmeff = self.calcInsituStress([0.5,5.2],
                                                    out='all')
    out = 'eff': the effective vertical stress is output.
    Example:
        sigveff = self.calcInsituStress([0.5,5.2], out='eff')
out = 'meff': the mean effective vertical stress is output.

Example:

```
sigmeff = self.calcInsituStress([0.5, 5.2], out='meff')
```

```
out = kwargs.get('out', 'all')
gam_water = kwargs.get('gam_water', 9.81)
if len(args) > 0:
    depths = np.array(args)
else:
    depths = kwargs.get('depths', self.SoilObj.t_mid)
gwt = self.gwt
unit_wt = self.unit_wt
if np.isscalar(depths):
    depths = np.array([depths], dtype=float)
try:
    depths.ravel()
except AttributeError:
    depths = np.array(depths, dtype=float)
    depths.ravel()

h = np.append(self.t, 1000)
hsum = np.cumsum(h, dtype=float)
sigv = np.zeros(len(depths))
buoy = np.zeros(len(depths))
ko = np.zeros(len(depths))

# Find the layer for each depth and calc the total stresses
j = 0
for i in xrange(len(depths)):
    while depths[i] >= round(hsum[j], 3):
        j += 1
    if depths[i] < h[0]:
        d = depths[i]
    else:
        d = depths[i] - hsum[j-1]

    if depths[i] >= gwt:
        buoy[i] = (depths[i] - gwt) * gam_water
    else:
        buoy[i] = 0

    if j == 0:
        sigv[i] = unit_wt[j] * d
    else:
        sigv[i] = np.sum(h[:j] * unit_wt[:j]) + unit_wt[j] * d
        ko[i] = self.ko[j]

if out == 'total':
    return sigv
elif out == 'all':
    sigveff = sigv - buoy
    sigmeff = sigveff * (1. + 2. * ko) / 3.
    return sigv, sigveff, sigmeff
elif out == 'meff':
    sigveff = sigv - buoy
    sigmeff = sigveff * (1. + 2. * ko) / 3.
return sigmeff

def calcVs30(self,**kwargs):
    
    Calculates the Vs30 of the profile according to eqn 20.4-1 of ASCE 7-10.

    Optional Keyword Argument:
    SiteClass = True or False [default].
    If true, the site class according to ASCE 7-10 will also be output with the Vs30.
    If False, the thickness of the entire soil profile is returned instead.
    returns = True or False [default]. Whether or not anything is returned, the following 'data attributes' or variables are created:
    self.Vs30
    self.SiteClass

    Example:
    Vs30 = SoilObject.calcVs30(Vs_array, t_array, returns = True)
    Vs30,SiteClass = SoilObject.calcVs30(Vs_array,
                                            t_array,
                                            SiteClass=True,
                                            returns = True)

    t = np.zeros(self.Vs.shape, dtype=float)
    t[:-1] = self.t
    Vsprofile = self.Vs
    returns = kwargs.get('returns',False)
    SiteClass = kwargs.get('SiteClass',False)

    n=-1
    if np.sum(t) <= 30:
        t[-1] = 30 - np.sum(t[:-1])
    else:
        t2 = np.zeros(t.shape,dtype=float)
        while np.sum(t2) < 30:
            n += 1
            t2[n] = t[n]
        if np.sum(t2) > 30:
            t2[n] = t2[n] - (np.sum(t2)-30)
        t = t2

    self.Vs30 = np.sum(t) / np.sum(t/Vsprofile)

    if SiteClass == True:
if self.Vs30 > 1524:
    self.SiteClass = 'A'
elif self.Vs30 >= 762:
    self.SiteClass = 'B'
elif self.Vs30 >= 365.76:
    self.SiteClass = 'C'
elif self.Vs30 >= 182.88:
    self.SiteClass = 'D'
else:
    self.SiteClass = 'E'

if returns == True:
    return self.Vs30, self.SiteClass
else:
    if returns == True:
        return self.Vs30, np.sum(t)

def calcAvgVs(self, depth):
    '''
    Calculates the average shear wave velocity of the top
    'depth' of the profile according to eqn 20.4-1 of
    ASCE 7-10.
    '''
    t = np.zeros(self.Vs.shape, dtype=float)
    t[:-1] = self.t
    Vsprofile = self.Vs
    n=-1
    if np.sum(t) <= depth:
        t[-1] = depth - np.sum(t[:-1])
    else:
        t2 = np.zeros(t.shape,dtype=float)
        while np.sum(t2) < depth:
            n += 1
            t2[n] = t[n]
        if np.sum(t2) > depth:
            t2[n] = t2[n] - (np.sum(t2)-depth)
        t = t2
    return np.sum(t) / np.sum(t/Vsprofile)

def plot(self, *args, **kwargs):
    '''
    Outputs standard plots that illustrate the soil profile.
    Positional Arguments:
    List the plots you want to see.
    Possible plots:
    Vs
    unit_wt

...
Or, you can leave it blank and all will be output.

Keywords Arguments:

- `save` = False (default) or True
  - For now, if `save` = True, then the figures will also be closed.
  - (Haven't figured it out yet.)
- `extension` = '.png' (default) or any other that matplotlib handles
- `layerlabels` = array of labels for each layer

If `layerlabels` is specified, the following kwargs may be specified:
- `labeldepths` = depth at which the label should be placed
- `labelxvals` = x value at which the label is placed.

Note that I have only implemented the labeling for the Vs plot.

Example:

```python
self.plot('Vs','unit_wt', save=True, extension='.png')
```

No data attributes are created with this method.

```
def profilecreator(array, **kwargs):
    
    Makes points at the top and bottom of each layer to make plotting
    better.
    
    depth = kwargs.get('depth',False)
    if depth == True:
```
output = [0]
for i in xrange(len(array)):
    if output[i] == 0:
        output.append(array[i])
    else:
        output.append(array[i-1])
        output.append(array[i])
else:
    output = []
    for i in xrange(len(array)):
        output.append(array[i])
    return output

def labeler(depths, labels, **kwargs):
    '''
    Adds labels to the plots.
    '''
    [xmin, xmax, ymin, ymax] = plt.axis()
xvals = kwargs.get('xvals', xmin)
for i, z in enumerate(depths):
    plt.annotate(labels[i], xy=(xvals[i], z))

depths = profilecreator(np.cumsum(self.t), depth=True)
t_mid = self.t_mid
if 'unit_wt' in args:
    unit_wt = profilecreator(self.unit_wt)
    plt.figure('unit_wt')
    plt.plot(unit_wt, depths, '-b')
    plt.xlabel('Unit Weight, $\gamma$ (kN/m$^3$)')
    plt.ylabel('Depth ($m$)')
    plt.title(self.filename)
    [xmin, xmax, ymax, ymin] = plt.axis()
    plt.axis([xmin, xmax, ymax, ymin])
if 'sigv' in args:
    sigv = self.sigv
    plt.figure('stress')
    plt.plot(sigv, t_mid, '-b', label='$\sigma_v$')
    plt.xlabel('Stress (kPa)')
    plt.ylabel('Depth ($m$)')
    plt.legend()
    plt.title(self.filename)
    [xmin, xmax, ymin, ymax] = plt.axis()
    plt.axis([xmin, xmax, ymin, ymax])
if 'sigmeff' in args:
    sigmeff = self.sigmeff
    plt.figure('stress')
    plt.plot(sigmeff, t_mid, '-r', label='$\sigma'_m$')
    plt.xlabel('Stress (kPa)')
    plt.ylabel('Depth ($m$)')
if 'sigveff' in args:
    sigveff = self.sigveff
    plt.figure('stress')
    plt.plot(sigveff, t_mid, '-g', label='$\sigma_\text{v}^\prime$')
    plt.xlabel('Stress (kPa)')
    plt.ylabel('Depth (m)')
    plt.legend()
    plt.title(self.filename)
    [xmin, xmax, ymin, ymax] = plt.axis()
    plt.axis([xmin, xmax, ymax, ymin])

while 'phi' in args:
    phi = profilecreator(self.phi)
    if max(phi) == 0:
        break
    plt.figure('phi')
    plt.plot(phi, depths[:-2], '-b')
    plt.xlabel('Friction Angle, $\phi$')
    plt.ylabel('Depth (m)')
    plt.title(self.filename)
    [xmin, xmax, ymin, ymax] = plt.axis()
    plt.axis([xmin, xmax, ymax, ymin])
    break

if 'Vs' in args:
    Vs = profilecreator(self.Vs)
    plt.figure('Vs')
    plt.plot(Vs, depths, mark, lw=lw)
    plt.xlabel('Shear Wave Velocity, $V_s$ (m/s)')
    plt.ylabel('Depth (m)')
    plt.title(self.filename)
    [xmin, xmax, ymin, ymax] = plt.axis()
    plt.axis([xmin, xmax, ymax, ymin])

    if layerlabels:
        labeler(labeldepths, layername, xvals=labelxvals)

while 'N160' in args:
    N160 = profilecreator(self.N160)
    if max(N160) == 0:
        break
    plt.figure('N160')
    plt.plot(N160, depths[:-2], '-b')
    plt.xlabel('Corrected SPT Blowcounts, $N_{1,60}$')
    plt.ylabel('Depth (m)')
    plt.title(self.filename)
    [xmin, xmax, ymin, ymax] = plt.axis()
    plt.axis([xmin, xmax, ymax, ymin])

    while 'ko' in args:
ko = profilecreator(self.ko)
if max(ko) == 0:
    break
plt.figure('ko')
plt.plot(ko,depths[:len(ko)],'-b')
plt.xlabel('Lateral Earth Pressure Coefficient, $K_0$')
plt.ylabel('Depth ($m$)')
plt.title(self.filename)
[xmin, xmax, ymin, ymax] = plt.axis()
plt.axis([xmin, xmax, ymax, ymin])
break
if save == True:
    import matplotlib
    figures=[manager.canvas.figure for manager in
               matplotlib._pylab_helpers.Gcf.get_all_fig_managers()]
    for i, figure in enumerate(figures):
        figure.savefig(self.profile_name +'-'+figure._label+ext)
        # figure.clf()

def calcDepth(self, stress, **kwargs):
    '''
    This method will return the depth at which a stress is felt.
    Keyword arguments: Meaning/Options:
    stresstype        'total', 'eff'[default], 'mean'
                       corresponding to
                       the total vertical stress, the vert
                       effective stress, and the mean
                       effective stress, respectively.
    Output:
    depths = the depths at which the corresponding stresses are felt.
    No data attributes are created with this method.
    Example:
    depths = self.calcDepth([50., 101.], stresstype='eff')
    '''
    unit_wt = self.unit_wt
t = self.t
    t_mid = self.t_mid
    ko = self.ko
gwt = self.gwt
    stresstype = kwargs.get('stresstype','eff')
    if np.isscalar(stress):
        stress = np.array([stress], dtype=float)
    try:
        stress.ravel()
    except AttributeError:
        stress = np.array(stress, dtype=float)
        stress.ravel()
    outdepths = np.zeros(stress.shape,dtype=float)
    if stresstype == 'total':
        stressprof = self.sigv
        ...
unit_wt_eff = unit_wt[:-1]

elif stresstype == 'eff':
    stressprof = self.sigveff
    unit_wt_eff = np.where(np.cumsum(t) <= gwt, unit_wt[:-1],
                           unit_wt[:-1]-9.81)
elif stresstype == 'mean':
    stressprof = self.sigmeff
    unit_wt_eff = np.where(np.cumsum(t) <= gwt, unit_wt[:-1],
                           unit_wt[:-1]-9.81) * (1 + 2 * ko[:-1]) / 3
else:
    print('I didn\'t understand the stresstype')
    return np.ones(stress.shape,dtype=float) * -1000.

for i, sig in enumerate(stress):
    try:
        no = np.where(sig < stressprof)[0][0]
    except IndexError:
        print('Stress of {} kPa not reached in this profile.'.format(sig))
        outdepths[i] = -1000
        continue

    stressinterface = stressprof[no-1] + (unit_wt_eff[no-1] *
                                          t[no-1] / 2)
    if stressinterface >= sig:
        outdepths[i] = t_mid[no-1] + ((sig - stressprof[no-1]) /
                                    unit_wt_eff[no-1])
    else:
        outdepths[i] = np.sum(t[:no]) + ((sig -
                                           stressinterface) / unit_wt_eff[no])

return outdepths

def getLayer(self, depth):
    '''
    Return the layer number for a given depth.
    Example:
    layernums = self.getLayer(10.25)
    layernums = self.getLayer([10.25, 13.7])
    No data attributes are created with this method.
    '''
    tsum = np.cumsum(self.t)
    if np.isscalar(depth):
        depth = np.array([depth], dtype=float)
    try:
        depth.ravel()
    except AttributeError:
        depth = np.array(depth, dtype=float)
        depth.ravel()
    layernumbers = np.ones(depth.shape, dtype=int) * -1

    return layernumbers
for i, z in enumerate(depth):
    layernumbers[i] = np.where(z <= tsum)[0][0]

if len(layernumbers) == 1:
    return layernumbers[0]
else:
    return layernumbers

def to_csv(self, **kwargs):
    '''
    Writes out a .csv file from this profile.
    '''
    filename = kwargs.get('filename', self.profile_name)
    f = open(filename, 'w')
    f.write('Name of Profile, {}
'.format(self.profile_name))
    f.write('Units, 0\n
    f.write('GWT Depth, {}
'.format(self.gwt))
    f.write('Location of Motion, {}
'.format(self.loc_mot))
    f.write('Outcrop Motion,{},'.format(self.outcrop_mot) +
      '|==== Darendeli and Stokoe Parameters ====|\n')
    f.write('Layer number, name, Unit Weight, Vs, Thickness, PI, ko, phi,'+
        'N160, OCR, Soil Type, N, Frequency\n')

    num = len(self.t)
    strout1 = '{},'*13 + '
    strout2 = '{},' * 4 + '

    for i, (no, name, utwt, vs, t, pi, ko, phi, n160) in enumerate(zip(
        self.layerno[:-1], self.layername[:-1],
        self.unit_wt[:-1], self.Vs[:-1], self.t,
        self.PI, self.ko, self.phi, self.N160)):
        ocr = self.OCR[i] if np.any(self.OCR) else ''
        soiltype = self.DS_soil[i] if np.any(self.DS_soil) else ''
        freq = self.DS_freq[i] if np.any(self.DS_freq) else ''
        n = self.DS_N[i] if np.any(self.DS_N) else ''

        f.write(strout1.format(no, name, utwt, vs, t, pi, phi, n160, +
            ocr, soiltype, n, freq))
        f.write(strout2.format(self.layerno[-1], self.layername[-1],
            self.unit_wt[-1], self.Vs[-1]))
    f.close()

class GroundMotion(object):
    '''
    This object acts as a container for all ground motion related variables.
    '''
    Keyword Arguments: Definition/defaults:
        name The name of the ground motion/ground motion file.
        filename The filename of ground motion file. If not specified, +
            name needs to be a valid filename in the path.
        scalefactor Factor by which the motion time history is scaled.
            This scaling occurs when the motion is read from
If the motion is specified as a keyword argument, no scaling occurs.

Butwrth  If True, a Butterworth filter is applied when the motion is called from the file. If the motion is specified as a keyword argument, the Butterworth filter is not applied. Default is False.

b_order  The order of the Butterworth filter. Default is 4.

cutofffreq  Cutoff frequency (in Hz) for the Butterworth filter. Default is 100 Hz.

g  Acceleration due to gravity. Default is 9.81. This is used to convert the motion from units of g to m/s/s. Apply the appropriate value for the units of the motion and the soil profile. This code assumes everything is in SI units unless specified.

==== The following are only needed if a valid filename is not given. ====

motion  The input acceleration time history. If this is not specified, a valid filename must be given.

NFFT  The number of points used in the FFT. Only required if the motion keyword argument is specified.

FA  The Fourier Amplitude spectrum of the input motion. Only required if the motion keyword argument is specified.

f  An array of frequencies corresponding to the FA in Hz. Only required if the motion keyword argument is specified.

w  An array of angular frequencies corresponding to the FA in rad/sec. Only required if the motion keyword argument is specified.

NPTS  Number of points in the input time history. Only required if the motion keyword argument is specified.

dt  The sample spacing of the time history input motion in seconds. Only required if the motion keyword argument is specified.

dummy  Let dummy=True if you just want to calc the transfer function of the profile.

'Data attributes' or variables created by the __init__ method:

self.name
self.filename
self.scalefactor
self.Butwrth
```python
def __init__(self, **kwargs):
    self.name = kwargs.get('name')
    self.filename = kwargs.get('filename')
    formatin = kwargs.get('formatin', 'PEER')
    self.scalefactor = kwargs.get('scalefactor', 1.)
    self.Butrwrth = kwargs.get('Butrwrth', False)
    if self.Butrwrth:
        self.b_order = kwargs.get('b_order', 4.)
        self.cutofffreq = kwargs.get('cutofffreq', 100)
        self.g = kwargs.get('g', 9.81)
        self.motion = kwargs.get('motion')
        self.NFFT = kwargs.get('NFFT')
        self.FA = kwargs.get('FA')
        self.f = kwargs.get('f')
        self.w = kwargs.get('w')
        self.NPTS = kwargs.get('NPTS')
        self.dt = kwargs.get('dt')
        self.dummy = kwargs.get('dummy', False)
        if self.NPTS and self.dt:
            self.time = np.linspace(0, (self.NPTS - 1) * self.dt, self.NPTS)
    if self.dummy == True:
        self.name = 'dummy'
        self.motion = np.ones([8192,], dtype=float) * -1.
        self.NPTS = 8192
        self.NFFT = self.FA = 8192
        self.dt = 0.01
        self.f = np.linspace(0, 1/self.dt/2, self.NFFT//2+1)
        self.w = self.f[:self.NFFT//2+1] * 2 * np.pi
        self.FA = np.ones(self.w.shape, dtype='complex128')
        if np.any(self.motion) == None:
            if self.filename == None:
                self.getInMotion(self.name, **kwargs)
            else:
                self.getInMotion(self.filename, **kwargs)
    if np.any(self.FA) == None:
        self.getMotInfo(self.motion, self.dt, **kwargs)

def getInMotion(self, motion_name, **kwargs):
```

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Reads in the input motion from a PEER-formatted file. Also converts it
to the frequency domain and applies scaling. Also, applies a Butterworth
lowpass filter, if specified.

Keyword Arguments:

formatin = 'PEER' [default], 'PEER-OLD', or 'PEER-scaled'
directout = False [default] or True. If true, the __init__ data
attributes are not updated.

The following 'data attributes' or variables may be created:
self.Ar = a normalized rms acceleration
self.predfreq = an estimation of the dominant frequency of the motion
self.Ar2 = self.Ar / self.predfreq

Buttrwrth = kwargs.get('Buttrwrth', False)
if self.Buttrwrth:
    self.b_order = kwargs.get('b_order',4.)
    self.cutofffreq = kwargs.get('cutofffreq',100)
# formatin = kwarg.get('formatin', 'PEER')
# baseline = kwarg.get('baseline', False)
extras = kwargs.get('extras', True)
directout = kwarg.get('directout', False)
# Import the ground motion
count = 0
eqmot = []
f = open(motion_name, 'rb')
if formatin == 'PEER-scaled':
    for line in f:
        count += 1
        if count == 7:
            NPTS = int(line.split()[1][:-1])
            dt = float(line.split()[3][:-4])
            if count > 7:
                for num in line.split():
                    eqmot.append(float(num))
elif formatin == 'PEER-OLD':
    for line in f:
        count += 1
        if count == 4:
            NPTS = int(line.split()[1].replace(',',''))
            dt = float(line.split()[3])
        if count > 4:
            for num in line.split():
                eqmot.append(float(num))
else:
    for line in f:
        count += 1
        if count == 4:
            NPTS = int(line.split()[0])
            dt = float(line.split()[1])
        if count > 4:
            for num in line.split():
                eqmot.append(float(num))

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motion = np.array(eqmot) * self.scalefactor
if max(motion.shape) != NPTS :
    print('NPTS discrepancy! {} {}'.format(max(motion.shape), NPTS))
    print(motion_name)
NPTS = max(motion.shape)
motion = motion.reshape([NPTS])
# if baseline == True:
#    motion = motion - np.average(motion)
f.close()
del eqmot, count, num
self.getMotInfo(motion, dt, **kwargs)

def getMotInfo(self, scaledmotion, dt, **kwargs):
    
    This will get the transform and other info of a motion if only the
    acceleration time history is input.
    
    extras = kwargs.get('extras',True)
    Butwrth = kwargs.get('Butwrth', False)
    if self.Butwrth:
        self.b_order = kwargs.get('b_order',4.)
        self.cutofffreq = kwargs.get('cutofffreq',100)
        g = self.g
        directout = kwargs.get('directout', False)
        g = self.g
        NPTS = len(scaledmotion)
        NFFT = 2 ** nextpow2(NPTS)
        f = np.linspace(0, 1/dt/2, NFFT//2+1)
        w = f[:NFFT/2+1] * 2 * np.pi
        if Butwrth == True:
            w_cutoff = self.cutofffreq * 2 * np.pi
            butter = (1 / (1 + (np.abs(w) / w_cutoff) ** (2 * self.b_order))
            ) ** 0.5
        else:
            butter = np.ones(w.shape)
        FA = np.fft.rfft(scaledmotion * g, NFFT) * butter
        if directout == True:
            return scaledmotion, NFFT, FA, f, w, NPTS, dt
        pass
    else:
        self.motion = np.fft.irfft(FA / g)[:NPTS]
        self.NFFT = NFFT
        self.FA = FA
        self.f = f
        self.w = w
        self.NPTS = NPTS
        self.dt = dt
        self.time = np.linspace(0,(NPTS-1) * dt,NPTS)
        if extras:
            sortedfreq = np.array(sorted(zip(np.abs(FA),f)))
            predfreq = (np.sum(sortedfreq[-NFFT/200::0]) *
sortedfreq[-NFFT/200:,1] / np.sum(sortedfreq[-NFFT/200:,0]))
Ar = calcAriasRatio(scaledmotion, dt)
Ar2 = Ar / predfreq
self.Ar = Ar
self.Ar2 = Ar2
self.predfreq = predfreq

class Dynamics(object):
    '''
    This class combines the soil profile and the ground motion objects to
    produce the dynamic Equivalent Linear Procedure.
    
    Input:
    SoilObject = This is the object created by instantiating the
    SoilProfile class
    MotionObject = This is the object created by instantiating the
    GroundMotion class.
    
    You can specify these two objects so that you can perform different
    analyses on the same profile with the same motion
    
    Keyword Arguments: Definition and default values:
    modtype = specifies complex shear modulus calculations.
    The options are:
    'FreqInd': Frequency Independent Complex Shear
    Modulus (Kramer, 1996) [default]
    'FreqDep': Frequency Dependent Complex Shear
    Modulus (Udaka, 1975)
    (used by SHAKE?)
    'Simplified': Simplified complex shear modulus
    (Kramer, 1996)
    The calculations can be found under the _calcWaves function.
    
    InitGratio The initial Gratio estimate. Should be either a
    scalar or the length of the layers (not
    counting bedrock). By default it is equal to
    Gmax.
    
    BaseGratio The initial Gratio for the bedrock. Since
    there are no iteration or degradation
    curves for the bedrock, this should be 1. [Default]
    
    InitDamping The initial estimate of damping for each layer,
    default is 0.05 (5%)
    
    BaseDamping The damping constant of the bedrock, as a decimal.
    0.01 is default. I may try to add the option of
    adding degradation curves later
    
    DegradCurves Specifies the method used to calculate the shear
    modulus and damping degradation curves.
    The only options currently supported are
    'IZ' Ishibashi and Zhang (1993) and
    'DS' for Darendeli and Stokoe (2001)
It shouldn't be difficult to add more.
If the 'DS' option is used, the DSVariables object is instantiated and used.

**Iters**
Max number of iterations, default is 20

**Error**
The threshold error (decimal, as a ratio of Gmax) at which iterations will stop, default is 0.02.

------------ Iterations continue until either the number of iterations is reached or the maximum computed error of the iteration is less than 'Error,' the threshold error.

**Outcrop_mot**
0 if the input motion is an outcrop, 1 otherwise.
This overrides the SoilProfile object data attribute, if specified, otherwise, the SoilObject value is used.

**Loc_mot**
Overrides the location of motion given in the SoilProfile object data attribute, if specified, otherwise, the SoilObject value is used.

**Strainratio**
Ratio of equivalent uniform strain divided by the maximum strain. This should be a single value; the default is given by the SoilObject. The default given by the SoilObject is 0.65.
If anything other than a numerical value is given, a strain ratio is calculated using dissipated energy to give a weighted average of the strain time history.
This is experimental; see self.calcDissEn to see how it works.

**Start_iters**
If False, code will wait until the DynamicsObject.iterate() method is called. Default is True.

**Run_all**
If True, the number of equivalent cycles and dissipated energy will be calculated for all mid-layer depths.

**Verbose**
True or False [default]. If True, details from each iteration are given.

The following options allow the user to finely specify degradation curves. They are all completely optional. They are useful when comparing outputs from different codes. ===============

**DCO_sigmEff**
Overrides the calculated mean effective stresses for use in the degradation curve equations. Default are the SoilObject values.

**DCO_PI**
Overrides soil profile PI values for use in the degradation curve equations. Default are the SoilObject values.

**DS_OCR**
Provides OCR values for the Darendeli and
Default is 1 for all layers.

**DS_soil** Soil number for Darendeli and Stokoe Degrad Curves

- 0 for a general set of curves
- Table 8.12 from Darendeli's Dissertation
- 1 for clean sand
- 2 for sands with high fines contents
- 3 for silts
- 4 for clays

Default is 10 for all layers.

Default is 1 Hz for all layers.

**DS_Dmin** An alternative way to calc Dmin for the Darendeli and Stokoe Degradation curves.
1 for 'Default', 0 for 'Green'

!!! Not Implemented !!!

**DCO_curve** If True, user must input their own degradation curves, specified with the following keywords:

- **DCO_gam** = shear strains as decimals (an array n long)
- **DCO_Gratio** = G/Gmax values (decimal) (an array m x n, where m is the number of layers above the baserock)
- **DCO_damping** = damping (decimal) in the same shape as DCO_Gratio

The following data attributes are created by the __init__ method.
Since the init method calls other methods, the list may not be complete.

```
self.g
self.Gmax
self.G
self.D
self.DegradCurves
self.modtype
self.iters
self.ComIter = Flag to show when iterations have completed.
self.Error
self.gam
self.Gratio
self.damping
self.loc_mot
self.SoilObj
self.MotObj
self.outcrop_mot
self.dissEn
self.strainratio
self.verbose
self.Ar = a normalized rms acceleration.
self.Ar_ratio = self.Ar / Ar of the input motion.
```
def __init__(self, SoilObject, MotionObject, **kwargs):
    self.g = SoilObject.g
    self.Gmax = (SoilObject.unit_wt / self.g) * SoilObject.Vs ** 2
    self.G = np.copy(self.Gmax)
    self.InitG = np.copy(self.G)
    self.ComIter = False
    self.D = np.ones(len(self.Gmax)) * 0.05
    self.D[:-1] = kwargs.get('InitDamping', 0.05)  # <------Initial estimate of damping; may want to change
    self.D[-1] = kwargs.get('BaseDamping', 0.01)  # <<<<<<<<<<<<<<<<<<<<
    self.DegradCurves = kwargs.get('DegradCurves', 'IZ')
    self.modtype = kwargs.get('modtype', 'FreqInd')
    self.iters = kwargs.get('iters', 30)
    self.Error = kwargs.get('Error', 0.02)

    # Get the degradation curves
    gam = kwargs.get('gam')
    if kwargs.get('DCO_curve', False) == True:
        self.Gratio = kwargs.get('DCO_Gratio')
        self.damping = kwargs.get('DCO_damping')
        self.DSvars = DSvariables(kwargs, SoilObject)
    elif self.DegradCurves == 'IZ':
    else:
        line = ('Degradation Method input not understood\n' + 'or a custom degradation curve has been entered.\n')
        print(line)

    self.SoilObj = SoilObject
    self.loc_mot = kwargs.get('loc_mot', self.SoilObj.loc_mot)
    self.MotObj = MotionObject
    self.outcrop_mot = kwargs.get('outcrop_mot', self.SoilObj.outcrop_mot)
    self.gammf = None
# Start Iterations
start_iters = kwargs.get('start_iters', True)
if start_iters:
    self.strainratio = kwargs.get('strainratio', self.SoilObj.strainratio)
    self.verbose = kwargs.get('verbose', False)
    self.iterate(ite=iters, E=Error, strainratio=strainratio, verbose=verbose)

# Run_all
run_all = kwargs.get('run_all', False)
if run_all:
    self.calcNeq()
    self.Ar, self.PeakTimeRatio = calcAriasRatio(self.calcAcc(domain='time', MotType='within', MaxOnly=False), self.MotObj.dt, returnall=True)
    Ar_input = calcAriasRatio(self.MotObj.motion, self.MotObj.dt)
    self.Ar_ratio = self.Ar / Ar_input

def reset(self):
    '''
    Resets G and D to initial values
    '''
    self.G = np.copy(self.InitG)
    self.D = np.copy(self.InitD)
    self.ComIter = False

def iterate(self, **kwargs):
    '''
    Performs the equivalent linear iterations until either the iteration limit is reached or the error goes below the predefined threshold.
    Keywords: Definition/Default:
    iters: number of iterations, default is that defined by the self.__init__ function
    Error: the error threshold, default is that defined by the self.__init__ function
    strainratio: Ratio of equivalent uniform strain divided by the maximum strain. This should be a single value; the default is given by the SoilObject. The default given by the SoilObject is 0.65.
    If anything other than a numerical value is given, a strain ratio is calculated using dissipated energy to give a weighted average of the strain time history.
    verbose: True or False [default]. If True, details from each iteration are given.
Data attributes created by this method:

- `self.gamavgarray`: average shear strain of all layers
- `self.Garray`: array of current degraded shear moduli for every layer for every iteration
- `self.Darray`: array of current degraded damping for every layer for every iteration
- `self.Errarray`: array of errors for every layer for every iteration
- `self.Gratiocurv`: an object to interpolate new values of modulus
- `self.Dcurv`: an object to interpolate new values of damping
- `self.count`: current or final count of iterations
- `self.ratio`: strain ratios used for the iteration
- `self.ReportError`: 'y' if an error has occurred, 'n' if not.

Updated or created data attributes:

- `self.G`
- `self.D`
- `self.A`
- `self.B`
- `self.ComIter`
- `self.gammf`: strain for mid point or each layer in freq domain
- `self.taumf`: stress for mid point or each layer in freq domain

```python
1309 self.gamavgarray = np.zeros((self.Gratio.shape[0], max(self.iters, 1)), dtype=float)
1310 self.Garray = np.zeros((self.Gratio.shape[0], max(self.iters, 1)), dtype=float)  # G/Gmax
1311 self.Darray = np.zeros((self.Gratio.shape[0], max(self.iters, 1)), dtype=float)  # D
1312 self.Errarray = np.zeros((max(self.iters, 1), len(self.G)-1), dtype=float)
1313
1314 self.Gratiocurv = interp1d(np.log10(self.gam), self.Gratio, kind='linear', axis = 1)
1315 self.Dcurv = interp1d(np.log10(self.gam), self.damping, kind='linear', axis = 1)
```

```
1316 while iterate == True:  # Begin Iterations
1317     self.count += 1
1318     self._calcWaves()  # Get the new upgoing and down going waves
1319     try:
1320         # Won't work if the strain ratio is a string, go to except
1321         self.ratio = (float(self.strainratio) * np.ones(self.G[:-1].shape))
1322         # Get the max stress and strain values
1323         taumax, gammax = self._calcTauGam(MaxOnly=True, domain='time', returns=True)
1324     except ValueError:
1325         # Get the stress and strain for each layer in the time domain
```

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taut, gamt = self._calcTauGam(MaxOnly=False, domain='time',
                           returns=True)
# Calc the strain ratio using the dissipated energy method
self.ratio = self.calcStrainRatio_DE(taut, gamt)
gamma = np.max(np.abs(gamt), axis=1)
self.gamavgarray[:, self.count - 1] = self.ratio * gamma
self.gammax = gamma
# For really stiff profiles or soft motions, self.ratio * gamma
# may fall below the gam range. Here we make sure we can interpolate.
if np.max(self.ratio * gamma) > self.gam[-1]:
    exceedcount += 1

gamma = np.min((
    np.max((
        self.ratio * gamma,
        self.gam[0] * np.ones(gamma.shape), axis=0),
        self.gam[-1] * np.ones(gamma.shape)
    ), axis=0)
# Get the new G and D from interpolated curves
try:
    Gnewmat = self.Gratiocurv(np.log10(gamma))
    Gnew = self.Gmax[:-1] * np.diag(Gnewmat)
    Dnewmat = self.Dcurv(np.log10(gamma))
    Dnew = np.diag(Dnewmat)
except ValueError:
    print('ValueError!')
    print('Soil Profile: {}'.format(self.SoilObj.profile_name))
    print('Ground Motion: {} {}'.format(self.MotObj.name,
                                         self.MotObj.filename))
    print('Strain Ratio: {}'.format(self.ratio))
    print('Gamma Max: {}'.format(gamma))
    print('G: {}'.format(self.G))
    print('D: {}'.format(self.D))
    pdb.set_trace()
    raise Exception("ValueError in the interpolation of the" +
                    " degradation curves")

Err = (self.G[:-1] - Gnew)/self.Gmax[:-1]  # calc the error
self.Errarray[self.count - 1, :] = Err
# Check if we can duck out of iterations
if np.max(abs(Err)) <= Error:
    iterate = False
    self.ReportError = 'n'
    self.ComIter = True
    self.MaxError = np.max(abs(Err))

    if exceedcount >= 2:
        iterate = True
    if exceedcount >= 3:
        pdb.set_trace()
if self.count >= self.iters:
    iterate = False
    if np.max(abs(Err)) <= Error:
        pass
        self.ReportError = 'n'
        self.ComIter = True
    else:
        print('Reached {:d} iterations without converging!'.format(self.iters))
        self.ReportError = 'y'
        self.ComIter = False
self.MaxError = np.max(abs(Err))
# print out data about each iteration/layer
if self.verbose == True:
    print('Iteration: {}
'.format(self.count))
    # print('Gamma Max: {}'.format(gammax))
    # print('G:'.format(self.G))
    # print('D:'.format(self.D))
    # print(np.max(self.A))
    print('{:^11} {:^9} {:^9} {:^9} {:^9} {:^9}'.format('Gamma_max:', 'Gold', 'Gnew', 'Dold', 'Dnew', 'Error'))
    for i in xrange(len(Gnew)):
        print('{:^10.6e} {:^9.0f} {:^9.0f}'.format(gammax[i], self.G[i], Gnew[i]) + '{:^9.4f} {:^9.4f} {:^9.4}'.format(self.D[i], Dnew[i], Err[i]))
# Get ready for the new iteration.
if iterate == True:
    self.G[:-1] = Gnew
    self.D[:-1] = Dnew

def _calcWaves(self):
    '''
    Calculates the up-going and down-going wave amplitudes.
    
    This method is called without input arguments to calculate the
    amplitudes of the upgoing and downgoing waves (A & B). The input
    are already defined as part of the object.
    
    The following data attributes are created:
    self.Gstr = complex shear modulus
    self.Vsstr = complex shear wave velocity
    self.ks = wave number?
    self.alps = alpha, the layer impedance ratio
    
    
    
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self.A = amplitude of upgoing waves
self.B = amplitude of downgoing waves
self.Updated = flag for something.

```python
self.g = self.g
G = self.G
D = self.D
h = self.SoilObj.t
unit_wt = self.SoilObj.unit_wt
try:
    w = self.MotObj.w
    FA = self.MotObj.FA
except AttributeError:
    print(self.MotObj.filename)
    print(self.MotObj.dt)
# From the Deepsoil Manual:
if self.modtype == 'FreqDep':  # Frequency Dependent Complex Shear Modulus (Udaka, 1975) (Shake?)
    self.Gstr = G * (1 - 2 * D ** 2 + 1j * 2 * D * (1 - D ** 2) ** (0.5 + 0j))
ellif self.modtype == 'FreqInd':  # Frequency Independent Complex Shear Modulus
    self.Gstr = G * (1 + 1j * 2 * D)
ellif self.modtype == 'Simplified':  # Simplified complex shear modulus (Kramer, 1996)
    self.Gstr = G * (1 - D ** 2 + 1j * 2 * D)
Gstr = self.Gstr
self.Vsstr = (Gstr * g / unit_wt) ** 0.5
Vsstr = self.Vsstr
self.ks = w / Vsstr[:,:np.newaxis]
ks = self.ks
alps = ((unit_wt[:-1] * Vsstr[:-1]) / (unit_wt[1:] * Vsstr[1:]))
# Initialize the up and down going waves.
A=np.ones(ks.shape, dtype='complex128')
B=np.ones(ks.shape, dtype='complex128')
# Calculate the waves, this is somewhat computationally intensive. C code could be
# useful here in the future.
for i in xrange(len(h)):
    A[i+1,:] = (0.5 * A[i,:] * (1 + alps[i]) + np.exp(1j * ks[i,:] * h[i]) +
        0.5 * B[i,:] * (1 - alps[i]) + np.exp(-1j * ks[i,:] * h[i])
    B[i+1,:] = (0.5 * A[i,:] * (1 - alps[i]) + np.exp(1j * ks[i,:] * h[i]) +
        0.5 * B[i,:] * (1 + alps[i]) + np.exp(-1j * ks[i,:] * h[i])
# Get the input motion
FD = np.zeros(FA.shape, dtype='complex')
FD[1:] = FA[1:] / (1j*w[1:])**2 #
FD[0] = FA[0] # (self.MotObj.dt * (self.MotObj.NPTS - 1)) ** 2 #
```

if self.loc_mot == 0:
    index = -1
else:
    index = self.loc_mot - 1  # Subtracting one here to convert to python's 0
counting method
if index > len(A):
    index = -1

if self.outcrop_mot == 0:
    A1new = FD / (2 * A[index, :])
else:
    A1new = FD / (A[index, :] + B[index, :])

# Aratio = A1new / A[index, :] # <+++ Double checking my calcs: 3 Sept 2013,

# A2 = A * Aratio[np.newaxis, :]
# Bratio = A2[0, :] / A[0, :]
# B2 = B * Bratio[np.newaxis, :]
# Getting the corrected waves from the input motion
# self.A = A * A1new[np.newaxis, :]
# self.B = B * A1new[np.newaxis, :]

# plt.figure(1)
# plt.plot(abs(self.A[0, :]))
# plt.plot(abs(A2[0, :]), 'o')
# plt.figure(2)
# plt.plot(abs(self.B[0, :]))
# plt.plot(abs(B2[0, :]), 'o')
# plt.show()

# pdb.set_trace()

self.alps = alps
self.Updated = True

def _getDegrad(self, Degrad, PI, sigmeff, **kwargs):
    '''
    Gets the shear modulus and damping degradation curves.
    
    Outputs a 1D array (gam = shear strain (decimal) and 2- 2D arrays
    (Gratio = G/Gmax and damping (decimal)) that represent the shear
    modulus and damping degradation curves. It depends on the module
degcurv, so use that if you want to customize it. Or, create your own
degaration curves.
    Right now, Degrad must equal 'IZ' for the Ishibashi and Zhang (1993)
curves or 'DS' for Darendeli and Stokoe (2001).
sigmeff must be in kPa
    
    Keyword Arguments:
    (See the __init__ for these definitions, only for 'DS')
    OCR
    soil
    N
    freq
    Dmitype !!! Not Implemented !!!
    Everything but Degrad should be an array, or you will get errors.
    '''

    straindef = np.array([0.0000001, 0.000001, 0.000003, 0.00001,
                          0.00003, 0.0001, 0.0003, 0.001, 0.003,
                          0.01, 0.99])

    straindef = np.logspace(-6, -2, num=20, endpoint=True)

    if Degrad == 'DS':
        OCR = kwargs.get('OCR')
        soil = kwargs.get('soil')

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N = kwargs.get('N')
freq = kwargs.get('freq')
# Dmintype = kwargs.get('DS_Dmin')
if np.isscalar(OCR):
    OCR = np.ones(len(PI),dtype=float) * OCR
if np.isscalar(soil):
    soil = np.ones(len(PI),dtype=int) * soil
if np.isscalar(N):
    N = np.ones(len(PI),dtype=float) * N
if np.isscalar(freq):
    freq = np.ones(len(PI),dtype=float) * freq
gam = kwargs.get('gam', straindef)
if gam == None:
    gam = straindef
damping = np.zeros([len(PI),len(gam)],dtype=float)
Gratio = np.zeros([len(PI),len(gam)],dtype=float)
for i in xrange(len(PI)):
    if Degrad == 'IZ':
        gam, Gratio[i], damping[i] = dc.IZ_1993(gam = gam,
                                            PI=PI[i],
                                            sigm=sigmeff[i])
    elif Degrad == 'DS':
        gam,Gratio[i],damping[i] = dc.DS_2001(gam = gam,
                                              PI=PI[i],
                                              sigm=sigmeff[i],
                                              OCR=OCR[i],
                                              soil=soil[i],
                                              N=N[i],
                                              frq=freq[i])
return gam, Gratio, damping

def _calcTauGam(self, **kwargs):
    '''
    This calculate the stress and strains for arbitrary conditions.
    
    Keyword Arguments: Definitions/Default values:
    
    depths    array or single value of depth at which the
    stresses and strains should be calculated.
    Default is the mid-depth of each layer.
    
    domain    'time' [default] or 'freq'
    
    MaxOnly   True [default] or False. When True, only the
    absolute maximum value of each layer is returned. This will force the
    domain to be 'time' and the returns to be True.
    
    returns   True or False [default]. When True, the stresses
    and strains are returned. Otherwise, they are data attributes of the
    object (self.taumf and self.gammf, but only when the
    depths are equal to the mid-depths of the layers).
    
    BaseCorr  True or False [default]. Applies a baseline
    
    '''
    
    # Codeimplementation

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correction to the strain in time domain by
subtracting the average value.

Example:

```
tau, gam = [DynamicsObject]._calcTauGam(depths = [0.1,0.4],
domain = 'time'
returns = True)
```

Data attributes possibly created by this method:

```
self.taumf
self.gammf
```

```python
ComIter = self.ComIter
t_mid = self.SoilObj.t_mid
A = self.A
B = self.B
ks = self.ks
t = self.SoilObj.t
Gstr = self.Gstr
```

```python
depths = kwargs.get('depths',t_mid)
domain = kwargs.get('domain','time')
MaxOnly = kwargs.get('MaxOnly',True)
returns = kwargs.get('returns',False)
BaseCorr = kwargs.get('BaseCorr',False)
if MaxOnly == True:
domain = 'time'
returns = True
```

```python
def hardway(t):
    '''
    Gets the requested values when things are trickier.
    returns tau, gam
    '''
    returns = True
t = np.append(t, 1000)
gam = np.zeros([len(depths), np.shape(A)[1]], dtype='complex128')
tau = np.zeros([len(depths), np.shape(A)[1]], dtype='complex128')
tsum = np.cumsum(t, dtype=float)
j = 0
for i in xrange(len(depths)):
    while depths[i] >= round(tsum[j], 3):
        j += 1
    if depths[i] < t[0]:
d = depths[i]
    else:
d = depths[i] - tsum[j-1]
gam[i] = i[0] * ks[j] * (A[j, :] + np.exp(i[0] *
ks[j] * d) - B[j, :] * np.exp(-i[0] * ks[j] * d))
tau[i] = gam[i] * Gstr[j]
return tau,gam
```

# Check if I have to do it the hard way.
if len(np.ravel(depths)) != len(np.ravel(t_mid)):
tau, gam = hardway(t)

else:
    if np.equal(depths, t_mid).all():
        if ComIter == True:  # If the iterations are finished, I can call existing
            tau = self.taumf
            gam = self.gammf
        else:
            gam = (1j * ks[:-1] *
                   (A[:-1, :] * np.exp(1j * ks[:-1] *
                    t[:, np.newaxis] / 2) -
                    B[:-1, :] * np.exp(-1j * ks[:-1] *
                    t[:, np.newaxis] / 2)))
            tau = gam * Gstr[:-1, np.newaxis]
            self.gammf = gam
            self.taumf = tau
    else:
        tau, gam = hardway(t)

# Do I need to convert my motions to the time domain?
if domain == 'time':
    NPTS = self.MotObj.NPTS
    tau = np.fft.irfft(tau, axis=1)
    gam = np.fft.irfft(gam, axis=1)
    tau = tau[:, :NPTS]
    gam = gam[:, :NPTS]
    if BaseCorr == True:  # This correction is pretty elementary; I don't like it.
        basecorrect = np.mean(gam, axis=1)
        gam = gam - basecorrect[:, np.newaxis]  # Baseline correction

if MaxOnly == True:
    tau = abs(tau).max(1)
    gam = abs(gam).max(1)
if returns == True:
    return tau, gam

def _AccVelDisp(self, **kwargs):
    '''
    Calculates acceleration, velocity, or displacement.
    Keyword argument: Options: (Default listed first)
        which     = 'Acc', 'Vel' or 'Disp'
        domain    = 'time' or 'freq'
        MotType   = 'within', 'outcrop' or 'incoming'
        MaxOnly   = False or True
        depths    = mid-depths of each layer or list of desired
    It may be easier to use the self.calcAcc, self.calcDisp, or
    self.calcVel methods. This is meant for internal use only.
    '''
    Which = kwargs.get('which', 'Acc')
    domain = kwargs.get('domain', 'time')
MotType = kwargs.get('MotType','within')
MaxOnly = kwargs.get('MaxOnly',False)
depths = kwargs.get('depths',self.SoilObj.t_mid)
smooth = False
if domain == 'freq':
    smooth = kwargs.get('smooth',False)
window = kwargs.get('window',20)
A = self.A
B = self.B
h = self.SoilObj.t
h = np.append(h,1000)
w = self.MotObj.w
NPTS = self.MotObj.NPTS
g = self.g
ks = self.ks
disp = np.zeros([len(depths),np.shape(A)[1]], dtype='complex128')
hsum = np.cumsum(h, dtype=float)

# Figure out which layer we are in, and calc the displacement
j = 0
for i in xrange(len(depths)):
    while depths[i] > round(hsum[j],3):
        j += 1
    if depths[i] < h[0]:
        d = depths[i]
    else:
        d = depths[i] - hsum[j-1]
    if MotType == 'incoming':
        disp[i] = A[j, :]*np.exp(1j * ks[j] * d)
    elif MotType == 'within':
        disp[i] = (A[j, :]*np.exp(1j * ks[j] * d) +
                   B[j, :]*np.exp(-1j * ks[j] * d))
    else:
        disp[i] = 2 * A[j, :]*np.exp(1j * ks[j] * d)

# Convert to Acc or Vel, if needed.
if Which == 'Acc':
    out = disp * (1j * w[np.newaxis,:]) ** 2 / g
elif Which == 'Vel':
    out = disp * (1j * w[np.newaxis,:])
else:
    out = disp

if domain == 'time':
    out = np.fft.irfft(out, axis=1)
    out = np.delete(out, np.s_[NPTS:], axis=1)

# Not Fully implemented.
if smooth == True:
    del i, j
    ind = np.arange(out.shape[1],dtype=int)
    indlow = ind - window / 2
    indhigh = ind + window / 2
    np.putmask(indlow,indlow<0,0)
    np.putmask(indhigh, indhigh>ind[-1],ind[-1])
smoothout = np.zeros(out.shape, dtype=complex)
for j in ind:
    smoothout[:, j] = np.mean(out[:, indlow[j]:indh high[j]]) * (window)
out = smoothout

if MaxOnly == True:
    out = abs(out).max(1)

return out

def calcStress(self, *args, **kwargs):
    
    Use this method to obtain the stress at one or more depths.
    Keyword Argumentss: Definitions/Default values:
    depths array or single value of depth at which the stresses should be calculated.
    Default is the mid-depth of each layer.
    domain 'time' [default] or 'freq'
    MaxOnly True or False [default] . When True, only the absolute maximum value of each layer is returned. This will force the domain to be 'time' and the returns to be True.
    ratio True or False [default]. Calculates the cyclic stress ratio or CSR.
    ratiotype Choose 'verteff' or 'meaneff' {not implemented yet}
    time True or False[default]. Returns an array of the time if in the time domain. Else it returns the frequency array if the domain is frequency.
    
    This method calls the self._calcTauGam method. It does not set any data attributes.
    
    domain = kwargs.get('domain', 'time')
    MaxOnly = kwargs.get('MaxOnly', False)
    ratio = kwargs.get('ratio', False)
    ratiotype = kwargs.get('ratiotype')
    time = kwargs.get('time', False)

    if ratiotype:
        ratio = True
    if len(args) > 0:
        depths = np.array(args)
    else:
        depths = kwargs.get('depths', self.SoilObj.t_mid)

    out, strain = self._calcTauGam(depths=depths,
                                   domain=domain,
                                   MaxOnly=MaxOnly,
                                   returns=True)

    if ratio == True:
        if ratiotype == 'meaneff':
def calcStrain(self, *args, **kwargs):
    '''
    Use this method to obtain the strain at one or more depths.
    
    Keyword Argumentss: Definitions/Default values:
    depths array or single value of depth at which the strains should be calculated.
    Default is the mid-depth of each layer.
    domain 'time' [default] or 'freq'
    MaxOnly True [default] or False. When True, only the absolute maximum value of each layer is returned. This will force the domain to be 'time' and the returns to be True.
    time True or False[default]. Returns an array of the time if in the time domain. Else it returns the frequency array if the domain is frequency.
    
    This method calls the self._calcTauGam method. It does not set any data attributes.
    '''
    domain = kwargs.get('domain','time')
    MaxOnly = kwargs.get('MaxOnly',False)
    time = kwargs.get('time',False)
    if len(args) > 0:
        depths = np.array(args)
    else:
        depths = kwargs.get('depths',self.SoilObj.t_mid)
    stress, out = self._calcTauGam(depths=depths, domain=domain, MaxOnly=MaxOnly, returns=True)
if len(depths) == 1:
    out = np.ravel(out)
if time == True:
    if domain == 'time':
        xarr = self.MotObj.time
    else:
        xarr = self.MotObj.f
    return xarr, out
else:
    return out

def calcNeq(self,*args,**kwargs):
    r""
    Calculates the equivalent number of cycles using dissipated energy.
    r"
    Positional Arguments:
    depths at which equivalent number of cycles are calculated.
    ** Before refactoring, I allowed the args to be the strain ratio.
    Hopefully I have caught and changed all the old ones.
    Keyword Arguments Definition/Default
    depths = array of depths, default is mid-depth of each layer
    If the depths are specified as a keyword argument,
    these depths are not used.
    set_ratio = ratio of uniform sinusoidal amplitude and max strain
    Note: this sets the ratio_Neq attribute and
defaults to the ratio used in the iteration
    method self.ratio. Allows me to look at how
    the strain ratio affects the Neq in this calc.
    returns = False (default) or True. By default, this function does
    not return any values. Instead, the data attributes
    of N_eq, tau_avgNeq, Neq_ratio, and dissEn are created
    or updated.
    Data attributes created/updated by this method if he mid-layer depths
    are used. Note that these values will change for every set_ratio value.
    self.N_eq
    self.tau_avgNeq = the amplitude of the equiv. sinusoidal stress motions
    self.Neq_ratio = the strain ratio corresponding to the self.N_eq
    self.dissEn -> only created if the mid-layer depths are used.
    This method calls the self.calcDissEn method.
    ","""
    if len(args) > 0:
        depths = np.array(args)
    else:
        depths = kwargs.get('depths',self.SoilObj.t_mid)
    ratio = kwargs.get('set_ratio',self.ratio)
    returns = kwargs.get('returns',False)
    t_mid = self.SoilObj.t_mid
    t = self.SoilObj.t
def hardway(t):
    
    \`
    
    # Check if I have to use the hard way to get G, D.
    
    # if len(np.ravel(depths)) != len(np.ravel(t_mid)):
    same = False
    G,D = hardway(t)
    
    else:
        if np.equal(depths, t_mid).all():
            same = True
            G = self.G[:-1]
            D = self.D[:-1]
        else:
            same = False
            G,D = hardway(t)
    
    tau, gam = self._calcTauGam(domain='time',
                                MaxOnly=False,
                                depths=depths,
                                returns = True)
    DE = self.calcDissEn(tau, gam, output='normal')
    
    # get max stresses
    taumax = np.max(np.abs(tau),axis=1)
    tau_avgNeq = ratio * taumax
    
    #tau_avgNeq = 0.65 * taumax
    dissEn_one = 2 * np.pi * D * tau_avgNeq ** 2 / G
    N_eq = DE / dissEn_one
    
    if same == True:
        self.tau_avgNeq = tau_avgNeq
        self.N_eq = N_eq
        self.Neq_ratio = ratio
        self.dissEn = DE
    
    if returns == True:
        return N_eq, tau_avgNeq, ratio, DE
    
    def calcDissEn(self, stresses, strains, **kwargs):
        
        #
Calculates the dissipated energy for a given set of stress and strain time histories.

Input:
- **stresses** m x n array of stress time histories with each layer in a different row. Make sure to use
  \[ \text{stress} = \text{ifft}(G* \ast \text{strain}(\omega)) \]
  where \( G* \) is the complex shear modulus and
  \( \text{strain}(\omega) \) is the shear strain as a decimal in the frequency domain. \( m \) is the number of layers and \( n \) is the number of pts in the time history (\text{self.MotObj.NPTS})

- **strains** m x n array of strain time histories (decimal), in the same format as the stresses.

Keyword Arguments:
- **FinalValOnly** = True | False

Output:
- **DissE** The dissipated energy in units of stress per unit volume if output='normal'. Else, an array of strain ratios.
  To obtain the normalized dissipated energy like that given by SHAKEVT, divide the dissipated energy by the vertical effective stress.

```python
if kwargs.get('FinalValOnly', True):
    dissEn = np.zeros(np.shape(stresses)[0], dtype=float)
    dissEn = np.sum((stresses[:,1:] + stresses[:,:-1]) *
                     (strains[:,1:] - strains[:,:-1]), axis = 1) * 0.5
    return dissEn
else:
    dissEn = np.zeros(stresses.shape, dtype=float)
    dissEn = np.cumsum((stresses[:,1:] + stresses[:,:-1]) *
                        (strains[:,1:] - strains[:,:-1]) * 0.5,
                        axis = 1)
    return dissEn
```

```python

def calcStrainRatio_DE(self, stresses, strains, **kwargs):
    '''
    Calculates a strain ratio using the weighted average strain from the dissipated energy.
    
    Input:
    - **stresses** m x n array of stress time histories with each layer in a different row. Make sure to use
      \[ \text{stress} = \text{ifft}(G* \ast \text{strain}(\omega)) \]
      where \( G* \) is the complex shear modulus and
      \( \text{strain}(\omega) \) is the shear strain as a decimal in the frequency domain. \( m \) is the number of layers and \( n \) is the number of pts in the time history (\text{self.MotObj.NPTS})
    
    Output:
    - **DissE** The dissipated energy in units of stress per unit volume if output='normal'. Else, an array of strain ratios.
      To obtain the normalized dissipated energy like that given by SHAKEVT, divide the dissipated energy by the vertical effective stress.
    
    Keyword Arguments:
    - **FinalValOnly** = True | False
    
    if kwargs.get('FinalValOnly', True):
        dissEn = np.zeros(np.shape(stresses)[0], dtype=float)
        dissEn = np.sum((stresses[:,1:] + stresses[:,:-1]) *
                         (strains[:,1:] - strains[:,:-1]), axis = 1) * 0.5
        return dissEn
    else:
        dissEn = np.zeros(stresses.shape, dtype=float)
        dissEn = np.cumsum((stresses[:,1:] + stresses[:,:-1]) *
                            (strains[:,1:] - strains[:,:-1]) * 0.5,
                            axis = 1)
        return dissEn
```
strains \( m \times n \) array of strain time histories (decimal),
in the same format as the stresses.

Output: An array of strain ratios of length \( m \).

```python
plot = kwargs.get('plot', False)
dissEn = np.zeros(np.shape(stresses)[0], dtype=float)
dissEn = ((stresses[:,1:] + stresses[:, :-1]) * 
    (strains[:,1:] - strains[:, :-1])) * 0.5
x = stresses/strains
dx = np.diff(x)
avgstrain = np.zeros(strains.shape[0],)
for i in range(np.shape(x)[0]):
    ind = np.where((dx[i, :-2] < 0) & (dx[i,1:-1] > 0) & (dx[i,2:]<0))
    if ind[0][0] == 0:
        ind = ind[0] + 1
    else:
        ind = np.insert(ind[0],0,0)
dDE = np.zeros((ind.shape[0]),)
dstrain = np.zeros((ind.shape[0]),)
    dstress = np.zeros((ind.shape[0]),)
    for k in range(len(ind)-2):
        if k % 2 == 1:
            continue
        else:
            dstrain[k] = (np.max(strains[i,ind[k]:ind[k+2]]) - 
                            np.min(strains[i,ind[k]:ind[k+2]])) / 2
            dstress[k] = (np.max(stresses[i,ind[k]:ind[k+2]]) - 
                            np.min(stresses[i,ind[k]:ind[k+2]])) / 2
            dDE[k] = dissEn[i,ind[k+2]] - dissEn[i,ind[k]]
    if plot == True:
        plt.plot(strains[i,ind[k]:ind[k+2]],
                 stresses[i,ind[k]:ind[k+2]], '-b')
        plt.xlabel('Strain')
        plt.ylabel('Stress (kPa)')
        plt.show()
        avgstrain[i] = np.average(dstrain, weights=dDE)
        G = dstress / dstrain
        print(self.G[i])
        pdb.set_trace()
        del dDE, ind, dstrain#, dstress
strainratio = avgstrain / np.max(strains, axis=1)
np.putmask(strainratio, strainratio<0,0.1)
np.putmask(strainratio, strainratio>1,1.)
return strainratio
```

def calcDisp(self,*args,**kwargs):
    
    Calculates displacements using the _AccVelDisp method.

    Positional Arguments, if used, are the depths.
Keyword argument: Options: (Default listed first)

  domain = 'time' or 'freq'
  MotType = 'within', 'outcrop' or 'incoming'
  MaxOnly = False or True
  depths = mid-depths of each layer or list of desired
          These depths can also be listed as regular,
          non-keyword arguments; see the example.

Returns an array of velocities in units of m for time
histories, m/s for frequency domain. Array is 2D if more
than one depth is specified.

Example:

```python
disp = DynamicObject.calcDisp(2.0,4.5,
    domain='time',
    MaxOnly=False,
    MotType = 'within')
```

```python
domain = kwargs.get('domain','time')
MotType = kwargs.get('MotType','within')
MaxOnly = kwargs.get('MaxOnly',False)
```

if len(args) > 0:
    depths = np.array(args)
else:
    depths = kwargs.get('depths',self.SoilObj.t_mid)

out = self._AccVelDisp(which='Disp',depths=depths,domain=domain,
                      MotType=MotType, MaxOnly=MaxOnly)
if len(depths) == 1:
    out = np.ravel(out)
return out

def calcVel(self,*args,**kwargs):
    ",",
    Calculates velocity using the _AccVelDisp method.

Keyword argument: Options: (Default listed first)

  domain = 'time' or 'freq'
  MotType = 'within', 'outcrop' or 'incoming'
  MaxOnly = False or True
  depths = mid-depths of each layer or list of desired
          These depths can also be listed as regular,
          non-keyword arguments; see the example.

Returns an array of velocities in units of m/s for time
histories, m/s-s for frequency domain. Array is 2D if more
than one depth is specified.

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Example:

```python
dom = DynamicObject.calcVels(2.0,4.5,
    domain='time',
    MaxOnly=False,
    MotType = 'within')
```

Example:

```python
dom = kwags.get('domain','time')
MotType = kwags.get('MotType','within')
MaxOnly = kwags.get('MaxOnly',False)
if len(args) > 0:
depths = np.array(args)
ext:
depths = kwags.get('depths',self.SoilObj.t_mid)
out = self._AccVelDisp(which='Vel',depths=depths,domain=domain,
    MotType=MotType, MaxOnly=MaxOnly)
if len(depths) == 1:
    out = np.ravel(out)
return out
```

```
def calcAcc(self,*args,**kwags):
    '''
    Calculates acceleration using the _AccVelDisp method.
    Keyword argument: Options: (Default listed first)
    domain = 'time' or 'freq'
    MotType = 'within', 'outcrop' or 'incoming'
    MaxOnly = False or True
    depths = mid-depths of each layer or list of desired
    These depths can also be listed as regular,
    non-keyword arguments; see the example.
    Returns an array of accelerations.
    Example:
    acc = DynamicObject.calcAcc(2.0,4.5,
        domain='time',
        MaxOnly=False,
        MotType = 'within')
    Returns an array of velocities in units of m/s/s for time
    histories, m/s/s-s for frequency domain. Array is 2D if more
    than one depth is specified.
    '''
    domain = kwags.get('domain','time')
    MotType = kwags.get('MotType','within')
    MaxOnly = kwags.get('MaxOnly',False)
    smooth = kwags.get('smooth',False)
```

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window = kwargs.get('window', 20.)
if len(args) > 0:
    depths = np.array(args)
else:
    depths = kwargs.get('depths', self.SoilObj.t_mid)
out = self._AccVelDisp( which='Acc', depths=depths, domain=domain,
    MotType=MotType, MaxOnly=MaxOnly, smooth=smooth,
    window=window)
if len(depths) == 1:
    out = np.ravel(out)
return out

def TF(self, *args, **kwargs):
    '''
    Calculates the transfer function between two layers in the frequency
    domain.

    Positional Arguments:
    List of two layers. A 1 refers to the top layer.
    0 refers to bedrock.

    Keyword Arguments:
    MotType = 'outcrop'[default] or 'within',
    'rocktosurf','rocktobase'

    Output
    tf = the transfer function.
    '''
    args = list(args)
    layer1 = args[0]
    layer2 = args[1]
    MotType = kwargs.get('MotType', 'outcrop')
    A = self.A
    B = self.B
    layer1 -= 1
    layer2 -= 1
    if MotType == 'rocktosurf':
        tf = np.abs((A[0, :] + B[0, :])/(2 * A[-1, :]))
    elif MotType == 'rocktobase':
        tf = np.abs((A[-1, :] + B[-1, :])/(2 * A[-1, :]))
    elif MotType == 'outcrop':
        tf = np.abs(A[layer1, :]/A[layer2, :])
    else:
        tf = np.abs((A[layer1, :]+B[layer1, :])/
                    (A[layer2, :]+B[layer2, :]))
    return tf

def calcTF(self, *args, **kwargs):
    '''
    Calculates the transfer function between two layers in the frequency
    domain.

    Positional Arguments:
    List of two layers. A 1 refers to the top layer.
    '''
Keyword Arguments:
- MotType = Tuple of size two with values of 'outcrop' or 'within', [default]

Output
- tf = the transfer function.

Example:
```python
tf = self.calcTF(1,0,MotType=('within', 'outcrop'))
```

```python
def _PiecewiseExact(self,acc_g,w,dt,zeta,**kwargs):
    ...

    Determines the spectral response of an SDOF structure.
```

Positional Arguments:
- acc_g = ground acceleration in units of g
- w = natural frequency of the SDOF structure.
- dt = sampling interval or time interval of the input acceleration
- zeta = the damping ratio of the structure = c/c_crit (decimal)

Keyword Arguments:
- returnextra If True, returns displacement, velocity, and total acceleration. Only useful for single value of w. Else, returns Spectral Acceleration. Default is False.
Code from rsc.c at
This would be a good function to move to C.

```
returnextra = kwargs.get('returnextra', False)
a = np.float64(np.ravel(acc_g) * 9.80665) # m/s²
w = np.float64(np.ravel(w))
dt = np.float64(dt)
z = np.float64(zeta)

root = np.sqrt(1. - z ** 2)
w = w * root
sine = np.sin(wd * dt)
cosn = np.cos(wd * dt)
expo = np.exp(-z * w * dt)

zratio = z / root
blue = 2. * z / (w ** 3 * dt)
yell = (2 * z ** 2 - 1) / (w ** 2 * dt)

a11 = expo * (zratio * sine + cosn)
a12 = expo * sine / wd
a21 = -w / root * expo * sine
a22 = expo * (cosn - zratio * sine)

b11 = expo * ((yell + z / w) * (sine / wd)
+ (blue + 1. / w ** 2) * cosn) - blue
b12 = -expo * (yell * sine / wd + blue * cosn)
- (1. / w ** 2) + blue
b21 = -expo * ((yell + z / w) * (cosn - zratio * sine)
- (blue + 1. / w ** 2) * (wd * sine + z * w * cosn)) +
1. / (w ** 2 * dt))
b22 = -expo * (yell * (cosn - zratio * sine) -
blue * (wd * sine + z * w * cosn)) -
1. / (w ** 2 * dt))

if np.isscalar(w):
    u = np.zeros([[1,len(a)], dtype=np.float64)
    v = np.zeros([[1,len(a)], dtype=np.float64])
    for i in xrange(len(a) - 1):
        u[:,i+1] = u[:,i] + a12 * v[:,i] + b11 * a[i] +
                    b12 * a[i+1])
        v[:,i+1] = (a21 * u[:,i] + a22 * v[:,i] + b21 * a[i] +
                    b22 * a[i+1])
    TA = - (2 * z * w * v + w ** 2 * u) / 9.80665

else:
    u = np.zeros([len(w),len(a)], dtype=np.float64)
    v = np.zeros([len(w),len(a)], dtype=np.float64)
    for i in xrange(len(a) - 1):
        u[:,i+1] = (a11 * u[:,i] + a12 * v[:,i] + b11 * a[i] +
                    b12 * a[i+1])
        v[:,i+1] = (a21 * u[:,i] + a22 * v[:,i] + b21 * a[i] +
                    b22 * a[i+1])
    TA = - (2 * z * w[:,np.newaxis] * v +
            w[:,np.newaxis] ** 2 * u) / 9.80665
```
if returnextra:
    return np.ravel(u), np.ravel(v), np.ravel(TA)
else:
    Sa = np.max(np.abs(TA), axis=1)
    return Sa

def StressRedCoef(self, *args, **kwargs):
    '''
    Deprecated name. Use calc_r_d instead.
    '''
    print('Function name deprecated. ' +
          'Use "calc_r_d" instead of "StressRedCoef"')
    if kwargs.get('returns', False):
        rd = self.calc_r_d(*args, **kwargs)
        return rd
    else:
        self.calc_r_d(*args, **kwargs)

def calc_r_d(self, *args, **kwargs):
    '''
    Calculates the stress reduction coefficient for the profile and
    ground motion.
    
    Positional Arguments:
    Depths at which the r_d coefficient should be calculated.
    
    Keyword Arguments: Definition/Default
    depths Default is the mid-depth of each layer.
    Disregarded if positional arguments are used.
    
    returns False [default] or True.
    
    If returns == True, stress reduction coefficient (r_d) is returned.
    This will return the calculated values.
    
    If the mid-layer depths are used, the self.rd data attribute is created
    by this method.
    '''
    if len(args) > 0:
        depths = np.array(args)
    else:
        depths = kwargs.get('depths', self.SoilObj.t_mid)
        returns = kwargs.get('returns', False)
    if np.equal(depths, self.SoilObj.t_mid).all():
        same = True
        sigv = self.SoilObj.sigv
    else:
        pdb.set_trace()
        same = False
        sigv = self.SoilObj.calcInsituStress(*depths, out='total')
    taumax, gammmax = self._calcTauGam(depths=depths, domain='time',
                                       MaxOnly=True, returns=True)
    amax = self.calcAcc(depths=[0.], MaxOnly=True, MotType='outcrop',
                        returns=True, returns=returns)
```python
    domain='time')
    rd = taumax / (amax * sigv)
    if same == True:
        self.rd = rd
    if returns == True:
        return rd

    def RespSpec(self, *args, **kwargs):
        '''
        Calculates the response spectra for a given depth(s).
        
        Positional Arguments:
        Depths at which RS is to be calculated. If none are given,
        it will calculate the response spectra for
        all mid-depths (very slow).
        
        Keyword Arguments: Values:
        depths an array of depths. Disregarded if the
        positional arguments are used.
        damping any damping value as decimal, default is 0.05
        w an array of frequencies. Computationally
        intensive if this array is large.
        method 'piecewiseexact' is the only one implemented now.
        MotType = 'within', 'outcrop' or 'incoming'
        
        Returns Sa, w
        
        This method calls the self._PiecewiseExact method.
        '''
        if len(args) > 0:
            depths = np.array(args)
        else:
            depths = kwargs.get('depths',self.SoilObj.t_mid)
            damping = kwargs.get('damping',0.05)
            w = kwargs.get('w',np.arange(0.001,600,1.2))
            method = kwargs.get('method', 'piecewiseexact')
            MotType = kwargs.get('MotType','within')
        
        if method == 'piecewiseexact':
            acc = self.calcAcc(depths=depths, domain='time', MaxOnly=False, MotType = MotType)
            else:
                print('Did not understand the method. Please try again.')
                return
            SA = np.zeros([len(depths),len(w)],dtype='float')
            for i in xrange(len(depths)):
                if len(depths) == 1:
                    SA = self._PiecewiseExact(acc, w, self.MotObj.dt,damping)
                else:
                    SA[i,:] = self._PiecewiseExact(acc[i,:], w,
```
def ASCE_RS_ratios(self,**kwargs):
    '''
    Calculates the ratio between the 5% damped surface
    response spectra of surface ground motions to input base motions.
    See ASCE 7-05, sec. 21.1.3.
    
    Keyword Arguments:
    T       array of periods
    
    Returns the surface to base response ratio and the corresponding
    array of periods.
    
    This method calls the self.RespSpec method and assumes 5% damping,
    'within' surface motion, and 'outcrop' base motion.
    
    Example:
    RS_ratio, T = self.ASCE_RS_ratios(T=np.logspace(-3,1,num=1000))
    T = kwargs.get('T',np.logspace(-3,1,num=1000))
    # Obtain the surface response spectrum
    surf,w = self.RespSpec(0.,damping=0.05,w=2.*np.pi/T,MotType='within')
    # Obtain the input base motion response spectrum
    basedepth = np.sum(self.SoilObj.t) + 0.001
    base,w = self.RespSpec(basedepth,damping=0.05,w=w,MotType='outcrop')
    ratio = surf / base
    return ratio,T

def plot(self, *args, **kwargs):
    '''
    Outputs standard plots that illustrate the equivalent linear response.
    
    Positional Arguments:
    List the plots you want to see.
    Possible plots:
    mod      modulus profile
    damp     damping profile
    maxacc   max acceleration profile
    csr      max stress ratio profile
    maxstrain max strain profile
    dissen   dissipated energy profile
    (calc'd only at mid points)
    strainratio strain ratio profile used to obtain average strain
    from max
    cycles   number of equivalent cycles profile

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For keywords arguments:

- \( \text{dz} = \) For profiles: depth increments (in meters)
- \( \text{acc} = \) an array containing the following:
  - [depth, 'time' or 'freq', 'outcrop' or 'within']
- \( \text{vel} = \) an array containing the following:
  - [depth, 'time' or 'freq', 'outcrop' or 'within']
- \( \text{disp} = \) an array containing the following:
  - [depth, 'time' or 'freq', 'outcrop' or 'within']
- \( \text{tf} = \) an array containing the following:
  - [toplayer, bottomlayer, 'outcrop' or 'within']
  - Use the layer numbers. If only one value is given, the bottom layer is assumed to be bedrock.
- \( \text{respspec} = \) an array containing the following:
  - [depth, damping, 'outcrop' or 'within']
- \( \text{plottype} = \) 'loglog' [default], 'semilogx', 'linear' (only for freq domain)
- \( \text{period} = \) False [default] or True. Specifies if the horizontal axis should show period or frequency.
- \( \text{save} = \) False (default) or True. For now, if save = True, then the figures will also be closed. (Haven’t figured it out yet.)
- \( \text{extension} = \) '.png' (default) or any other that matplotlib handles
- \( \text{sym1} = \) matplotlib line symbols. Default is '-b'
- \( \text{sym2} = \) matplotlib line symbols. Default is 'ob'
- \( \text{linelabel} = \) label for plot. Default is ''

Example:

```python
DynamicsObj.plot('mod', 'maxacc', save=True, dz=1)
```

```python
syms1 = kwargs.get('sym1', '-b')
syms2 = kwargs.get('sym2', 'ob')
linelabel = kwargs.get('linelabel', '')
t = self.SoilObj.t
if 'all' in args:
    args = ('mod', 'damp', 'maxacc', 'csr', 'maxstrain',
            'dissem', 'strainratio', 'cycles', 'rd')
```
if 'allprofile' in args:
    args = ('mod', 'damp', 'maxacc', 'csr', 'maxstrain',
             'dissen', 'strainratio', 'cycles', 'rd')

dz = kwargs.get('dz')
acc = kwargs.get('acc')
vel = kwargs.get('vel')
disp = kwargs.get('disp')
tf = kwargs.get('tf')
respspec = kwargs.get('respspec')
period = kwargs.get('period', False)
plottype = kwargs.get('plottype', 'loglog')
save = kwargs.get('save', False)
ext = kwargs.get('extension', 'png')
return_fig = kwargs.get('fig')

if return_fig != None:
    plt.figure(return_fig.number)

if dz:
    depths = np.arange(0., basedepth + dz, dz, dtype=float)
else:
    depths = t_mid

def profilecreator(array, **kwargs):
    '''
    Makes points at the top and bottom of each layer to make plotting
    better.
    '''
    depth = kwargs.get('depth', False)
    if depth == True:
        output = [0]
        for i in xrange(len(array)):
            if output[i] == 0:
                output.append(array[i])
        else:
            output.append(array[i - 1])
            output.append(array[i])
            output.append(array[-1])
            output.append(array[-1] * 1.05)
    else:
        output = []
        for i in xrange(len(array)):
            output.append(array[i])
        output.append(array[i])
        return np.array(output)

def profinterp(depth2, values2, newdepths):
    newvalues = []
    for i in xrange(len(newdepths)):
        for j in xrange(1, len(depth2), 2):
            if (newdepths[i] <= depth2[j]) & (newdepths[i] >= depth2[j - 1]):
                newvalues.append(values2[j])
                break
    return newvalues
depth2 = profilecreator(np.cumsum(t), depth=True)

if 'mod' in args:
    mod = profilecreator(self.G)
    plt.figure('Shear Modulus Profile')
    plt.plot(mod, depth2, sym1)
    plt.xlabel(r'Degraded Shear Modulus, $G$ ($kPa$)')
    plt.ylabel(r'Depth ($m$)')
    plt.title(self.SoilObj.filename + '-' + self.MotObj.filename)
    [xmin, xmax, ymin, ymax] = plt.axis()
    plt.axis([xmin, np.max(self.G[:-1]) * 1.1, ymax, ymin])
    fig = plt.gcf()

if 'damp' in args:
    damp = profilecreator(self.D)
    plt.figure('Damping Profile')
    plt.plot(damp, depth2, sym1)
    plt.xlabel(r'Degraded Damping, $D$ ($\%$)')
    plt.ylabel(r'Depth ($m$)')
    plt.title(self.SoilObj.filename + '-' + self.MotObj.filename)
    [xmin, xmax, ymin, ymax] = plt.axis()
    plt.axis([xmin, xmax, ymax, ymin])
    fig = plt.gcf()

if 'dissen' in args:
    if self.dissEn != None:
        dissen = self.dissEn
    else:
        self.calcNeq()
        dissen = self.dissEn
    dissen2 = profilecreator(dissen)
    plt.figure('DissEn')
    plt.plot(dissen2, depth2[:-2], sym1)
    plt.xlabel(r'Dissipated Energy ($kJ/m^3$)')
    plt.ylabel(r'Depth ($m$)')
    plt.title(self.SoilObj.filename + '-' + self.MotObj.filename)
    [xmin, xmax, ymin, ymax] = plt.axis()
    plt.axis([xmin, xmax, ymax, ymin])
    fig = plt.gcf()

if 'cycles' in args:
    try:
        cyc = self.N_eq
    except AttributeError:
        self.calcNeq()
        cyc = self.N_eq
    cyc2 = profilecreator(cyc)
    plt.figure('NumCyc')
    plt.plot(cyc2, depth2[:-2], sym1)
    plt.xlabel(r'Number of Equivalent Cycles Based on Dissipated Energy')
    plt.ylabel(r'Depth ($m$)')
plt.title(self.SoilObj.filename+'-'+self.MotObj.filename)
[xmin, xmax, ymin, ymax] = plt.axis()
plt.axis([xmin, xmax, ymax, ymin])
fig = plt.gcf()

if 'maxacc' in args:
    accel = self.calcAcc(domain='time',
                        MotType='within',
                        MaxOnly=True,
                        depths=depths)
    plt.figure('AccProfile')
    plt.plot(accel,depths, syms1)
    plt.xlabel(r'Max Acceleration ($g$)')
    plt.ylabel(r'Depth ($m$)')
    plt.title(self.SoilObj.filename+'-'+self.MotObj.filename)
    [xmin, xmax, ymin, ymax] = plt.axis()
    plt.axis([xmin, xmax, ymax, ymin])
    fig = plt.gcf()

if ('maxstrain' in args) or ('csr' in args):
    tau,gam = self._calcTauGam(domain='time',
                                returns=True,
                                MaxOnly=True,
                                depths=depths)
    if 'maxstrain' in args:
        plt.figure('MaxStrain')
        plt.plot(gam*100,depths, syms1)
        plt.xlabel(r'Max Shear Strain, $\gamma$, ($\%$)')
        plt.ylabel(r'Depth ($m$)')
        plt.title(self.SoilObj.filename+'-'+self.MotObj.filename)
        [xmin, xmax, ymin, ymax] = plt.axis()
        plt.axis([xmin, xmax, ymax, ymin])
        fig = plt.gcf()

if 'csr' in args:
    Gnew = np.array(profinterp(depth2,mod,depths))
    sigveff = self.SoilObj.calcInsituStress(depths,out='eff')
    CSR = gam * Gnew / sigveff
    plt.figure('CSR')
    plt.plot(CSR,depths, syms1)
    plt.xlabel(r'Max Cyclic Stress Ratio, $CSR$')
    plt.ylabel(r'Depth ($m$)')
    plt.title(self.SoilObj.filename+'-'+self.MotObj.filename)
    [xmin, xmax, ymin, ymax] = plt.axis()
    plt.axis([xmin, xmax, ymax, ymin])
    fig = plt.gcf()

if 'strainratio' in args:
    ratio1 = np.ones(t.shape)*np.array(self.ratio)
    ratio = profilecreator(ratio1)
    plt.figure('StrainRatio')
    plt.plot(ratio,depth2[:-2], syms1)
    # plt.plot(ratio1,t_mid,'or')
    plt.xlabel('Strain Ratio')
    plt.ylabel(r'Depth ($m$)')
    plt.title(self.SoilObj.filename+'-'+self.MotObj.filename)

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# Specific Depth plots

```python
def plothelpers(x, y, domain, plottype, period, figure, dt=True, label=None):
    '''
    x should be frequency or time, not angular frequency
    If dt is True, the response is multiplied by dt.
    '''
    plt.figure(figure.number)
    if domain == 'freq':
        if dt:
            y = np.abs(y) * self.MotObj.dt
        if period:
            x = 1./x
        plt.xlabel(r'Frequency ($Hz$)')
        if plottype == 'loglog':
            plt.loglog(x, y, label=label)
        elif plottype == 'semilogx':
            plt.semilogx(x, y, label=label)
        else:
            plt.plot(x, y, label=label)
    else:
        plt.xlabel('Time (s)')
        if plottype == 'loglog':
            plt.loglog(x, y, label=label)
        elif plottype == 'semilogx':
            plt.semilogx(x, y, label=label)
        else:
            plt.plot(x, y, label=label)
    return curr_fig
```

if acc:
    if acc[2] == 'outcrop':
        mot = 'outcrop'
    else:
        mot = 'within'
    Accel = np.ravel(self.calcAcc(acc[0], domain=acc[1], MotType=mot))
    if acc[1] == 'time':
        x = self.MotObj.time
    else:
        x = self.MotObj.f
    if return_fig:
        plt.figure(return_fig.number)
    else:
        plt.figure(r'Acceleration at z = %s' % str(acc[0]))
    if acc[1] == 'time':
        plt.ylabel(r'Acceleration ($g$)')
```

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else:
    plt.ylabel(r'Acceleration ($\frac{m}{s^2}$ $-s$)'
    %str(acc[0])
    plt.title(self.SoilObj.filename+' - '+self.MotObj.filename)
    fig = plt.gcf()
    label = 'Acc %s m'$%str(acc[0])
    fig = plothelpers(x,Accel,acc[1],plottype,period,fig,label=label)

if vel:
    if vel[2] == 'outcrop':
        mot = 'outcrop'
    else:
        mot = 'within'
    Veloc = np.ravel(self.calcVel(vel[0],domain=vel[1],MotType=mot))
    if vel[1] == 'time':
        x = self.MotObj.time
    else:
        x = self.MotObj.f

if return_fig:
    plt.figure(return_fig.number)
else:
    plt.figure(r'Velocity at z = %s'%str(vel[0]))
    if vel[1] == 'time':
        plt.ylabel(r'Velocity ($\frac{m}{s}$)')
    else:
        plt.ylabel(r'Velocity ($\frac{m}{s}$ $-s$)'
        %str(vel[0])
    plt.title(self.SoilObj.filename+' - '+self.MotObj.filename)
    fig = plt.gcf()
    label = 'Vel %s m'%str(vel[0])
    fig = plothelpers(x,Veloc,vel[1],plottype,period,fig,label=label)

if disp:
    if disp[2] == 'outcrop':
        mot = 'outcrop'
    else:
        mot = 'within'
    Disp = np.ravel(self.calcDisp(disp[0],domain=disp[1],MotType=mot))
    if disp[1] == 'time':
        x = self.MotObj.time
    else:
        x = self.MotObj.f

if return_fig:
    plt.figure(return_fig.number)
else:
    plt.figure(r'Displacement at z = %s'%str(disp[0]))
    if disp[1] == 'time':
        plt.ylabel(r'Displacement ($m$)')
    else:
        plt.ylabel(r'Displacement ($m$ $-s$)'
        %str(disp[0])
    plt.title(self.SoilObj.filename+' - '+self.MotObj.filename)
    fig = plt.gcf()
    label = 'Disp %s m'%str(disp[0])
    fig = plothelpers(x,Disp,disp[1],plottype,period,fig,label=label)
if tf:
    x = self.MotObj.f
    if len(tf) == 1:
        try:
            layer1 = int(tf[0])
            layer2 = 'Bedrock'
        except:
            print("I didn’t understand the transfer function input")
            break
    y = self.TF(layer1,0)
elif len(tf) == 2:
    try:
        layer1 = int(tf[0])
        layer2 = int(tf[1])
        y = self.TF(layer1,layer2)
    except:
        print("Assuming the second value of the TF " +
        "specifies motion type")
        mot = tf[1]
        layer2 = 'Bedrock'
        y = self.TF(layer1,0,MotType=mot)
else:
    layer1 = int(tf[0])
    layer2 = int(tf[1])
    mot = tf[2]
    y = self.TF(layer1,layer2,MotType=mot)
plt.figure('Transfer Function')
plt.ylabel(r'Transfer Function Between Layers %s and %s' % (str(layer1),str(layer2)))
plt.title(self.SoilObj.filename+' - '+self.MotObj.filename)
fig = plt.gcf()
label = 'Layer #%s' % str(layer1)
fig = plothelpers(x,y,'freq',plottype,period,fig,dt=False,
        label=label)

if respspec:
    plt.figure('Response Spectrum')
    plt.ylabel(r'Response Spectrum at a Depth of %s m' % str(respspec[0]))
    plt.title(self.SoilObj.filename+' - '+self.MotObj.filename)
    y,w = self.RespSpec(respspec[0],
        damping=respspec[1],
        MotType=respspec[2],
        w=self.MotObj.w[1:])
    x = self.MotObj.f[1:]  
    y = np.ravel(y)
    fig = plt.gcf()
    label = 'Depth: %s m, Damping: %s' % (str(respspec[0]),str(respspec[1]))
    fig = plothelpers(x,y,'freq',plottype,period,fig,dt=False,
        label=label)

if save == True:
    import matplotlib
    fig=[manager.canvas.figure for manager in 
        matplotlib._pylab_helpers.Gcf.get_all_fig_managers()]
for i, figure in enumerate(fig):
    figure.savefig(self.SoilObj.profile_name[:5] + '_' +
                    self.MotObj.filename[:5] + '-' +
                    figure._label + ext)
return fig

def calcPMNeq(self, *args, **kwargs):
    
    Calculates Neq using the traditional (Seed et al. 1975) Palmgren-Miner
    Implementation.

    # I've assigned m all the way up at line 24
    m = 0.35
    cutoff = 0.3
    m = kwars.get('m', 0.34)
    self.pm_m = m
    cutoff = kwars.get('cutoff', 0.3)
    self.pm_cutoff = cutoff
    self.pm_cutoff = cutoff
    self.pm_Neq = []
    self.pm_Discards = []

    amplitude = kwars.get('VectorSum', False)

    # returns = kwars.get('returns', True)
    amax = self.calcAcc(depths=[0.], MaxOnly=False, MotType='outcrop',
                        domain='time')
    mm = m
    mymax = np.max(np.abs(amax))
    amaxn = amax / mymax
    # Now I need to get the peak values for the positive and negatives parts.
    ind = np.where(np.sign(amaxn[:-1]) != np.sign(amaxn[1:]))[0] # Index of each zero
    crossing
    myN = 0.
    discard = 0.
    Ncyc = 0.5 # I'm assuming the result of the mean crossing is one half cycle, change
    if needed.
    for i, val in enumerate(ind):
        try:
            # I == 0:
            peak = np.max(np.abs(amaxn[0:val]))
            #sign = np.sign(np.mean(amaxn[0:val]))
            else:
                peak = np.max(np.abs(amaxn[ind[i-1]:val]))
                #sign = np.sign(np.mean(amaxn[ind[i-1]:val]))
        except ValueError:
            continue
        if peak < cutoff:
            discard += Ncyc * np.exp(np.log(peak / 0.65) / mm)
            continue
        else:
            myN += Ncyc * np.exp(np.log(peak / 0.65) / mm)
    self.pm_Neq.append(myN) # Just summing here since Ncyc is 0.5
    self.pm_Discards.append(discard)
    if VectorSum:
        # This is a la Liu et al. 2001
        P2P = False
        VS = np.sqrt(self.amax_surf[0] ** 2 + self.amax_surf[1] ** 2)
        VS = VS / np.max(VS)
        alt = False

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if alt:
    import CycleCounting as cc
    CC = cc.Load(VS)
    Peaks, Cycles = CC.calcPeak2Peak(AmpType='ASTM')
    self.PMNeqVS = self.PMFloor(Peaks, Cycles)
self.PMNeqVSdis = 0. # Not a good way to do this using the alt method.
else:
    if P2P:
        import CycleCounting as cc
        CC = cc.Load(VS)
        Peaks, Cycles = CC.calcPeak2Peak(AmpType='ASTM')
        ind1 = np.where(Peaks >= cutoff)
        ind2 = np.where(Peaks < cutoff)
        self.PMNeqVS = np.sum(Cycles[ind1] * np.exp(np.log(
            Peaks[ind1] / 0.65)/m))
        self.PMNeqVSdis = np.sum(Cycles[ind2] * np.exp(np.log(
            Peaks[ind2] / 0.65)/m))
    else:
        # Find the location of the peaks:
        dVS = np.diff(VS)
        ind0 = np.where(np.sign(dVS[1:]) != np.sign(dVS[:-1]))[0] + 1
        Peaks = VS[ind0]
        #import matplotlib.pyplot as plt
        #plt.plot(VS)
        #plt.plot(ind0, Peaks, 'or')
        #plt.show()
        #pdb.set_trace()
        ind1 = np.where(Peaks >= cutoff)
        ind2 = np.where(Peaks < cutoff)
        self.PMNeqVS = np.sum(0.5 * np.exp(np.log(
            Peaks[ind1] / 0.65)/m))
        self.PMNeqVSdis = np.sum(0.5 * np.exp(np.log(
            Peaks[ind2] / 0.65)/m))
        #print(self.PMNeqVS, self.PMNeqVSdis)
    return myN, discard

class DSvariables(object):
    '''
    A simple object to hold data for Darendeli and Stokoe's degradation curve options.
    '''
    def __init__(self,kwvars,SoilObj):
        # Degradation Curve Overrides and Special Values:
        self.sigmeff = kwvars.get('DCO_sigmeff',SoilObj.sigmeff)
        self.PI = kwvars.get('DCO_PI',SoilObj.PI)
        PI = self.PI
        if (SoilObj.OCR is None) or (len(SoilObj.OCR) == 0):
            self.OCR = np.ones(len(PI),dtype=float) #Non-over consolidated as default
        else:
            self.OCR = SoilObj.OCR
        self.soiltype = kwvars.get('DS_soil', SoilObj.DS_soil)
        if np.any(self.soiltype):# Not sure if this is right. Before: if self.soiltype == None:
            pass

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else:
    self.soiltype = 0. * np.ones(len(PI),dtype=float)  # General default
self.N = kwargs.get('DS_N', SoilObj.DS_N)
if np.any(self.N):
    pass
else:
    self.N = 10. * np.ones(len(PI),dtype=float)  # 10 cycles default
self.freq = kwargs.get('DS_freq', SoilObj.DS_freq)
if np.any(self.freq):
    pass
else:
    self.freq = 1. * np.ones(len(PI),dtype=float)  # 1 Hz default

def nextpow2(i):
    '''
    Returns the log-base-2 of the next power of 2 greater than the input value.
    Example:
    >>> y = nextpow2(5)
    >>> print y
    3
    >>> 2**nextpow2(5)
    8
    '''
    n = 2
    while n < i:
        n = n * 2
    return int(round(np.log2(n)))

def calcAriasRatio(motion, dt, **kwargs):
    '''
    Calculates the following:
    \[ \frac{a_{rms}}{\text{max(abs(motion))}} \]
    It should be unitless.
    Although it uses the rms acceleration, any type of motion can be used.
    Positional Arguments:
    motion can be a 2D array of motions (each motion is a row)
    or a 1D array of motions
    dt the time step of the motion(s) in seconds, can be an array
    Keyword Arguments:
    returnall If True, returns Ar and PeakTimeRatio, else, returns only Ar. Default is False.
    duration '5to95' [Default], '5to75', or 'total'. If '5to95' uses from 5% to 95% of the motion squared (Husid?) plot.
    This keyword is passed directly to the calcRmsAccel function.
    returnall = kwargs.get('returnall',False)
    if 1 in motion.shape or len(motion.shape) == 1:
        NumMotions = 1
else:
    NumMotions = np.min(motion.shape)

    if np.isscalar(dt) & NumMotions!=1:
        dt = np.ones([NumMotions], dtype=float) * dt
    if NumMotions == 1:
        if np.isscalar(dt):
            pass
        else:
            pdb.set_trace()
            dt = dt[0]

    Ar = np.zeros([NumMotions,], dtype=float)
    PTR = np.zeros([NumMotions,], dtype=float)

    if returnall:
        if NumMotions == 1:
            RMS, PTR = calcRmsAcc(motion, dt, **kwargs)
            Ar = (RMS / np.max(np.abs(motion))) # Assume data is in rows
        else:
            for i in xrange(NumMotions):
                # pdb.set_trace()
                RMS, PTR[i] = calcRmsAcc(motion[i,:], dt, **kwargs)
            Ar[i] = (RMS / np.max(np.abs(motion[i,:]))) # Assume data is in rows
        return Ar, PTR
    else:
        if NumMotions == 1:
            Ar = (calcRmsAcc(motion, dt, **kwargs) / np.max(np.abs(motion))) # Assume data is in rows
        else:
            for i in xrange(NumMotions):
                pdb.set_trace()
                Ar[i] = (calcRmsAcc(motion[i,:], dt[i], **kwargs)[0] / np.max(np.abs(motion[i,:]))) # Assume data is in rows
            return Ar

def calcRmsAcc(motion, dt, **kwargs):
    '''
    Calculates the rms acceleration.
    
    Positional Arguments:
    motion      a 1D array of a motion, for now.
    dt          the time step of the motion(s) in seconds, a scalar
    
    Keyword Arguments:
    duration    'Sto95' [default] Uses the duration from 5-95% of
                 the area under the motion squared
    'Sto75'
    'total'     Uses the entire time of the input motion
    
    returnall   If True, returns Ar and PeakTimeRatio, else, returns only
                Ar. Default is False.
    
    '''
    returnall = kwargs.get('returnall',False)
motion = np.ravel(motion)
durationtype = kwargs.get('duration','Sto95')
NPTS = len(motion)
if np.isscalar(dt):
    pass
else:
    dt = dt[0]
time = np.linspace(0,(NPTS-1) * dt,NPTS)
asqr = np.cumsum(motion ** 2) * dt
indPeak = np.where(np.abs(motion) == np.max(np.abs(motion)))
if durationtype == 'Sto95':
    int1 = interp1d( asqr, time, kind='linear')
    T = int1(0.95 * asqr[-1]) - int1(0.05 * asqr[-1])
    PeakTimeRatio = (time[indPeak] - int1(0.05 * asqr[-1])) / T
elif durationtype == 'Sto75':
    int1 = interp1d( asqr, time, kind='linear')
    T = int1(0.75 * asqr[-1]) - int1(0.05 * asqr[-1])
    PeakTimeRatio = (time[indPeak] - int1(0.05 * asqr[-1])) / T
else:
    T = time[-1]
    PeakTimeRatio = time[indPeak] / T
if returnall:
    return np.sqrt(asqr[-1] / T), PeakTimeRatio
else:
    return np.sqrt(asqr[-1] / T)
def input_soil_profile(csvprofile):
    '''
    Creates a soil profile object using Lake's format of the csv.
    The new format is simpler and doesn't contain any options for output.
    Positional Argument:
    Name or path of a profile .csv file.
    '''
    layerno = []
layername = []
unit_wt = []
t = []
ko = []
phi = []
Vs = []
PI = []
N160 = []
OCR = []
DS_soil = []
DS_N = []
DS_freq = []
count = 0
filein = open(csvprofile, "rU")
reader = csv.reader(filein)
for line in reader:
    count += 1
    if count == 1:
        Profile_name = str(line[1])
elif count == 2:
    units = int(line[1])
elif count == 3:
    gwt = float(line[1])
elif count == 4:
    loc_mot = int(line[1])
elif count == 5:
    outcrop_mot = int(line[1])
elif count == 6:
    pass
else:
    layerno.append(int(line[0]))
    layername.append(line[1])
    unit_wt.append(float(line[2]))
    try:
        t.append(float(line[4]))
    except (ValueError, IndexError):
        break  # Notice I kick out if the thicknesses run out.
    try:
        PI.append(float(line[5]))
    except (ValueError, IndexError):
        PI.append(0.)  # If there is no number, I assume 0.
    try:
        ko.append(float(line[6]))
    except (ValueError, IndexError):
        ko.append(0.)  # If there is no number, I assume 0.
    try:
        phi.append(float(line[7]))
    except (ValueError, IndexError):
        phi.append(0.)  # If there is no number, I assume 0.
    try:
        N160.append(float(line[8]))
    except (ValueError, IndexError):
        N160.append(0.)  # If there is no number, I assume 0.
    try:
        OCR.append(float(line[9]))
    except (IndexError, ValueError):
        OCR.append(1.)  # If there is no number, I assume 1.
    try:
        DS_soil.append(int(line[10]))
    except (IndexError, ValueError):
        DS_soil.append(0)  # If there is no number, I assume 0, general soil.
    try:
        DS_N.append(int(line[11]))
    except (IndexError, ValueError):
        DS_N.append(10)  # If there is no number, I assume 10.
    try:
        DS_freq.append(float(line[12]))
    except (IndexError, ValueError):
        DS_freq.append(1)  # If there is no number, I assume 1.
filein.close()

# Convert to numpy arrays
layerno = np.array(layerno)
J.3 Shear Modulus Reduction and Damping Curves

The file degrcurv.py returns the shear modulus and damping degradation curves from Darendeli and Stokoe (2001) or Ishibashi and Zhang (1993).
13 sigm = float(sigm)
14
15 if PI == 0.:
16     n = 0.0
17 elif PI <= 15:
18     n = 3.37e-6 * PI ** 1.404
19 elif PI <= 70:
20     n = 7e-7 * PI ** 1.976
21 else:
22     n = 2.7e-5 * PI ** 1.115
23
24 K = 0.5 * (1 + np.tanh(np.log(((0.000102 + n) / gam) ** 0.492)))
25 m = (0.272 * (1 - np.tanh(np.log((0.000556 / gam) ** 0.4)))) *
26     np.exp(-0.0145 * PI ** 1.3))
27 Gratio = K * sigm ** m
28 np.putmask(Gratio, Gratio>1, 1)
29
30 #use np.copyto when updates to numpy 1.7 or use Gratio.clip(max=1)
31 D = 0.1665 * (1 + np.exp(-0.0145 * PI ** 1.3)) * (0.586 * Gratio ** 2. -
32     1.547 * Gratio + 1.)
33
34 return gam, Gratio, D
35
36 def DS_2001(gam=straindef, PI=0., sigm=100., OCR=1., soil=0, N=15., frq=1.):
37     '''
38     Darendeli and Stokoe (2001) shear modulus reduction and damping curves.
39     gam= shear strain (decimal)
40     PI= Plasticity Index
41     sigm = the initial mean effective confining stress (kPa)
42     OCR = the overconsolidation ratio
43     soil = the soil type indicator:
44     0 for general
45     1 for clean sand
46     2 for sands with high fines contents
47     3 for silts
48     4 for clays
49     N = the number of cycles
50     frq = the frequency of loading
51     Dmintype = 1 for 'Default', 0 for 'Green' (Suggest using Green's for now!!!!)
52     !!!Not Implemented !!!
53     The output of the function is:
54     gam = the same input shear strain as a decimal
55     Gratio = G/Gmax = the shear modulus normalized by the small strain
56     shear modulus.
57     D = damping (decimal)
58     '''
59     PI = float(PI)
60     sigm = float(sigm)
61     OCR = float(OCR)
62     N = float(N)
63     frq = float(frq)
64     soil = int(soil)
65     phi1 = np.array([ 3.52E-02, 4.74E-02, 3.34E-02, 4.16E-02, 2.58E-02])
66     phi2 = np.array([ 1.01E-03,-2.34E-03,-5.79E-05, 6.89E-04, 1.95E-03])
67     phi3 = np.array([ 3.246E-01, 2.50E-01, 2.49E-01, 3.21E-01, 9.92E-02])
68     phi4 = np.array([ 3.483E-01, 2.34E-01, 4.82E-01, 2.80E-01, 2.26E-01])
phi5 = np.array([  9.19E-01,  8.95E-01,  8.45E-01,   1.00E+00,   9.75E-01])
phi6 = np.array([   6.88E-01,   8.99E-01,   7.12E-01,   9.58E-01])
phi7 = np.array([  1.29E+00,  1.22E+00,  2.02E+00,  3.03E+00,  5.66E+00])
phi8 = np.array([ -1.00E+00, -1.00E+00, -1.00E+00, -1.00E+00, -1.00E+00])
phi9 = np.array([ -2.89E+00, -1.27E+00, -3.72E+00, -1.89E+00, -1.96E+00])
phi10 = np.array([   2.91E+00,   2.88E+00,   2.33E+00,   2.34E+00,   3.68E+00])
phi11 = np.array([   5.329E+00,   7.67E+00,   7.76E+00,   5.92E+00,   4.66E+00])
phi12 = np.array([   -5.66E+00,   -2.83E+00,   -2.94E+00,   -7.67E-04,   2.23E+00])

# Calculate the reference shear strain:
gamr = ((phi1[soil] + phi2[soil] * PI * OCR ** phi3[soil])
        * (sigm / 101.325) ** phi4[soil]) # percent

gam = gam * 100 # convert to percent

# Calculate assorted variables:
a = phi5[soil]
b = phi11[soil] + phi12[soil] * np.log(N)
C1 = -1.1143 * a ** 2 + 1.8618 * a + 0.2523
C2 = 0.0805 * a ** 2 - 0.0710 * a - 0.0096
C3 = -0.0005 * a ** 2 + 0.0002 * a + 0.0003

# Calculate G/Gmax
Gratio = 1. / (1. + (gam / gamr) ** a)

Dmasinga1 = 100 / np.pi * (4 * (gam - gamr * np.log((gam + gamr)
                               / gamr)) / (gam ** 2 / (gam + gamr)) - 2 )
Dmasing = C1 * Dmasinga1 + C2 * Dmasinga1 ** 2 + C3 * Dmasinga1 ** 3
Dmin = ((phi6[soil] + phi7[soil] * PI * OCR ** phi8[soil])
        * (sigm / 101.3) ** phi9[soil] * (1 + phi10[soil] * np.log(frq)))

D = (b * (Gratio ** 0.1) * Dmasing + Dmin) / 100. #Return damping to a decimal

return gam / 100, Gratio, D

if __name__ == '__main__':
    import matplotlib.pyplot as plt
    gam = np.logspace(-4, 0, 100) /100. # into a decimal
    G_IZ, D_IZ = IZ_1993(gam=gam, PI=0, sigm=25)
    G_DS, D_DS = DS_2001(gam=gam, PI=0, sigm=25, OCR=1)
    fig, (axG, axD) = plt.subplots(nrows=2, ncols=1)
    axG.plot(gam * 100, G_IZ, 'b')
    axG.plot(gam * 100, G_DS, 'r')
    axD.plot(gam * 100, D_IZ*100, 'b')
    axD.plot(gam * 100, D_DS*100, 'r')
    axD.set_xscale('log')
    plt.show()
J.4 Batch Site Response Analyses

The file Run_Master.py runs site response analyses for either earthquake dataset and all combinations of motions and profiles.

```python
import os
import numpy as np
import tables as pt
try:
    import pdb as pdb
except:
    import pdb
import sys
sys.path.append('/media/Storage/Documents/Python/Modules')
import EquivLin as el

from scipy.interpolate import interp1d

m = np.linspace(0.2, 0.4, 11)

fullprofilenames = {
    'Profile000': 'Balboa Boulevard-Northridge Earthquake (1994)',
    'Profile001': 'Malden Street-Northridge Earthquake (1994)',
    'Profile002': 'Wynne Avenue-Northridge Earthquake (1994)',
    'Profile003': 'MBARI NO:3 EB-1-Loma Prieta Earthquake (1989)',
    'Profile004': 'MBARI NO:3 EB-5-Loma Prieta Earthquake (1989)',
    'Profile005': 'MBARI NO:3 UC-B-10-Loma Prieta Earthquake (1989)',
    'Profile006': 'Treasure Island-Loma Prieta Earthquake (1989)',
    'Profile007': 'SFOBB-1-Loma Prieta Earthquake (1989)',
    'Profile008': 'SFOBB-2-Loma Prieta Earthquake (1989)',
    'Profile009': 'POD7-2-Loma Prieta Earthquake (1989)',
    'Profile010': 'POD7-3-Loma Prieta Earthquake (1989)',
    'Profile011': 'Woodward Marine UC-B4-Loma Prieta Earthquake (1989)',
    'Profile012': 'Moss Landing UC-B1-Loma Prieta Earthquake (1989)',
    'Profile013': 'Moss Landing UC-B2-Loma Prieta Earthquake (1989)',
    'Profile014': 'Marine Lab. B1-Loma Prieta Earthquake (1989)',
    'Profile015': 'Marine Lab. B2-Loma Prieta Earthquake (1989)',
    'Profile016': 'Miller Farm CMF 3-Loma Prieta Earthquake (1989)',
    'Profile017': 'Miller Farm CMF 5-Loma Prieta Earthquake (1989)',
    'Profile018': 'Miller Farm CMF 8-Loma Prieta Earthquake (1989)',
    'Profile019': 'Miller Farm CMF 10-Loma Prieta Earthquake (1989)',
    'Profile020': 'Richmond City Hall-Loma Prieta Earthquake (1989)',
    'Profile021': 'Port of Richmond POR-2-Loma Prieta Earthquake (1989)',
    'Profile022': 'Port of Richmond POR-3-Loma Prieta Earthquake (1989)',
    'Profile023': 'Port of Richmond POR-4-Loma Prieta Earthquake (1989)',
    'Profile024': 'Miller Farm-Loma Prieta Earthquake (1989)',
    'Profile025': 'Farris Farm-Loma Prieta Earthquake (1989)',
    'Profile026': 'Wildlife Site-Elmore Ranch (1987)',
    'Profile027': 'Wildlife Site-Superstition Hills (1987)',
    'Profile028': 'Radio Tower B1-Superstition Hills (1987)',
}
```

Profile029': 'Radio Tower B2-Superstition Hills (1987)',
'Profile030': 'McKim Ranch A-Superstition Hills (1987)',
'Profile031': 'Kornbloom-Superstition Hills (1987)',
'Profile032': 'River Park A & C-Superstition Hills (1987)',
'Profile033': 'Heber Road A1-Superstition Hills (1987)',
'Profile034': 'Heber Road A2-Superstition Hills (1987)',
'Profile035': 'Heber Road A3-Superstition Hills (1987)',
'Profile036': 'Kornbloom-Westmorland (1981)',
'Profile037': 'McKim Ranch-Westmorland (1981)',
'Profile038': 'Radio Tower B1-Westmorland (1981)',
'Profile039': 'Radio Tower B2-Westmorland (1981)',
'Profile040': 'River Park A & C-Westmorland (1981)',
'Profile041': 'Wildlife-Westmorland (1981)',
'Profile042': 'Heber Road A1-Imperial Valley (1979)',
'Profile043': 'Heber Road A2-Imperial Valley (1979)',
'Profile044': 'Heber Road A3-Imperial Valley (1979)',
'Profile045': 'Kornbloom-Imperial Valley (1979)',
'Profile046': 'Radio Tower B1-Imperial Valley (1979)',
'Profile047': 'Radio Tower B2-Imperial Valley (1979)',
'Profile048': 'River Park A & C-Imperial Valley (1979)',
'Profile049': 'Wildlife Site-Imperial Valley (1979)'}

class WUSComb(pt.IsDescription):
    #Motion Name
    RecSeq = pt.Int16Col(pos=1)
    Motion0 = pt.StringCol(itemsize=32, pos=2)
    Motion1 = pt.StringCol(itemsize=32, pos=3)

    #Profile Name
    Profile = pt.StringCol(itemsize=32, pos=4)
    profiletype = pt.Int32Col(pos=5)

    # Calc'd Info
    DissEn0 = pt.Float32Col(pos=6)
    DissEn1 = pt.Float32Col(pos=7)
    N_EQ0 = pt.Float32Col(pos=8)
    N_EQ1 = pt.Float32Col(pos=9)
    TauAvg0 = pt.Float32Col(pos=10)
    TauAvg1 = pt.Float32Col(pos=11)
    DE_comb = pt.Float32Col(pos=12)
    Neq_comb = pt.Float32Col(pos=13)
    RepErr0 = pt.StringCol(itemsize=1, pos=16)
    iters_0 = pt.Int32Col(pos=17)
    maxerror_0 = pt.Float32Col(pos=18)
    RepErr1 = pt.StringCol(itemsize=1, pos=19)
    iters_1 = pt.Int32Col(pos=20)
    maxerror_1 = pt.Float32Col(pos=21)
    #Degrad = pt.Float32Col(pos=21)

    # Profile Info
    Depth = pt.Float32Col(pos=22)
    Sigv = pt.Float32Col(pos=23)
    Sigveff = pt.Float32Col(pos=24)
    Sigm eff = pt.Float32Col(pos=25)
    Mod = pt.Float32Col(pos=26)
    Damp = pt.Float32Col(pos=27)
# Other calc’d info
rd_0 = pt.Float32Col(pos=72)
rd_1 = pt.Float32Col(pos=73)
Ar_0 = pt.Float32Col(pos=74)
Ar_1 = pt.Float32Col(pos=75)
Artype = pt.StringCol(itemsizes=8, pos=75)
# Ar_ratio_0 = pt.Float32Col(pos=76)
# Ar_ratio_1 = pt.Float32Col(pos=77)
# DE_ratio_0 = pt.Float32Col(pos=78)
# DE_ratio_1 = pt.Float32Col(pos=79)
# Neq_ratio_0 = pt.Float32Col(pos=80)
# Neq_ratio_1 = pt.Float32Col(pos=81)
# PeakTimeRatio_0 = pt.Float32Col(pos=82)
# PeakTimeRatio_1 = pt.Float32Col(pos=83)
MaxError = pt.Float32Col(pos=76)
Discard0 = pt.Float32Col(pos=77)
Discard1 = pt.Float32Col(pos=77)
m = pt.Float32Col(pos=77)
cutoff = pt.Float32Col(pos=77)
PMNeq0 = pt.Float32Col(pos=77)
PMNeq1 = pt.Float32Col(pos=77)
PMNeqVS = pt.Float32Col(pos=77)
PMNeqVSdis = pt.Float32Col(pos=77)

class WUSSingle(pt.IsDescription):
    # Motion Name
    RecSeq = pt.Int16Col(pos=1)
    Motion = pt.StringCol(itemsizes=32, pos=2)

    # Profile Name
    Profile = pt.StringCol(itemsizes=32, pos=3)
    profiletype = pt.Int32Col(pos=4)

    # Calc’d Info
    DissEn = pt.Float32Col(pos=5)
    N_EQ = pt.Float32Col(pos=6)
    TauAvg = pt.Float32Col(pos=7)
    RepErr = pt.StringCol(itemsizes=1, pos=9)
    iters = pt.Int32Col(pos=10)
    maxerror = pt.Float32Col(pos=11)

    # Profile Info
    Depth = pt.Float32Col(pos=12)
    Sigv = pt.Float32Col(pos=13)
    Sigveff = pt.Float32Col(pos=14)
    Sigmaeff = pt.Float32Col(pos=15)
    Mod = pt.Float32Col(pos=16)
    Damp = pt.Float32Col(pos=17)
    Vs = pt.Float32Col(pos=18)
    UnitWt = pt.Float32Col(pos=19)
    LayerName = pt.StringCol(itemsizes=32, pos=20)
    t = pt.Float32Col(pos=21)
    PI = pt.Float32Col(pos=22)
    z_bed = pt.Float32Col(pos=23)
Vsbed = pt.Float32Col(pos=24)
V30 = pt.Float32Col(pos=25)
Vs12 = pt.Float32Col(pos=26)
NEHRP = pt.StringCol(itemsize=1,pos=27)
Vs30_pref = pt.Float32Col(pos=28)

# EQ Info
EpicD = pt.Float32Col(pos=29)
Eq_Mag = pt.Float32Col(pos=30)
Mag_Type = pt.StringCol(itemsize=2,pos=31)
Hypd = pt.Float32Col(pos=32)
J_BD = pt.Float32Col(pos=33)
RMSD = pt.Float32Col(pos=34)
CLSTD = pt.Float32Col(pos=35)

# EQEvent = pt.Int32Col(pos=36)
PAG = pt.Float32Col(pos=37)
PGV = pt.Float32Col(pos=38)
PGD = pt.Float32Col(pos=39)
ThetaD = pt.Float32Col(pos=40)
X = pt.Float32Col(pos=41)
Y = pt.Float32Col(pos=42)
Rake = pt.Float32Col(pos=43)
Dip = pt.Float32Col(pos=44)

# More motion info
T_d01 = pt.Float32Col(pos=47)
T_d05 = pt.Float32Col(pos=48)
T_tb95 = pt.Float32Col(pos=49)
T_tb75 = pt.Float32Col(pos=50)
I_a = pt.Float32Col(pos=51)

amax_surf = pt.Float32Col(pos=52)

# Other calc’d info
rd = pt.Float32Col(pos=53)
Ar = pt.Float32Col(pos=54)
Artype = pt.StringCol(itemsize=8, pos=54)
MaxError = pt.Float32Col(pos=55)
Discard = pt.Float32Col(pos=56)
m = pt.Float32Col(pos=56)
cutoff = pt.Float32Col(pos=56)
PMNeq = pt.Float32Col(pos=56)

class CEUSComb(pt.IsDescription):
    # Motion Name
    RecSeq = pt.Int32Col(pos=1)
    Motion0 = pt.StringCol(itemsize=32,pos=2)
    Motion1 = pt.StringCol(itemsize=32,pos=3)

    # Profile Name
    Profile = pt.StringCol(itemsize=32,pos=4)
    profiletype = pt.Int32Col(pos=5)

    # Calc’d Info
DissEn0 = pt.Float32Col(pos=6)
N_EQ0 = pt.Float32Col(pos=7)
TauAvg0 = pt.Float32Col(pos=8)
DissEn1 = pt.Float32Col(pos=9)
N_EQ1 = pt.Float32Col(pos=10)
TauAvg1 = pt.Float32Col(pos=11)
RepErr0 = pt.StringCol(itemsize=1, pos=12)
iters_0 = pt.Int32Col(pos=13)
maxerror_0 = pt.Float32Col(pos=14)
RepErr1 = pt.StringCol(itemsize=1, pos=15)
iters_1 = pt.Int32Col(pos=16)
maxerror_1 = pt.Float32Col(pos=17)
DE_comb = pt.Float32Col(pos=18)
Neq_comb = pt.Float32Col(pos=19)

# Profile Info
Depth = pt.Float32Col(pos=22)
Sigv = pt.Float32Col(pos=23)
Sigveff = pt.Float32Col(pos=24)
Sigmeff = pt.Float32Col(pos=25)
Mod = pt.Float32Col(pos=26)
Damp = pt.Float32Col(pos=27)
Mod1 = pt.Float32Col(pos=26)
Damp1 = pt.Float32Col(pos=27)
Vs = pt.Float32Col(pos=28)
UnitWt = pt.Float32Col(pos=29)
LayerName = pt.StringCol(itemsize=32, pos=30)
t = pt.Float32Col(pos=31)
PI = pt.Float32Col(pos=32)
z_bed = pt.Float32Col(pos=33)
Vsbed = pt.Float32Col(pos=34)
Vs30 = pt.Float32Col(pos=35)
Vs12 = pt.Float32Col(pos=36)
sa_vs30 = pt.Float32Col(pos=37)
Vs30 pref = pt.Float32Col(pos=38)

# EQ Info
Eq_Mag = pt.Float32Col(pos=39)
CLSTD = pt.Float32Col(pos=40)
EQEvent = pt.StringCol(itemsize=64, pos=41)
PGA = pt.Float32Col(pos=42)
PGV = pt.Float32Col(pos=43)
PGD = pt.Float32Col(pos=44)
PGA_2 = pt.Float32Col(pos=45)
PGV_2 = pt.Float32Col(pos=46)
PGD_2 = pt.Float32Col(pos=47)
T_d01_0 = pt.Float32Col(pos=59)
T_d01_1 = pt.Float32Col(pos=60)
T_d05_0 = pt.Float32Col(pos=61)
T_d05_1 = pt.Float32Col(pos=62)
#_a_rms01_0 = pt.Float32Col(pos=63)
#_a_rms01_1 = pt.Float32Col(pos=64)
T_tb95_0 = pt.Float32Col(pos=65)
T_tb95_1 = pt.Float32Col(pos=66)
T_tb75_0 = pt.Float32Col(pos=63)
T_tb75_1 = pt.Float32Col(pos=64)
I_a_0 = pt.Float32Col(pos=67)
I_a_1 = pt.Float32Col(pos=68)
amax_surf_0 = pt.Float32Col(pos=60)
amax_surf_1 = pt.Float32Col(pos=61)
amax_surf_max = pt.Float32Col(pos=62)

# Other calc'd info
rd_0 = pt.Float32Col(pos=63)
rd_1 = pt.Float32Col(pos=64)
Ar_0 = pt.Float32Col(pos=65)
Ar_1 = pt.Float32Col(pos=66)
Artype = pt.StringCol(itemsize=8, pos=66)
Bin = pt.StringCol(itemsize=16, pos=67)
MaxError = pt.Float32Col(pos=68)
Discard0 = pt.Float32Col(pos=77)
Discard1 = pt.Float32Col(pos=77)
m = pt.Float32Col(pos=77)
cutoff = pt.Float32Col(pos=77)
PMNeq0 = pt.Float32Col(pos=77)
PMNeq1 = pt.Float32Col(pos=77)
PMNeqVS = pt.Float32Col(pos=77)
PMNeqVSdis = pt.Float32Col(pos=77)

class CEUSSingle(pt.IsDescription):
    # Motion Name
    RecSeq = pt.Int32Col(pos=1)
    Motion = pt.StringCol(itemsize=32, pos=2)
    # Profile Name
    Profile = pt.StringCol(itemsize=32, pos=3)
    profiletype = pt.Int32Col(pos=4)
    # Calcd Info
    DissEn = pt.Float32Col(pos=5)
    N_EQ = pt.Float32Col(pos=6)
    TauAvg = pt.Float32Col(pos=7)
    RepErr = pt.StringCol(itemsize=1, pos=8)
    iters = pt.Int32Col(pos=9)
    maxerror = pt.Float32Col(pos=10)
    # Profile Info
    Depth = pt.Float32Col(pos=12)
    Sigy = pt.Float32Col(pos=13)
    Sigyeff = pt.Float32Col(pos=14)
    Simgeff = pt.Float32Col(pos=15)
    Mod = pt.Float32Col(pos=16)
    Damp = pt.Float32Col(pos=17)
    Vs = pt.Float32Col(pos=18)
    UnitWt = pt.Float32Col(pos=19)
LayerName = pt.StringCol(itemsize=32, pos=20)

t = pt.Float32Col(pos=21)

PI = pt.Float32Col(pos=22)

z_bed = pt.Float32Col(pos=23)

Vsbed = pt.Float32Col(pos=23)

Vs30 = pt.Float32Col(pos=24)

Vs12 = pt.Float32Col(pos=25)

sa_vs30 = pt.Float32Col(pos=26)

Vs30_pref = pt.Float32Col(pos=27)

# EQ Info

Eq_Mag = pt.Float32Col(pos=28)

CLSTD = pt.Float32Col(pos=29)

EQEvent = pt.StringCol(itemsize=64, pos=30)

PGA = pt.Float32Col(pos=31)

PGV = pt.Float32Col(pos=32)

PGD = pt.Float32Col(pos=33)

# Other calc'd info

rd = pt.Float32Col(pos=40)

Ar = pt.Float32Col(pos=41)

Artype = pt.StringCol(itemsize=8, pos=41)

Bin = pt.StringCol(itemsize=16, pos=42)

MaxError = pt.Float32Col(pos=43)

Discard = pt.Float32Col(pos=44)

m = pt.Float32Col(pos=44)

cutoff = pt.Float32Col(pos=44)

PMNeq = pt.Float32Col(pos=44)

def TokimatsuSeedDirect(gam,Gratio,damping,Gmax, tau_avg, **kwargs):

    returnError = kwargs.get('returnError', False)

    G_ = np.zeros(Gratio.shape[0],dtype=float)

    D_ = np.zeros(Gratio.shape[0],dtype=float)

    gam_ = np.zeros(Gratio.shape[0],dtype=float)

    ErrorList = []

    # Inputs:

    gam An array of shear strains (decimal) of length n

    Gratio An array (matrix) of shear modulus degradation curves of

    shape m X n where m is the number of layers

    damping An array of damping degradation curves, also m X n

    Gmax The small strain shear modulus

    tau_avg The average shear stress

    # Outputs:

    Three arrays: G, D, and gamma each of length m.

    # Code:

    returnError = kw_args.get('returnError', False)

    G_ = np.zeros(Gratio.shape[0],dtype=float)

    D_ = np.zeros(Gratio.shape[0],dtype=float)

    gam_ = np.zeros(Gratio.shape[0],dtype=float)

    ErrorList = []
if np.isscalar(Gmax):
    Gmax = [Gmax]
if np.isscalar(tau_avg):
    tau_avg = [tau_avg]
for i in xrange(len(Gmax)):
    #if i == 208: pdb.set_trace()
    Gratiocurv = interp1d(np.log10(gam_Grat), np.log10(gam),
        kind='linear')
    G_1[i] = Gmax[i] * Gratiocurv(np.log10(newgam))
    D_1[i] = Dcurv(np.log10(newgam))
    gam_1[i] = newgam
    if returnError:
        if len(G_) == 1:
            return G_[0], D_[0], gam_[0], ErrorList
        else:
            return G_, D_, gam_, ErrorList
    else:
        if len(G_) == 1:
            return G_[0], D_[0], gam_[0]
        else:
            return G_, D_, gam_
tau_avg = [tau_avg]

Gmax = [Gmax]

G_ = np.zeros([len(tau_avg)], dtype=float)

D_ = np.zeros([len(tau_avg)], dtype=float)

gam_ = np.zeros([len(tau_avg)], dtype=float)

for j in xrange(len(tau_avg)):
    if len(tau_avg) == 1:
        Damp = np.ravel(damping)
        Grat = np.ravel(Gratio)
    else:
        Damp = np.ravel(damping[j,:])
        Grat = np.ravel(Gratio[j,:])
    gamma = gam[0]
    gamma0 = gamma 0.0000001

    Gratiocurv = interp1d(np.log10(gam), Grat,
                          kind='linear')
    Dcurv = interp1d(np.log10(gam), Damp,
                     kind='linear')
    thiserror = 1
    count = 0
    try:
        while thiserror > error:
            count += 1
            if count > 50:
                print('Layer %s did not converge!'%str(j))
                print('Error = {:.5f}'.format(thiserror))
                break
            G = Gmax[j] * Gratiocurv(np.log10(gamma))
            gamma = tau_avg[j] / G
            thiserror = abs(gamma - gamma0) / gamma0
            gamma0 = gamma
            D = Dcurv(np.log10(gamma))
            gam__ = gamma
        except ValueError:
            if gamma > gam[-1]:
                G = Gmax[j] * Grat[-1]
                D = Damp[-1]
                gam__ = gam[-1]
            else:
                G = Gmax[j] * Grat[0]
                D = Damp[0]
                gam__ = gam[0]
            print('Interp error!')

    G_[j] = G
    D_[j] = D
    gam_[j] = gam__
    if len(tau_avg) == 1:
        return G_[0], D_[0], gam_[0]
    else:
        return G_, D_, gam_

class Profiles(object):
    def __init__(self, **kwargs):
        self.CEUS = kwargs.get('CEUS', False)
        self.CEUS = kwargs.get('CEUS', False)
        if os.name == 'posix':
self.myfile = pt.open_file(
    u'/media/Storage/Documents/00-VtResearch/Energy-based/' +
    u'Soil Profiles/SoilProfilesSimp7.h5')
else:
    self.myfile = pt.open_file(
    u'../../Documents/00-VtResearch/Energy-based/' +
    u'Soil Profiles/SoilProfilesSimp7.h5')
if self.CEUS:
    self.mywhere = '/CetinProfiles_CEUS/'
else:
    self.mywhere = '/CetinProfiles/'
self.groups = dict(
    # Soil profile group categories
groupA = ['Profile000','Profile001','Profile002'],
groupB = ['Profile003','Profile004','Profile005',
    'Profile011', 'Profile012', 'Profile013',
    'Profile014', 'Profile015', 'Profile016',
    'Profile017', 'Profile018', 'Profile019',
    'Profile024', 'Profile025'],
groupC = ['Profile006'],
groupD = ['Profile007','Profile008','Profile009', 'Profile010'],
groupE = ['Profile020', 'Profile021', 'Profile022', 'Profile023'],
groupF = ['Profile026', 'Profile027'],
groupG = ['Profile028', 'Profile029', 'Profile030',
    'Profile031', 'Profile032', 'Profile033',
    'Profile034', 'Profile035', 'Profile036',
    'Profile037', 'Profile038', 'Profile039',
    'Profile040', 'Profile041', 'Profile045',
    'Profile046', 'Profile047', 'Profile048',
    'Profile049'],
groupH = ['Profile042', 'Profile043', 'Profile044'])

self.i = -1
self.profilelist = self.myfile.list_nodes(self.mywhere)
self.grouplist = [self.getGroup(prof.title) for prof
    in self.profilelist]
def close(self):
    self.myfile.close()
def __iter__(self):
    return self
def next(self):
    self.i += 1
    if self.i < len(self.profilelist):
        self.profile = self.profilelist[self.i]
        self.group = self.grouplist[self.i]
        sys.stdout.write(' {} --- {} ---'.format(self.profile.title,
            strftime("%H:%M:%S", gmtime())))
        sys.stdout.flush()
        return self.profile
    else:
self.i = -1
raise StopIteration()

def status(self, prof):
    sys.stdout.write(' {} --- {} ---'.format(prof.title,
        strftime("%H:%M:%S", gmtime())))
sys.stdout.flush()

def getGroup(self, name):
    i = -1
    for values in self.groups.itervalues():
        i += 1
        if name in values:
            return i

class Motions(object):
    def __init__(self, **kwargs):
        self.CEUS = kwargs.get('CEUS', False)
        self.combined = kwargs.get('combinecomps', False)
        if os.name == 'posix':
            if kwargs.get('PM', False):
                deffile = ('/media/Storage/Documents/00-VtResearch/EQ_Motions/' +
                    'NGA_Motions/WEST/RockAll-paired.h5')
                SummaryFile = ('/media/Storage/Documents/00-VtResearch/' +
                    'EQ_Motions/NGA_Motions/WEST/NGA_Motions_Summary.h5')
            else:
                if self.CEUS:
                    deffile = ('/media/Storage/Documents/00-VtResearch/EQ_Motions/' +
                        'McGuire/CEUS/Rock-paired.h5')
                    SummaryFile = ('/media/Storage/Documents/00-VtResearch/' +
                        'EQ_Motions/McGuire/CEUS/Rock_Motions_Summary.h5')
                else:
                    deffile = ('/media/Storage/Documents/00-VtResearch/EQ_Motions/' +
                        'NGA_Motions/WEST/Rock650-paired.h5')
                    SummaryFile = ('/media/Storage/Documents/00-VtResearch/' +
                        'EQ_Motions/NGA_Motions/WEST/NGA_Motions_Summary.h5')
        else:
            if kwargs.get('PM', False):
                deffile = ('/../../../Documents/00-VtResearch/EQ_Motions/' +
                    'NGA_Motions/WEST/RockAll-paired.h5')
                SummaryFile = ('/../../../Documents/00-VtResearch/' +
                    'EQ_Motions/NGA_Motions/WEST/NGA_Motions_Summary.h5')
            else:
                if self.CEUS:
                    deffile = ('/../../../Documents/00-VtResearch/EQ_Motions/' +
                        'McGuire/CEUS/Rock-paired.h5')
                    SummaryFile = ('/../../../Documents/00-VtResearch/' +
                        'EQ_Motions/McGuire/CEUS/Rock_Motions_Summary.h5')
                else:
                    deffile = ('/../../../Documents/00-VtResearch/EQ_Motions/' +
                        'NGA_Motions/WEST/Rock650-paired.h5')
                    SummaryFile = ('/../../../Documents/00-VtResearch/' +
                        'EQ_Motions/NGA_Motions/WEST/NGA_Motions_Summary.h5')
        self.motfile = pt.open_file(kwargs.get('file', deffile), 'r')
self.sumfile = pt.open_file(kwargs.get('sumfile', SummaryFile), 'r')
self.sumtable = self.sumfile.root.SummaryTable
self.count = 0

def close(self):
    self.motfile.close()
    self.sumfile.close()

def __call__(self):
    for mot in self.motfile.list_nodes('/Motions/ '):
        self.count += 1
        self.RecNum = int(mot.col('RecSeqNum') [0])
        self.motstats = self.getMotStats(self.RecNum)
        print('
'.format(self.count, mot.title,
        strftime("%Y-%m-%d %H:%M:%S", gmt ime())))
        yield mot

def getMotStats(self, RecNum):
    rownum = self.sumtable.get_where_list('RecSeqNum == RecNum') [0]
    return self.sumtable[rownum]

class Dynamics(object):
    def __init__(self, mot, Combined, **kwargs):
        self.MakeProfs = kwargs.get('ProfMaker', False)
        self.mot = mot
        self.Combined = Combined
        self.modtype = kwargs.get('modtype', 'FreqInd')
        self.degradcurves = kwargs.get('DC', 'IZ')
        self.iters = kwargs.get('iters', 20)
        self.error = kwargs.get('error', 0.02)
        self.verbose = kwargs.get('verbose', False)
        self.m = kwargs.get('m', 0.34)
        self.cutoff = kwargs.get('cutoff', 0.3)
        self.VectorSum = False
        self.Mot = [

        for row in mot.iterrows():
            motion = row['MotionData']
            NPTS = int(row['NPTS'])
            dt = float(row['TimeStep'])
            if max(motion.shape) != NPTS :
                print('NPTS discrepancy!', max(motion.shape), NPTS)
                NPTS = max(motion.shape)
            NFFT = 2 ** el.nextpow2(NPTS)
            f = np.linspace(0, 1/dt/2, NFFT//2+1)
            w = f[:NFFT/2+1] * 2 * np.pi
            fa = np.fft.rfft(motion * 9.81, NFFT)

            self.Mot = []
            for row in mot.iterrows():
                motion = row['MotionData']
                NPTS = int(row['NPTS'])
                dt = float(row['TimeStep'])
                if max(motion.shape) != NPTS :
                    print('NPTS discrepancy!', max(motion.shape), NPTS)
                    NPTS = max(motion.shape)
                NFFT = 2 ** el.nextpow2(NPTS)
                f = np.linspace(0, 1/dt/2, NFFT//2+1)
                w = f[:NFFT/2+1] * 2 * np.pi
                fa = np.fft.rfft(motion * 9.81, NFFT)
self.Mot.append(
    el.GroundMotion(
        name=str(self.mot.title),
        g = 9.81,
        motion=motion,
        NFFT = NFFT,
        FA = fa,
        f = f,
        w = w,
        NPTS = NPTS,
        dt = dt,
    )
)

def calcResults(self):
    '''
    Performs the equivalent linear site response analysis and other calcs
    '''
    self.Results = []
    for MotObj in self.Mot:
        self.Results.append(
            el.Dynamics(
                self.profile,
                MotObj,
                modtype=self.modtype,
                verbose=self.verbose,
                DegradCurves=self.degradcurves,
                iters = self.iters,
                Error = self.error,
                start_iters=True,
                run_all=True
            )
        )
        if self.Combined and not self.comb_alt:
            self.calcCombined()

    self.amax_surf = []
    self.Neq = []
    self.tau_avg = []
    self.ratio = []
    self.DE = []
    self.Vs30,H = self.profile.calcVs30(returns=True)
    self.Vs12 = self.profile.calcAvgVs(12.)
    self.Sa = []
    for result in self.Results:
        self.amax_surf.append(result.calcAcc(0.0, MaxOnly=False,
                                               domain='time', MotType='within'))
        result.calc_r_d()
        N_eq, tau_avg, ratio, DE = result.calcNeq(set_ratio=0.65,
                                                  returns=True)
        self.Neq.append(N_eq)
        self.tau_avg.append(tau_avg)
        self.ratio.append(ratio)
        self.DE.append(np.maximum(DE, 0))
        # In some weird cases, DE can be slightly negative.
        # I only saw this occur for one motion, at depth (>100m).
        # I think it occurred because the motion (CAD340) had a strong
        # sinusoidal pattern.
self.Sa.append(result.RespSpec(0.,
    w=[2 * np.pi * self.Vs30 / (4 * H)]))
if self.Combined:
    #if self.comb_alt:
    tau_avg = np.sqrt(self.tau_avg[0] * self.tau_avg[1]) # Geometric mean
    # G, D, gam = TokinatsuSeedDirect(# I have to get the D and G corresponding to
    # this tau_avg
    G, D, gam = DobryIter(# I have to get the D and G corresponding to this tau_avg
    self.Results[0].gam,
        self.Results[0].Gratio,
        self.Results[0].damping,
        self.Results[0].Gmax[:-1],
        tau_avg,
        #returnError=False
    )
    self.DE1 = 2 * np.pi * D * tau_avg ** 2 / G
#else:
    #self.DE1 = (2 * np.pi * self.Results[0].D[:-1] *
    #self.tau_avg[0] * self.tau_avg[1]) / self.Results[0].G[:-1])# Geometric mean
    self.Neq_comb = (self.DE[0] + self.DE[1]) / self.DE1
self.calcDurations()
self.calcPMNeq()
def calcCombined(self):
    '''
    A few calcs for when I want the results from both components of motion.
    '''
    # G original is the non-softened shear modulus
    Gorig = self.profile.Vs ** 2 * self.profile.unit_wt / 9.81
    # Find out which profile is softer and keep it.
    if (np.average(self.Results[0].G[:-1], weights=self.profile.t) >
        np.average(self.Results[1].G[:-1], weights=self.profile.t)):
        G = self.Results[1].G
        D = self.Results[1].D
        Gratio = G / Gorig
    else:
        G = self.Results[0].G
        D = self.Results[0].D
        Gratio = G / Gorig
    # G = np.min((self.Results[0].G, self.Results[1].G), axis=0)
    D = np.max((self.Results[0].D, self.Results[1].D), axis=0)
    #print(np.all(self.Results[0].G>=self.Results[1].G))
    if np.all(self.Results[0].G>=self.Results[1].G) == False:
        #print(self.Results[0].G>=self.Results[1].G)
        #pdb.set_trace()
    #print(np.all(self.Results[1].G>=self.Results[0].G))
    Gratio = G / Gorig
    Vs2 = (G * 9.81 / self.profile.unit_wt) ** 0.5
    # Run both motions again using the softer profile, for one iteration
    for i in range(2):
        self.Results[i] = el.Dynamics(
            self.profile,
            self.Mot[i],
            modtype=self.modtype,
            verbose=self.verbose,
DegradCurves=self.degradcurves,
    iters = 0,
    InitDamping=D[:-1],
    BaseDamping=D[-1],
    InitGratio=Gratio[:-1],
    BaseGratio=Gratio[-1],
    Error = 100.,
    start_iters=True,
    run_all=True)

def calcDurations(self):
    '''
    These are the durations of the calculated surface motions.
    '''
    self.Tb_01 = []
    self.Tb_05 = []
    self.Ttb_75 = []
    self.Ttb_95 = []
    self.I_a = []
    self.Ar = []
    self.Artype= '5to75'
    for i,amax in enumerate(self.amax_surf):
        dt = self.Mot[i].dt
        #Bracketed duration
        time = np.arange(len(amax)) * dt
        ind1 = np.where(np.abs(amax) > 0.01)  # Notice this!!! 0.01g’s
        time1 = time[ind1]
        try:
            self.Tb_01.append(time1[-1] - time1[0])
            #rms acceleration in m/s/s
            #a_rms01 = np.sqrt(1/T_d01 *
            #np.trapz((motion[ind1[0][0]:ind1[0][-1]] * 9.81)
            #** 2,dx=dt))
        except IndexError:
            self.Tb_01.append( np.nan)
            #a_rms01 = np.nan
        ind2 = np.where(np.abs(amax) > 0.05)
        time2 = time[ind2]
        try:
            self.Tb_05.append(time2[-1] - time2[0])
            #rms acceleration in m/s/s
            #a_rms05 = np.sqrt(1/T_d05 *
            #np.trapz((motion[ind2[0][0]:ind2[0][-1]] * 9.81)
            #** 2,dx=dt))
        except IndexError:
            self.Tb_05.append( np.nan)
            #a_rms05 = np.nan
        # Another Duration (Significant)
        acc2 = (amax * 9.81) ** 2
        cumacc2 = np.cumsum(acc2)
        ind3 = np.where((cumacc2 > 0.05 * cumacc2[-1]) &
            (cumacc2 < 0.95 * cumacc2[-1]))
        time3 = time[ind3]
        self.Ttb_95.append(time3[-1] - time3[0])
ind4 = np.where((cumacc2 > 0.05 * cumacc2[-1]) &
               (cumacc2 < 0.75 * cumacc2[-1]))
time4 = time[ind4]
self.Ttb_75.append(time4[-1] - time4[0])
# Arias intensity in m/s
self.I_a.append(np.pi / (2 * 9.81) * np.trapz(acc2 , dx=dt))
self.Ar.append(el.calcAriasRatio(amax, dt, duration=self.Artype))

def calcPMNeq(self):
    # m = 0.35 # I've assigned m all the way up at line 24
    # cutoff = 0.3
    m = self.m
    cutoff = self.cutoff
    self.PMNeq = []
    self.Discards = []
    overallmax = np.max(self.amax_surf) # I may need to make this an array first
    combinedhere = False
    for amax in self.amax_surf:
        if np.isscalar(m):
            mm = np.array([m])
        else:
            mm = m
        mymax = np.max(np.abs(amax))
        if combinedhere:
            amaxn = amax / overallmax
        else:
            amaxn = amax / mymax
        # Now I need to get the peak values for the positive and negatives parts.
        ind = np.where(np.sign(amaxn[:-1]) != np.sign(amaxn[1:]))[0] # Index of each
        # zero crossing
        Npos = 0.#np.zeros(mm.shape)
        Nneg = 0.#np.zeros(mm.shape)
        myN = 0.
        discard = 0.
        Ncyc = 0.5 # I'm assuming the result of the mean crossing is one half cycle,
        # change if needed.
        for i, val in enumerate(ind):
            try:
                if i == 0:
                    peak = np.max(np.abs(amaxn[0:val]))
                    #sign = np.sign(np.mean(amaxn[0:val]))
                else:
                    peak = np.max(np.abs(amaxn[ind[i-1]:val]))
                    #sign = np.sign(np.mean(amaxn[ind[i-1]:val]))
            except ValueError:
                continue
            if peak < cutoff:
                discard += Ncyc * np.exp(np.log(peak / 0.65) / mm)
                continue
            else:
                myN += Ncyc * np.exp(np.log(peak / 0.65) / mm)
                if sign == -1:
                    #Nneg += Ncyc * np.exp(np.log(peak / 0.65) / mm)
                else:
                    #Npos += Ncyc * np.exp(np.log(peak / 0.65) / mm)
                self.PMNeq.append(myN) # Just summing here since Ncyc is 0.5
self.Discards.append(discard)

if self.VectorSum:
    P2P = False
    VS = np.sqrt(self.amaxsurf[0] ** 2 + self.amaxsurf[1] ** 2)
    VS = VS / np.max(VS)
else:
    import CycleCounting as cc
    CC = cc.Load(VS)
    Peaks, Cycles = CC.calcPeak2Peak(AmpType='ASTM')
    self.PMNevVS = self.PMFloor(Peaks, Cycles)
    self.PMNevVSDis = 0. # Not a good way to do this using the alt method.
else:
    if P2P:
        import CycleCounting as cc
        CC = cc.Load(VS)
        Peaks, Cycles = CC.calcPeak2Peak(AmpType='ASTM')
        ind1 = np.where(Peaks >= cutoff)
        ind2 = np.where(Peaks < cutoff)
        self.PMNevVS = np.sum(Cycles[ind1] * np.exp(np.log(Peaks[ind1] / 0.65) / m))
        self.PMNevVSDis = np.sum(Cycles[ind2] * np.exp(np.log(Peaks[ind2] / 0.65) / m))
    else:
        # Find the location of the peaks:
        dVS = np.diff(VS)
        ind0 = np.where(np.sign(dVS)[1:] != np.sign(dVS[:-1]))[0] + 1
        Peaks = VS[ind0]
        #import matplotlib.pyplot as plt
        #plt.plot(VS)
        #plt.plot(ind0, Peaks, 'or')
        #plt.show()
        #pdb.set_trace()
        ind1 = np.where(Peaks >= cutoff)
        ind2 = np.where(Peaks < cutoff)
        self.PMNevVS = np.sum(0.5 * np.exp(np.log(Peaks[ind1] / 0.65) / m))
        self.PMNevVSDis = np.sum(0.5 * np.exp(np.log(Peaks[ind2] / 0.65) / m))
        #print(self.PMNevVS, self.PMNevVSDis)
    else:
        self.PMNevVS = 0.
        self.PMNevVSDis = 0.

def __call__(self, profile):
    layernames = list(profile.col('LayerName'))
    unit_wt = profile.col('UnitWt')
    t = profile.col('Thickness')[:-1]
    ko = profile.col('LatPressCo')
    phi = profile.col('FricAngle')[:-1]
    Vs = profile.col('ShearWaveVel')
    PI = profile.col('PlastIndex')[:-1]
    DS OCR = profile.col('DS OCR')
    DS soil = profile.col('DS soil')
    gwt = 0
self.profile = el.SoilProfile(
    str(profile.title),
    unit_wt,
    Vs,
    t,
    ko=ko,
    phi=phi,
    PI=PI,
    gut=gwt,
    layername=layername,
    DS_soil=DS_soil,
    OCR=DS_OCR,
    strainratio=0.65,
    loc_mot=0, #bedrock
    outcrop_mot=0 # 0 for outcrop
)
if self.MakeProfs:
    if not os.path.exists('./CSVProfiles/');
        os.makedirs('./CSVProfiles/
self.profile.to_csv(filename='./CSVProfiles/{}.csv'.format(
    self.profile.profile_name))
    return 0
self.calcResults()
return 0

class Output(object):
    def __init__(self, CEUS, combinecomps, **kwargs):
        self.CEUS = CEUS
        self.combined = combinecomps
        DC = kwargs.get('DC')
        self.archive = kwargs.get('archive', False)
        if kwars.get('PM', False):
            filename = 'IO{}-{}-{}.h5'.format('_WUS_PM',
                strftime('%d%b%Y', gmtime()))
            OutTable = WUSPM
            self.writer = self.PM
            self.outfile = pt.open_file(filename, mode='w',
                title='Results of EL Iterations')
            self.outtable = self.outfile.createTable('/', 'EquivLinIters',
                OutTable, expectedrows=7000)
        else:
            if kwargs.get('comb_alt', False):
                Altstr = 'ALT'
            else:
                Altstr = ''
            outdirbase = './Archive/'
            if CEUS:
                if combinecomps:
                    filename = 'IO{}-{}-{}.h5'.format('_CEUS_Comb' + Altstr, DC, strftime('%d%b%Y', gmtime()))
                    OutTable = CEUSComb
                    self.writer = self.Combed
                    self.outdir = (outdirbase + strftime('%d%b%Y', gmtime()) +
                        '/CEUS' + Altstr + '/')
                else:
                    filename = 'IO{}-{}-{}.h5'.format('_CEUS_Sing', DC, strftime('%d%b%Y', gmtime()))
OutTable = CEUSSingle
self.writer = self.Single
else:
    if combinecomps:
        filename = 'IO{}-{}-{}.h5'.format('_WUS_Comb' + Altstr,
                                        DC, strftime('%d%b%Y', gmtime()))
        OutTable = WUSComb
        self.writer = self.Combed
        self.outdir = (outdirbase + strftime('%d%b%Y', gmtime()) + '/WUS' + Altstr + '/')
    else:
        filename = 'IO{}-{}-{}.h5'.format('_WUS_Sing', DC,
                                          strftime('%d%b%Y', gmtime()))
        OutTable = WUSSingle
        self.writer = self.Single
        self.outfile = pt.open_file(filename, mode='w',
                                     title='Results of EL Iterations')
        self.outtable = self.outfile.createTable('/', 'EquivLinIters', OutTable,
                                                  expectedrows=200000)
        def close(self):
            self.outfile.close()
        def __call__(self, ResObj, ProfileGroup, Motions):
            self.writer(ResObj, ProfileGroup, Motions)
        def Single(self, ResObj, ProfileGroup, Motions):
            for j, result in enumerate(ResObj.Results):
                t = ResObj.profile.t
                ptmotions = Motions.motions
                motstats = Motions.motstats
                soilprofile = ResObj.profile
                for i in xrange(len(t)):
                    entry = self.outtable.row
                    entry['RecSeq'] = ptmotions[j]['RecSeqNum']
                    entry['Profile'] = soilprofile.profile_name
                    entry['Depth'] = soilprofile.t_mid[i]
                    entry['Sigv'] = soilprofile.sigv[i]
                    entry['Sigveff'] = soilprofile.sigveff[i]
                    entry['Sigmeff'] = soilprofile.sigmeff[i]
                    entry['Mod'] = result.G[i] # Softened condition
                    entry['Damp'] = result.D[i] # Softened condition
                    entry['DissEn'] = ResObj.DE[j][i]
                    entry['N_EQ'] = ResObj.Neq[j][i]
                    entry['TauAvg'] = ResObj.tau_avg[j][i]
                    entry['RepErr'] = result.ReportError
                    entry['iters'] = result.count
                    entry['maxerror'] = result.MaxError
                    entry['rd'] = result.rd[i]
                    entry['Vs'] = soilprofile.Vs[i] # Original shear wave velocity, not softened.
                    entry['UnitWt'] = soilprofile.unit_wt[i]
                    entry['LayerName'] = str(soilprofile.layername[i])

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if self.CEUS:
    if j == 0:
        entry['PGA'] = motstats['PGA_H1']
        entry['PGV'] = motstats['PGV_H1']
        entry['PGD'] = motstats['PGD_H1']
    else:
        entry['PGA'] = motstats['PGA_H2']
        entry['PGV'] = motstats['PGV_H2']
        entry['PGD'] = motstats['PGD_H2']
        entry['Bin'] = motstats['Bin']
    entry['Motion0'] = str(ptmotions[0]['Station_Name'])
    entry['EQEvent'] = motstats['EQ_name']
else:
    entry['EpicD'] = motstats['EpiD']
    entry['Mag_Type'] = motstats['Mag_type']
    entry['Hypd'] = motstats['HypD']
    entry['J_BD'] = motstats['Joy_Boore']
    entry['RMSD'] = motstats['RmsD']
    entry['Vs30 pref'] = motstats['Vs30 pref']
    entry['NEHRP'] = motstats['NEHRP']
    entry['ThetaD'] = motstats['ThetaD']
    entry['PhiD'] = motstats['Phi_D']
    entry['Y'] = motstats['Y']
    entry['Y'] = motstats['Y']
    entry['Rake'] = motstats['Rake']
    entry['EQ_Mech'] = motstats['EQ_Mech']
    entry['Dip'] = motstats['Dip']
    entry['EQEvent'] = motstats['EQID']
    entry['PGA'] = motstats['PGA']
    entry['PGV'] = motstats['PGV']
    entry['PGD'] = motstats['PGD']
entry['Motion'] = str(ptmotions[j]['Name'])
entry['Eq_Mag'] = motstats['EQ_Mag']
entry['CLSTD'] = motstats['ClstD']
entry['T_d01'] = ResObj.Tb_01[j]
entry['T_d05'] = ResObj.Tb_05[j]
entry['T_tb95'] = ResObj.Ttb_95[j]
entry['T_tb75'] = ResObj.Ttb_75[j]
entry['I_a'] = ResObj.I_a[j]
entry['Ar'] = ResObj.Ar[j]
entry['Artype'] = ResObj.Artype
entry['t'] = t
entry['z_bed'] = np.sum(t)
entry['Vsbed'] = soilprofile.Vs[-1]
entry['amax_surf'] = np.max(np.abs(ResObj.amax_surf[j]))
entry['PI'] = soilprofile.PI[i]
entry['profiletype'] = ProfileGroup
entry['Vs30'] = ResObj.Vs30
entry['Vs12'] = ResObj.Vs12
entry['sa_vs30'] = Sa0
def Combed(self, ResObj, ProfileGroup, Motions):
    t = ResObj.profile.t
    pmotions = Motions.motions
    pmotstats = Motions.motstats
    soilprofile = ResObj.profile
    DE_comb = np.sum(ResObj.DE, axis=0)

    if self.archive:
        self.makeCSVs(ResObj, ProfileGroup, Motions)

    for i in xrange(len(t)):
        entry = self.outtable.row
        entry['RecSeq'] = pmotions[0]['RecSeqNum']
        entry['Profile'] = soilprofile.profile_name
        entry['Depth'] = soilprofile.t_mid[i]
        entry['Sigv'] = soilprofile.sigv[i]
        entry['Sigveff'] = soilprofile.sigveff[i]
        entry['Sigmeff'] = soilprofile.sigmeff[i]
        entry['Mod'] = ResObj.Results[0].G[i]  # Softened condition
        entry['Damp'] = ResObj.Results[0].D[i]  # Softened condition
        entry['Mod1'] = ResObj.Results[1].G[i]  # Softened condition
        entry['Damp1'] = ResObj.Results[1].D[i]  # Softened condition
        entry['DissEn0'] = ResObj.DE[0][i]
        entry['N_EQ0'] = ResObj.Neq[0][i]
        entry['TauAvg0'] = ResObj.tau_avg[0][i]
        entry['RepErr0'] = ResObj.Results[0].ReportError
        entry['iters_0'] = ResObj.Results[0].count
        entry['maxerror_0'] = ResObj.Results[0].MaxError
        entry['DissEn1'] = ResObj.DE[1][i]
        entry['N_EQ1'] = ResObj.Neq[1][i]
        entry['TauAvg1'] = ResObj.tau_avg[1][i]
        entry['RepErr1'] = ResObj.Results[1].ReportError
        entry['iters_1'] = ResObj.Results[1].count
        entry['maxerror_1'] = ResObj.Results[1].MaxError
        entry['DE_comb'] = DE_comb[i]
entry['Neq_comb'] = ResObj.Neq_comb[i]
entry['rd_0'] = ResObj.Results[0].rd[i]
entry['rd_1'] = ResObj.Results[1].rd[i]

element['Vs'] = soilprofile.Vs[i]  # Original shear wave velocity, not softened.
entry['UnitWt'] = soilprofile.UnitWt[i]
entry['LayerName'] = str(soilprofile.layername[i])

if self.CEUS:
    entry['PGA_2'] = motstats['PGA_H2']
    entry['PGV_2'] = motstats['PGV_H2']
    entry['PGD_2'] = motstats['PGD_H2']
    entry['PGA'] = motstats['PGA_H1']
    entry['PGV'] = motstats['PGV_H1']
    entry['PGD'] = motstats['PGD_H1']
    entry['Bin'] = motstats['Bin']
    #entry['Motion0'] = str(ptmotions[0]['Station_Name'])  # for CEUS: Station_Name
    #entry['Motion1'] = str(ptmotions[1]['Station_Name'])
    entry['EQEvent'] = motstats['EQ_name']
else:
    entry['EpicD'] = motstats['EpiD']
    entry['Mag_Type'] = motstats['Mag_type']
    entry['Hypd'] = motstats['Hypd']
    entry['J_BD'] = motstats['J_BD']
    entry['RMSD'] = motstats['RMSD']
    entry['Vs30 pref'] = motstats['Vs30 pref']
    entry['NEHRP'] = motstats['NEHRP']  # StringCol(itemsize=1)
    entry['ThetaD'] = motstats['ThetaD']
    entry['PhiD'] = motstats['Phi_D']
    entry['X'] = motstats['X']
    entry['Y'] = motstats['Y']
    entry['Rake'] = motstats['Rake']
    entry['EQ_Mech'] = motstats['EQ_Mech']
    entry['Dip'] = motstats['Dip']
    entry['EQEvent'] = motstats['EQID']
    entry['PGA'] = motstats['PGA']
    entry['PGV'] = motstats['PGV']
    entry['PGD'] = motstats['PGD']

    entry['Motion0'] = str(ptmotions[0]['Name'])
    entry['Motion1'] = str(ptmotions[1]['Name'])
    entry['CLSTD'] = motstats['CLSTD']

    entry['T_d01_0'] = ResObj.Tb_01[0]  # Bracketed duration (> 0.01g)
    entry['T_d05_0'] = ResObj.Tb_05[0]  # Bracketed duration (> 0.05g)
    entry['T_tb95_0'] = ResObj.Ttb_95[0]  # Trifunac and Brady duration based on 5-95% energy
    entry['T_tb75_0'] = ResObj.Ttb_75[0]  # Trifunac and Brady duration based on 5-95% energy

    entry['I_a_0'] = ResObj.I_a[0]  # Arias Intensity
    entry['Ar_o'] = ResObj.Ar_o[0]
    entry['T_d01_1'] = ResObj.Tb_01[1]  # Bracketed duration (> 0.01g)
    entry['T_d05_1'] = ResObj.Tb_05[1]  # Bracketed duration (> 0.05g)
    entry['T_tb95_1'] = ResObj.Ttb_95[1]  # Trifunac and Brady duration based on 5-95% energy
    entry['T_tb75_1'] = ResObj.Ttb_75[1]  # Trifunac and Brady duration based on 5-95% energy

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entry['I_a_1'] = ResObj.I_a[1]  # Arias Intensity
entry['Ar_1'] = ResObj.Ar[1]
entry['Arttype'] = ResObj.Arttype
entry['t'] = t[i]  # layer thickness
entry['z_bed'] = np.sum(t)
entry['Vsbed'] = soilprofile.Vs[-1]
entry['amax_surf_0'] = np.max(np.abs(ResObj.amax_surf[0]))
entry['amax_surf_1'] = np.max(np.abs(ResObj.amax_surf[1]))
entry['amax_surf_max'] = np.max(np.abs(ResObj.amax_surf))
entry['PI'] = soilprofile.PI[i]
entry['profiletype'] = ProfileGroup
entry['Vs30'] = ResObj.Vs30
entry['Vs12'] = ResObj.Vs12
# entry['sa_vs30'] = Sa0
# entry['sa_vs31'] = Sa1
entry['PMNeq0'] = ResObj.PMNeq[0]
entry['PMNeq1'] = ResObj.PMNeq[1]
entry['PMNeqVS'] = ResObj.PMNeqVS
entry['PMNeqVSdis'] = ResObj.PMNeqVSdis
entry['Discard0'] = ResObj.Discards[0]
entry['Discard1'] = ResObj.Discards[1]
entry['m'] = ResObj.m
entry['cutoff'] = ResObj.cutoff
# entry['PMNeq020'] = ResObj.PMNeq[0][0]
# entry['PMNeq022'] = ResObj.PMNeq[0][1]
# entry['PMNeq024'] = ResObj.PMNeq[0][2]
# entry['PMNeq026'] = ResObj.PMNeq[0][3]
# entry['PMNeq028'] = ResObj.PMNeq[0][4]
# entry['PMNeq030'] = ResObj.PMNeq[0][5]
# entry['PMNeq032'] = ResObj.PMNeq[0][6]
# entry['PMNeq034'] = ResObj.PMNeq[0][7]
# entry['PMNeq036'] = ResObj.PMNeq[0][8]
# entry['PMNeq038'] = ResObj.PMNeq[0][9]
# entry['PMNeq040'] = ResObj.PMNeq[0][10]
# entry['PMNeq120'] = ResObj.PMNeq[1][0]
# entry['PMNeq122'] = ResObj.PMNeq[1][1]
# entry['PMNeq124'] = ResObj.PMNeq[1][2]
# entry['PMNeq126'] = ResObj.PMNeq[1][3]
# entry['PMNeq128'] = ResObj.PMNeq[1][4]
# entry['PMNeq130'] = ResObj.PMNeq[1][5]
# entry['PMNeq132'] = ResObj.PMNeq[1][6]
# entry['PMNeq134'] = ResObj.PMNeq[1][7]
# entry['PMNeq136'] = ResObj.PMNeq[1][8]
# entry['PMNeq138'] = ResObj.PMNeq[1][9]
# entry['PMNeq140'] = ResObj.PMNeq[1][10]
entry.append()
self.outtable.flush()
def makeCSVs(self, ResObj, ProfileGroup, Motions):
    '''
    This creates .csv files for Dr. Green's archiving purposes
    '''
    soilprofile = ResObj.profile
ptmotions = Motions.motions
outdir = self.outdir + '/{}'./format(soilprofile.profile_name)
if not os.path.exists(outdir):
    os.makedirs(outdir)

headerlinesprof = ['Depth (m)',
    'Layer Name',
    'Total Stress (kPa)',
    'Eff. Stress (kPa)',
    'Mean Eff. Stress (kPa)',
    'Diss En 1 (kPa)',
    'Diss En 2 (kPa)',
    'G 1 (kPa)',
    'G 2 (kPa)',
    'D 1',
    'D 2',
    'Tau_avg1 (kPa)',
    'Tau_avg2 (kPa)',
    'Neq_comb',
    'r_d1',
    'r_d2']
outarrayprof = np.vstack((soilprofile.t_mid,
    #layername[:-1],
    soilprofile.sigv,
    soilprofile.sigveff,
    soilprofile.sigmeff,
    ResObj.DE[0],
    ResObj.DE[1],
    ResObj.Results[0].G[:-1],
    ResObj.Results[1].G[:-1],
    ResObj.Results[0].D[:-1],
    ResObj.Results[1].D[:-1],
    ResObj.tau_avg[0],
    ResObj.tau_avg[1],
    ResObj.Neq_comb,
    ResObj.Results[0].rd,
    ResObj.Results[1].rd)).T
footerprof = ('Profile: {}, '.format(soilprofile.profile_name) +
    'Motion 1: {}, Motion2: {} '.format(str(ptmotions[0]['Name']),
    str(ptmotions[1]['Name'])))
if self.CEUS:
    filenameprof = (outdir + '{}_profile.csv'.format(str(ptmotions[0]['Name'])+
    str(ptmotions[0]['Bin'][:7])))
else:
    filenameprof = (outdir + '{}_profile.csv'.format(str(ptmotions[0]['Name'])+
    str(ptmotions[0]['Bin'][:7])))
np.savetxt(filenameprof, outarrayprof, delimiter=',
    newline='\n', header=''.join(headerlinesprof),
    footer=footerprof, comments='')

NPTS = ptmotions[0]['NPTS']
NPTS = ptmotions[0]['MotionData'].shape[0]
dt = ptmotions[0]['TimeStep']
num = np.arange(NPTS) * dt
headerlinesth = ['Time (s)', 'Base Acc 1 (g)',

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outarrayth = np.vstack((time,
    ptmotions[0]['MotionData'],
    ptmotions[1]['MotionData'],
    ResObj.Results[0].calcAcc(0.,
        MaxOnly=False,
        domain='time',
        MotType='within').ravel(),
    ResObj.Results[1].calcAcc(0.,
        MaxOnly=False,
        domain='time',
        MotType='within').ravel())).T

if self.CEUS:
    filenames = (outdir + '{}_timehist.csv'.format(
        str(ptmotions[0]['Name'])+str(ptmotions[0]['Bin'][:7])))
else:
    filenames = (outdir + '{}_timehist.csv'.format(
        str(ptmotions[0]['Name'][:7:-4])))
np.savetxt(filenames, outarrayth, delimiter=',
    newline='
', header=','.join(headerlinesth),
    comments='')

def PM(self, ResObj, PlaceHolder, Motions):
    for j in range(2):
        ptmotions = Motions.motions
        motstats = Motions.motstats
        entry = self.outtable.row
        entry['RecSeq'] = ptmotions[j]['RecSeqNum']

        if self.CEUS:
            if j == 0:
                entry['PGA'] = motstats['PGA_H1']
                entry['PGV'] = motstats['PGV_H1']
                entry['PGD'] = motstats['PGD_H1']
            else:
                entry['PGA'] = motstats['PGA_H2']
                entry['PGV'] = motstats['PGV_H2']
                entry['PGD'] = motstats['PGD_H2']
                entry['Bin'] = motstats['Bin'

        #entry['Motion0'] = str(ptmotions[0]['Station_Name']) #for CEUS: Station_Name
        #entry['EQEvent'] = motstats['EQ_name']

        if self.CEUS:
            if j == 0:
                entry['EpicD'] = motstats['EpiD']
                entry['Mag_Type'] = motstats['Mag_type']
                entry['Hypd'] = motstats['HypD']
                entry['J_BD'] = motstats['Joy_Boore']
                entry['RMSD'] = motstats['RmsD']
                entry['Vs30_pref'] = motstats['Vs30_pref']
entry['NEHRP'] = motstats['NEHRP']  # StringCol(itemsize=1)
entry['ThetaD'] = motstats['ThetaD']
entry['PhiD'] = motstats['Phi_D']
entry['X'] = motstats['X']
entry['Y'] = motstats['Y']
entry['Rake'] = motstats['Rake']
entry['EQ_Mech'] = motstats['EQ_Mech']
entry['Dip'] = motstats['Dip']
entry['EQEvent'] = motstats['EQID']
entry['PGA'] = motstats['PGA']
entry['PGV'] = motstats['PGV']
entry['PGD'] = motstats['PGD']

entry['Motion'] = str(ptmotions[j]['Name'])  # for CEUS: Station_Name
entry['Eq_Mag'] = motstats['EQ_Mag']
entry['CLSTD'] = motstats['ClstD']

entry['T_d01'] = ResObj.Tb_01[j]  # Bracketed duration (> 0.01g)
entry['T_d05'] = ResObj.Tb_05[j]  # Bracketed duration (> 0.05g)
entry['T_tb95'] = ResObj.Ttb_95[j]  # Trifunac and Brady duration based on 5-95% energy
entry['T_tb75'] = ResObj.Ttb_75[j]  # Trifunac and Brady duration based on 5-95% energy
entry['I_a'] = ResObj.I_a[j]  # Arias Intensity
entry['Ar'] = ResObj.Ar[j]
entry['Artype'] = ResObj.Artype

entry['amax_surf'] = ResObj.amax_surf[j]
entry['PMNeq'] = ResObj.PMNeq[j]
entry['PMNeqVS'] = ResObj.PMNeqVS
entry['PMNeqVSdis'] = ResObj.PMNeqVSdis
entry['Discard'] = ResObj.Discards[j]
entry['m'] = ResObj.m
entry['cutoff'] = ResObj.cutoff
entry.append()
self.outtable.flush()

def Runner(**kwargs):
    CEUS = kwargs.get('CEUS', True)
    combinecomps = kwargs.get('combinecomps', False)
    comb_alt = kwargs.get('comb_alt', True)
    archive = kwargs.get('archive', False)
    DC = kwargs.get('DC', 'DS')

    motions = Motions(CEUS=CEUS)
    profiles = Profiles(CEUS=CEUS)
    out = Output(CEUS, combinecomps, DC=DC, comb_alt=comb_alt, archive=archive)

    for mot in motions:
        if CEUS:
            pass
        else:
            if str(mot.col('Orient')[0]) == 'Vert':
                print('Contained a vertical component... Skipping!')
                continue
if len(mot.col('Name')) < 2:
    print('Contained less than 2 components... Skipping!')
    continue
DynObj = Dynamics(mot, combinecomps, DC=DC, comb_alt=comb_alt)
for prof in profiles:
    retcode = DynObj(prof)
    #if retcode != 0:
    #    pdb.set_trace()
    out(DynObj, profiles.group, motions)
del DynObj

out.close()
motions.close()
profiles.close()

def ProfCSVMaker(**kwargs):
    '''
    This writes out my input profiles as *.csv files
    '''
    CEUS = kwargs.get('CEUS', False)
    combinecomps = kwargs.get('combinecomps', False)
    DC = kwargs.get('DC', 'DS')
    motions = Motions(CEUS=CEUS)
    profiles = Profiles(CEUS=CEUS)
    #out = Output(CEUS, combinecomps, DC=DC)
    for mot in motions():
        if CEUS:
            pass
        else:
            if str(mot.col('Orient')[0]) == 'Vert':
                print('Contained a vertical component... Skipping!')
                continue
            if len(mot.col('Name')) < 2:
                print('Contained less than 2 components... Skipping!')
                continue
        DynObj = Dynamics(mot, combinecomps, DC=DC, ProfMaker=True)
        for prof in profiles:
            retcode = DynObj(prof)
            #if retcode != 0:
            #    pdb.set_trace()
            #    out(DynObj, profiles.group, motions)
            del DynObj
            break
        #out.close()
motions.close()
profiles.close()
J.5 Regression of $n_{eq}$

The file NeqStats2.py uses the R language and bootstrapping to obtain the regression coefficients for $n_{eq}$.

```python
import sys
sys.path.append('/media/Storage/Documents/Python/Modules')
# import pdb
from time import gmtime, strftime
try:
    import ipdb as pdb
except:
    import pdb
import numpy as np
import pandas as pd
import matplotlib
matplotlib.rcParams.update({'font.size': 18, 'font.family': 'STIXGeneral', 'mathtext.fontset': 'stix'})
import matplotlib.pyplot as plt
import statsmodels.api as sm
import pandas.rpy.common as com
import rpy2.robjects as robjects
from rpy2.robjects.packages import importr
base = importr('base')
stats = importr('stats')
lme4 = importr('lme4')
lattice = importr('lattice')
sys.path.append('/media/Storage/Documents/Python/GMPEs')
from AS_2014_nga import AS_2014
from BA_2014_nga import BA_2014
from CY_2014_nga import CY_2014
from CB_2014_nga import CB_2014
from numpy.random import normal
import pandoctable as pan

def Neq(**kwargs):
    comb = kwargs.get('comb', False)
    CEUS = kwargs.get('CEUS', False)

    if comb:
        if CEUS:
            infile = kwargs.get('infile', 'IO_CEUS_Comb23Mar2015.h5')
        else:
            infile = kwargs.get('infile', 'IO_WUS_Comb23Mar2015.h5')
    else:
        if CEUS:
            infile = kwargs.get('infile', 'IO_CEUS_Sing20Mar2015.h5')
        else:
            infile = kwargs.get('infile', 'IO_WUS_Sing19Mar2015.h5')

    fileout = 'NeqStats-out.txt'
```

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```python
results0 = pd.read_hdf(infile, 'EquivLinIters')
#PICutoff = kwargs.get('PICutoff', 50)
Depthcutoff = kwargs.get('Depthcutoff', 100)
if comb:
    results = results0[(results0['Depth'] < Depthcutoff) & (results0.Neq_comb > 0)]
else:
    results = results0[(results0['Depth'] < Depthcutoff) & (results0.N_EQ > 0)]
results['EQEvent'] = results['EQEvent'].astype('category')
eqvnt = pd.Categorical.from_array(results['EQEvent'])
results['EQEvent'] = eqvnt.codes
results['profiletype'] = results['profiletype'].astype('category')
results['profiletype'] = results['profiletype'].astype(int)
results['profiletype'] = results['profiletype'].astype(int)
print('File In: {}'.format(infile))
print('File Out: {}'.format(fileout))
N = kwargs.get('N', 10)
samplesize = kwargs.get('samplesize', 1000)
print('Number of Iterations: {}'.format(N))
print('Sample Size: {}'.format(samplesize))
if comb:
    results['amax_surf'] = np.sqrt(results['amax_surf_0'].values * results['amax_surf_1'].values)
    results['N_EQ'] = np.maximum(results.Neq_comb.values, 1e-10)
else:
    results.loc[:, 'N_EQ'] = np.maximum(results.N_EQ.values, 1e-10)
ycol = kwargs.get('ycol', 'N_EQ')  # Assume this is log() for now
mycolumns = kwars.get('mycolumns',
    ['N_EQ', 'amax_surf', 'Eq_Mag', 'Depth',
     'EQEvent', 'profiletype', 'CLSTD', 'Vs'])
if CEUS:
    formulas = [
        'log(N_EQ) ~ log(amax_surf) + Eq_Mag + ' +
        '(1|profiletype)',
        'log(N_EQ) ~ Eq_Mag + log(CLSTD) + ' +
        '(1|profiletype)']
    lenresults = [3, 3]
else:
    formulas = [
        'log(N_EQ) ~ log(amax_surf) + Eq_Mag + ' +
        '(1|EQEvent) + (1|profiletype)',
        'log(N_EQ) ~ Eq_Mag + log(CLSTD) + ' +
        '(1|EQEvent) + (1|profiletype)']
    lenresults = [3, 3]
mycoeffs = []
stdevs = []
means = []
stdevsa = []
meansa = []
taupro = []
tauEQ = []
formulas = kwars.get('formulas', formulas)
lenresults = kwars.get('lenresults', lenresults)
results = results[results['Vs30_pref']>= 760]
for i in xrange(N):
```

if i % 5 == 0:
    sys.stdout.write(' .
if i % 25 == 0:
    sys.stdout.write('{}
format(i))
    sys.stdout.flush()
ind = np.random.choice(results.index.values, samplesize, replace=False)
subset = results.loc[ind, mycolumns]
subset.dropna(inplace=True) # I have to do this because of missing CLSTD values
for j, formula in enumerate(formulas):
    n = len(results[j])
    if i == 0:
        mycoeffs.append(np.zeros((N,n), dtype=float))
        stdevs.append(np.zeros((N,)))
        means.append(np.zeros((N,)))
        meansa.append(np.zeros((N,)))
        taupro.append(np.zeros((N,)))
    if not CEUS:
        tauEQ.append(np.zeros((N,)))
    # Do it with rpy2
dfr = com.convert_to_r_dataframe(subset, True)
test1 = lme4.lmer(robjects.Formula(formula), data=dfr)
    testsum = base.summary(test1)
    coefs = np.array(testsum.rx2("coefficients"))[:n,0]
    varcor = com.convert_robj(testsum.rx2("varcor"))
    taupro[j][i] = varcor["profiletype"]['(Intercept)']['(Intercept)'] ** 0.5
    if not CEUS:
        tauEQ[j][i] = varcor["EQEvent"]['(Intercept)']['(Intercept)'] ** 0.5
    try:
        resid = (np.log(subset[ycol].values) - # Need to change this if predicting
            np.array(stats.predict(test1,REform=robjects.r("NULL"))))
        residA = (np.log(subset[ycol].values) - # Need to change this if predicting
            np.array(stats.predict(test1,REform=robjects.r("NA"))))
        stdevs[j][i] = np.std(resid)
        means[j][i] = np.mean(resid)
        stdevsa[j][i] = np.std(residA)
        meansa[j][i] = np.mean(residA)
        mycoeffs[j][i,:] = coefs
    except ValueError:
        pdb.set_trace()
    if kwargs.get(‘ranefs’, False):
        randicts = com.convert_robj(robjects.r.ranef(test1))
        pft = randicts[’profiletype’]
        eqe = randicts[’EQEvent’]
        pft[’profiletype’] = pft.index
        eqe[’EQEvent’] = eqe.index
        subset = pd.merge(subset, pft)
        subset.rename(columns=(’(Intercept)’:’ranefpt{}’
format(j)), inplace=True)
        subset = pd.merge(subset, eqe)
subset.rename(columns={'(Intercept)':'ranefEQ{}'.format(j)}, inplace=True)
plt.figure('EQ')
plt.plot(subset.Eq_Mag, subset['ranefEQ{}'.format(j)],'o', color='0.3')
plt.xlabel('\$M_w\$')
plt.ylabel('Random Effect of EQEvent')
plt.figure('pt')
plt.plot(subset.profiletype, subset['ranefpt{}'.format(j)],'o')
plt.xlabel('Profile Type')
plt.ylabel('Random Effect of ProfileType')

if j == 0:
    plt.figure('Resid vs amax')
    plt.semilogx(subset.amax_surf.values, resids, '.', color='0.3')
    plt.xlabel('PGA')
    plt.ylabel('Residuals')
    plt.figure('Resid vs Mw')
    plt.plot(subset.Eq_Mag.values, resids, 'o', color='0.3')
    plt.xlabel('$M_w$')
    plt.ylabel('Residuals')
else:
    plt.figure('Resid vs CLSTD')
    plt.semilogx(subset.CLSTD.values, resids, 'o', color='0.3')
    plt.xlabel('\$R\$ (km)')
    plt.ylabel('Residuals')
    plt.figure('Resid vs Mw')
    plt.plot(subset.Eq_Mag.values, resids, 'o', color='0.3')
    plt.xlabel('$M_w$')
    plt.ylabel('Residuals')

if kwargs.get('plots', False):
    print(np.std(resids))
    fig, axs = plt.subplots(nrows=2, ncols=1, sharex=False, sharey=True)
    ms = 2.5
    alpha = 0.8
    marker = 'o'
    color = '0.2'
    linestyle = ''
    ylim = 2
    if j == 0:
        #plt.figure('Resid vs amax')
        axs[0].semilogx(subset.amax_surf.values[:10], resids[:10],
                        marker=marker, linestyle=linestyle, ms=ms, color=color,
                        alpha=alpha)
        xmin, xmax = subset.amax_surf.min(), subset.amax_surf.max()
        axs[0].axis([0.00001, 5, 0, 2])
        axs[0].set_xlabel('PGA (g)')
        axs[0].set_ylabel('Residuals')
    #plt.figure('Resid vs Mw')
    axs[1].plot(subset.Eq_Mag.values[:10], resids[:10],
                marker=marker, linestyle=linestyle, ms=ms, color=color,
                alpha=alpha)
    xmin, xmax = subset.Eq_Mag.min(), subset.Eq_Mag.max()
    axs[1].axis([0, 3, 0, 2])
    axs[1].set_xlabel('$M_w$')
```python
axs[1].set_ylabel('Residuals')
else:
    #plt.figure('Resid vs CLSTD')
    axs[0].semilogx(subset.CLSTD.values[::10], resids[::10],
                 marker=marker, linestyle=linestyle, ms=ms, color=color,
                 alpha=alpha)
xmin, xmax = subset.CLSTD.min(), subset.CLSTD.max()
axs[0].axis([1, 200], [0, 0], lw=0.8, color='0.30')
axs[0].set_xlabel('$R$ (km)')
axs[0].set_ylabel('Residuals')
    #plt.figure('Resid vs Mw')
    axs[1].plot(subset.Eq_Mag.values[::10], resids[::10],
                 marker=marker, linestyle=linestyle, ms=ms, color=color,
                 alpha=alpha)
xmin, xmax = subset.Eq_Mag.min(), subset.Eq_Mag.max()
axs[1].axis([xmin, xmax, ylim, ylim])
axs[1].set_xlabel('$M_w$')
axs[1].set_ylabel('Residuals')
    #plt.tight_layout()
    plt.subplots_adjust(wspace=0.2, hspace=0.55)
    plt.locator_params(axis='y', nbins=4)
    plt.show()

# Write the results out
if kwargs.get('PrintOut', True):
    #pdb.set_trace()
    with open(fileout, 'a') as f:
        f.write(strftime('%d%b%Y', gmtime())+ '
')
        f.write('Data File: {}
'.format(infile))
        f.write('Number of Iterations: {}
'.format(N))
        f.write('Sample Size: {}
'.format(samplesize))
        #f.write('PI<{}

'.format(PIcutoff))
        f.write('z<{}m

'.format(Depthcutoff))
        f.write('Table: Regression Coefficients

')
        align = [('^','<')]+[('^','^') for j in range(lenresults[i]+1)]
        header = [['Approach', 'Database'] +
                   [ '$a_{}$'.format(j+1) for j in range(lenresults[i]+1)]
                   for i in range(len(formulas))]
        database = 'CEUS' if CEUS else 'WUS'
        if comb:
            Component = '23'
        else:
            Component = '1'
        data = [tuple([Component, database] +
                      [ '{:10.4g}'.format(val) for val
                       in np.median(mycoeffs[i], axis=0)])
                   for i in range(len(results)+2)]
        f.write([header[i] + align + ['\n\n']
                  for i in range(len(formulas))])
        f.write('Table: Regression Coefficients\n\n')
        f.write([align + [ '{}'.format(j) for j in range(len(results)+1)]
                  + ['\n\n']
                  for i in range(len(formulas))])
        f.write([\n\n'.format(j) for j in range(len(results)+1)])
        f.write('Table: Regression Coefficients\n\n')
        f.write([align + [ '{}'.format(j) for j in range(len(results)+1)]
                  + ['\n\n']
                  for i in range(len(formulas))])
        f.write([\n\n'.format(j) for j in range(len(results)+1)])
```

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The file `rdstats.py` uses the R language and bootstrapping to obtain the regression coefficients for $r_d$. 

**J.6 Regression of $r_d$**
import pandas.rpy.common as com
import rpy2.robjects as robjects
from rpy2.robjects.packages import importr
base = importr('base')
stats = importr('stats')
lme4 = importr('lme4')
lattice = importr('lattice')

def g_rd(*beta, **kwargs):
    '''
    This is for rd
    '''
    df = kwargs.get('df')
    Mw = kwargs.get('Mw', df.Eq_Mag.values)
    z = kwargs.get('z', df.Depth.values)
    a = np.exp(beta[0] + beta[1] * Mw )
    g = (1.-a) * np.exp(-(z) / b) + a
    #g = 1./ (a + 1.) * np.exp(-(z) / b) + a
    return g

def g_rd_complex(*beta, **kwargs):
    '''
    This is for rd
    '''
    beta_Lasley6e = [-6.2, 0.4, -0.005, 1.3, -16, 2.3, -2.4, 2.8, 0.15]
    df = kwargs.get('df')
    amax = df['amax_surf'].values
    Mw = df['Eq_Mag'].values
    z = df['Depth'].values
    Vs12 = df.Vs12.values
    g = (1.-a) * np.exp(-(z) / b) + a
    #g = 1./ (a + 1.) * np.exp(-(z) / b) + a
    return g

def g_rd_2(*beta, **kwargs):
    '''
    This is for rd
    '''
    #beta_Lasley6ab = [-4.5, 0.43, -13, 3.1, 0.15]
    df = kwargs.get('df')
    Mw = df['Eq_Mag'].values
    z = df['Depth'].values
    Vs12 = df.Vs12.values
    a = np.exp(beta[0] + beta[1] * Mw)
    g = (1.-a) * np.exp(-(z) / b) + a
    #g = 1./ (a + 1.) * np.exp(-(z) / b) + a
    return g
def g_rd_2a(*beta, **kwargs):
    
    This is for rd
    
    df = kwargs.get('df')
    Mw = df['Eq_Mag'].values
    z = df['Depth'].values
    Vs12 = df.Vs12.values
    g = (1 - a) * np.exp(-(z) / b) + a
    #g = 1./(a + 1.) * np.exp(-(z) / b) + a
    return g

def g_rd_2b(*beta, **kwargs):
    
    This is for rd
    
    df = kwargs.get('df')
    Mw = df['Eq_Mag'].values
    z = df['Depth'].values
    Vs12 = df.Vs12.values
    g = (1 - a) * np.exp(-(z) / b) + a
    #g = 1./(a + 1.) * np.exp(-(z) / b) + a
    return g

def g_rd_2c(*beta, **kwargs):
    
    This is for rd
    
    df = kwargs.get('df')
    Mw = df['Eq_Mag'].values
    z = df['Depth'].values
    Vs12 = df.Vs12.values
    b = 123.5 * a
    g = (1 - a) * np.exp(-(z) / b) + a
    #g = 1./(a + 1.) * np.exp(-(z) / b) + a
    return g

def g_rd_med(*beta, **kwargs):
    
    This is for rd
    
    betaorig = [-4.18869375e+00, 4.07780834e-01, -1.08253122e-03, 891
df = kwargs.get('df')
Mw = df['Eq_Mag'].values
z = df['Depth'].values
Vs12 = df.Vs12.values

a = np.exp(beta[0] + beta[1] * Mw + beta[2]* (Vs12))
g = (1.-a) * np.exp(-(z) / b) + a
#g = 1./ (a + 1.) * np.exp(-(z) / b) + a
return g

def likelihood(beta, g, df, log, key, **kwargs):
x = df[key].values

sig = beta[-1]
xpred = g(*beta, df=df)

if log == True:
    like = - np.sum(np.log(1. / (sig * np.sqrt(2 * np.pi))) -
                    (xpred - x) ** 2 / (2 * sig ** 2))
else:
    like = - np.prod(1. / (sig * np.sqrt(2 * np.pi)) * np.exp(-(xpred - x) ** 2. / (2. * sig ** 2.)))
return like

def calcRd(df, **kwargs):
    beta = kwargs.get('beta', [ -4.49, 0.412, -46.3, 10, 0.5])
g = kwargs.get('g', g_rd)
method = kwargs.get('method', 'Nelder-Mead')
coefflen = len(beta) - 1
EQEvents = set(df.EQEvent.values)
profiletypes = set(df.profiletype.values)
coeffs = np.zeros((len(EQEvents), len(profiletypes), coefflen))
outcoeffs = np.zeros(4)

if kwargs.get('mixedeffects', False):
    for i,EQ in enumerate(EQEvents):
        for j,prof in enumerate(profiletypes):
            mydf = df[(df['EQEvent'] == EQ) & (df['profiletype'] == prof)]
            if len(mydf) < 30:
                print('i: {}, j:{}. Too few points({})'.format(i,j, len(mydf)))
                continue
            try:
                results = minimize(likelihood, beta, args=(g,mydf,True,'rd'),
                #results = minimize(likelihood, beta, args=(g,mydf,True,'rd'),
                continue
            except:
                coeffs[i,j,:] = np.nan
print(coeffs)

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def calcRdARM(df, **kwargs):
    
    formula='delta ~ (1|EQEvent) + (1|profiletype)'
    while error > 0.05:
        i += 1
        if i > 50:
            print('{} iterations w/o convergence'.format(i))
        results = minimize(likelihood, beta,
                           args=(g,df,True,'rd'),
                           method=method,
                           options=('maxiter': 1000, 'disp': False))
        df['delta'] = df.rd.values - g_rd(*results.x, df=df)
        df['Rdst'] = df['rd'].values
        n = len(beta) - 1
        beta = params[:n]
        error = 2.5
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
    
    if i > 0:
        print('{} iterations w/o convergence'.format(i))
    pdb.set_trace()
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
    
    results = minimize(likelihood, beta,
                       args=(g,df,True,'Rdst'),
                       method=method,
                       options=('maxiter': 1000, 'disp': False))
    df['delta'] = df.rd.values - g_rd(*results.x, df=df)
    return np.nan * np.ones(n), np.nan * np.ones(len(df))

def calcRdARM(df, **kwargs):
    
    formula='delta ~ (1|EQEvent) + (1|profiletype)'
    while error > 0.05:
        i += 1
        if i > 50:
            print('{} iterations w/o convergence'.format(i))
        results = minimize(likelihood, beta,
                           args=(g,df,True,'rd'),
                           method=method,
                           options=('maxiter': 1000, 'disp': False))
        df['delta'] = df.rd.values - g_rd(*results.x, df=df)
        df['Rdst'] = df['rd'].values
        n = len(beta) - 1
        beta = params[:n]
        error = 2.5
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
    
    if i > 0:
        print('{} iterations w/o convergence'.format(i))
    pdb.set_trace()
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
    
    results = minimize(likelihood, beta,
                       args=(g,df,True,'Rdst'),
                       method=method,
                       options=('maxiter': 1000, 'disp': False))
    df['delta'] = df.rd.values - g_rd(*results.x, df=df)
    return np.nan * np.ones(n), np.nan * np.ones(len(df))

def calcRdARM(df, **kwargs):
    
    formula='delta ~ (1|EQEvent) + (1|profiletype)'
    while error > 0.05:
        i += 1
        if i > 50:
            print('{} iterations w/o convergence'.format(i))
        results = minimize(likelihood, beta,
                           args=(g,df,True,'rd'),
                           method=method,
                           options=('maxiter': 1000, 'disp': False))
        df['delta'] = df.rd.values - g_rd(*results.x, df=df)
        df['Rdst'] = df['rd'].values
        n = len(beta) - 1
        beta = params[:n]
        error = 2.5
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
    
    if i > 0:
        print('{} iterations w/o convergence'.format(i))
    pdb.set_trace()
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
    
    results = minimize(likelihood, beta,
                       args=(g,df,True,'Rdst'),
                       method=method,
                       options=('maxiter': 1000, 'disp': False))
    df['delta'] = df.rd.values - g_rd(*results.x, df=df)
    return np.nan * np.ones(n), np.nan * np.ones(len(df))

def calcRdARM(df, **kwargs):
    
    formula='delta ~ (1|EQEvent) + (1|profiletype)'
    while error > 0.05:
        i += 1
        if i > 50:
            print('{} iterations w/o convergence'.format(i))
        results = minimize(likelihood, beta,
                           args=(g,df,True,'rd'),
                           method=method,
                           options=('maxiter': 1000, 'disp': False))
        df['delta'] = df.rd.values - g_rd(*results.x, df=df)
        df['Rdst'] = df['rd'].values
        n = len(beta) - 1
        beta = params[:n]
        error = 2.5
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
    
    if i > 0:
        print('{} iterations w/o convergence'.format(i))
    pdb.set_trace()
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
    
    results = minimize(likelihood, beta,
                       args=(g,df,True,'Rdst'),
                       method=method,
                       options=('maxiter': 1000, 'disp': False))
    df['delta'] = df.rd.values - g_rd(*results.x, df=df)
    return np.nan * np.ones(n), np.nan * np.ones(len(df))

def calcRdARM(df, **kwargs):
    
    formula='delta ~ (1|EQEvent) + (1|profiletype)'
    while error > 0.05:
        i += 1
        if i > 50:
            print('{} iterations w/o convergence'.format(i))
        results = minimize(likelihood, beta,
                           args=(g,df,True,'rd'),
                           method=method,
                           options=('maxiter': 1000, 'disp': False))
        df['delta'] = df.rd.values - g_rd(*results.x, df=df)
        df['Rdst'] = df['rd'].values
        n = len(beta) - 1
        beta = params[:n]
        error = 2.5
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
    
    if i > 0:
        print('{} iterations w/o convergence'.format(i))
    pdb.set_trace()
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
    
    results = minimize(likelihood, beta,
                       args=(g,df,True,'Rdst'),
                       method=method,
                       options=('maxiter': 1000, 'disp': False))
    df['delta'] = df.rd.values - g_rd(*results.x, df=df)
    return np.nan * np.ones(n), np.nan * np.ones(len(df))

def calcRdARM(df, **kwargs):
    
    formula='delta ~ (1|EQEvent) + (1|profiletype)'
    while error > 0.05:
        i += 1
        if i > 50:
            print('{} iterations w/o convergence'.format(i))
        results = minimize(likelihood, beta,
                           args=(g,df,True,'rd'),
                           method=method,
                           options=('maxiter': 1000, 'disp': False))
        df['delta'] = df.rd.values - g_rd(*results.x, df=df)
        df['Rdst'] = df['rd'].values
        n = len(beta) - 1
        beta = params[:n]
        error = 2.5
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
    
    if i > 0:
        print('{} iterations w/o convergence'.format(i))
    pdb.set_trace()
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
    
    results = minimize(likelihood, beta,
                       args=(g,df,True,'Rdst'),
                       method=method,
                       options=('maxiter': 1000, 'disp': False))
    df['delta'] = df.rd.values - g_rd(*results.x, df=df)
    return np.nan * np.ones(n), np.nan * np.ones(len(df))

if __name__ == '__main__':
    print('Perform mixed effects on the following equation')
    formula='delta ~ (1|EQEvent) + (1|profiletype)'
    while error > 0.05:
        i += 1
        if i > 50:
            print('{} iterations w/o convergence'.format(i))
        results = minimize(likelihood, beta,
                           args=(g,df,True,'Rdst'),
                           method=method,
                           options=('maxiter': 1000, 'disp': False))
        df['delta'] = df.rd.values - g_rd(*results.x, df=df)
        df['Rdst'] = df['rd'].values
        n = len(beta) - 1
        beta = params[:n]
        error = 2.5
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
    
    if i > 0:
        print('{} iterations w/o convergence'.format(i))
    pdb.set_trace()
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
    
    results = minimize(likelihood, beta,
                       args=(g,df,True,'Rdst'),
                       method=method,
                       options=('maxiter': 1000, 'disp': False))
    df['delta'] = df.rd.values - g_rd(*results.x, df=df)
    return np.nan * np.ones(n), np.nan * np.ones(len(df))
# get the random effects out and
randicts = com.convert_robj(robjects.r.ranef(test1))

pft = randicts['profiletype']
eqe = randicts['EQEvent']
pft['profiletype'] = pft.index
eqe['EQEvent'] = eqe.index
df = pd.merge(df,pft)
df.rename(columns={'(Intercept)':'ranefpt'}, inplace=True)
df = pd.merge(df,eqe)
df.rename(columns={'(Intercept)':'ranefEQ'}, inplace=True)
df['Rdst'] = df['rd'] - df['ranefpt'] - df['ranefEQ']
	error = np.max(np.abs(beta - results.x)/results.x)
beta = results.x

df.drop(['ranefpt', 'ranefEQ'], inplace=True, axis=1)

# Run the maximum likelihood on RDst
#Calculate Delta again and iterate until something converges.
return results.x[:-1], df['delta'].values

def calcRdCoeffs(**kwargs):
    funform = kwargs.get('funform', 'old')
    # This is for the old Method with Mw only...
    if funform == 'old':
        g = g_rd
        beta = [-4.49, 0.412, -46.3, 10, 0.5]
    elif funform == 'newsimp':
        g = g_rd_2
        beta = [-5.5, 0.58, -178, 38.7, 0.15]
    elif funform == 'newsimp2':
        g = g_rd_2b
        beta = [-4.23574983e+00, 4.04362656e-01, -6.01823842e-04, -8.72882189e-01,
                2.45975834e-01, 1.33266544e-02, 1.25455003e-01]
    elif funform == 'newsimpc':
        g = g_rd_2c
        beta = [-3.76528156e+00, 3.43265161e-01, -7.11339416e-04, -3.74960396e-01,
                1.32108560e-01]
    elif funform == 'complex':
        g = g_rd_complex
        beta = [-6.2, 0.4, -0.005, 1.3, -16, 2.3, -2.4, 2.8, 0.15]
    elif funform == 'med':
        g = g_rd_med
        beta = [-4.1889375e+00, 4.0778034e-01, -1.08253122e+00, 3.41554683e+00, 4.70286054e+01, 1.28247701e-01]
    else:
        g = kwargs.get('g')
        beta = kwargs.get('beta')

lenresults = len(beta) - 1
comb = kwargs.get('comb', False)
CEUS = kwargs.get('CEUS', False)
if comb:
    if CEUS:
        infile = kw_args.get('infile',
            'IO_CEUS_Comb23Mar2015.h5')
    else:
        infile = kw_args.get('infile',
            'IO_WUS_Comb23Mar2015.h5')
else:
    if CEUS:
        infile = kw_args.get('infile',
            'IO_CEUS_Sing20Mar2015.h5')
    else:
        infile = kw_args.get('infile',
            'IO_WUS_Sing19Mar2015.h5')
fileout = 'rdStats-out.txt'
results0 = pd.read_hdf(infile, 'EquivLinIters')
#PIcutoff = kwargs.get('PIcutoff', 50)
Depthcutoff = kwargs.get('Depthcutoff', 3555)
if comb:
    results = results0[(results0['Depth'] < Depthcutoff) & (results0.Neq_comb > 0)]
else:
    results = results0[(results0['Depth'] < Depthcutoff) & (results0.N_EQ > 0)]
results['EQEvent'] = results['EQEvent'].astype(int)
results['profiletype'] = results['profiletype'].astype(int)
print('

File In: {}'.format(infile))
print('File Out: {}'.format(fileout))
N = kwargs.get('N', 10)
samplesize = kw_args.get('samplesize', 1000)
#mycolumns = kw_args.get('mycolumns', ['rd', 'Eq_Mag', 'Depth',
    'EQEvent', 'profiletype', 'amax_surf', 'Vs12', 'Vs30'])
mycoeffs = np.zeros((N,lenresults), dtype=float)
stdevs = np.zeros((N,))
means = np.zeros((N,))
allresids = np.zeros((N, samplesize))
for i in xrange(N):
    if i % 5 == 0:
        sys.stdout.write(' .')
    if i % 25 == 0:
        sys.stdout.write('{:}'.format(i))
        sys.stdout.flush()
    ind = np.random.choice(results.index.values, samplesize, replace=False)
subset = results.loc[ind, mycolumns]
#subset.dropna(inplace=True) # I have to do this because of missing CLSTD values
#n = 4

if kwargs.get('RegressType', 'Old') == 'ARM':
    coefs, resids = calcRdARM(subset, g = g, beta=beta)
else:
    coefs, resids = calcRd(subset, g = g, beta=beta, mixedeffects=False)
stdevs[i] = np.sqrt(np.nanvar(resids))
means[i] = np.nanmean(resids)
if np.any(np.abs(resids) == np.inf):
    pdb.set_trace()
else:
    mycoeffs[i, :] = np.nan
    allresids[i, :] = resids

#Sanitize it
stdevs[stdevs == np.inf] = np.nan
means[means == np.inf] = np.nan
mycoeffs[mycoeffs == np.inf] = np.nan
allresids[allresids == np.inf] = np.nan
stdevs[stdevs == -np.inf] = np.nan
mycoeffs[mycoeffs == -np.inf] = np.nan
allresids[allresids == -np.inf] = np.nan

if kwargs.get('plots', False):
    print(np.std(resids))
    fig, axs = plt.subplots(nrows=2, ncols=1, num=j, sharex=False, sharey=True)
    ms = 2.5
    alpha = 0.8
    marker = 'o'
    color = '0.2'
    linestyle = ''
    ylim = 2
    if j == 0:
        #plt.figure('Resid vs amax')
        axs[0].semilogx(subset.amax_surf.values[::10], resids[::10],
                        marker=marker, linestyle=linestyle, ms=ms, color=color, alpha=alpha)
        xmin, xmax = subset.amax_surf.min(), subset.amax_surf.max()
        axs[0].plot([0.00001,5], [0,0], lw=0.8, color='0.30')
        axs[0].axis([xmin,xmax, -ylim, ylim])
        axs[0].set_xlabel('$PGA$ (g)')
        axs[0].set_ylabel('Residuals')
        #plt.figure('Resid vs Mw')
        axs[1].plot(subset.Eq_Mag.values[::10], resids[::10],
                    marker=marker, linestyle=linestyle, ms=ms, color=color, alpha=alpha)
        xlin, xmax = subset.Eq_Mag.min(), subset.Eq_Mag.max()
        axs[1].plot([xlin,xmax], [0,0], lw=0.8, color='0.30')
        axs[1].axis([xlin,xmax, -ylim, ylim])
        axs[1].set_xlabel('$M_w$')
        axs[1].set_ylabel('Residuals')
```python
else:
    #plt.figure('Resid vs CLSTD')
    axs[0].semilogx(subset.CLSTD.values[::10], resids[::10],
        marker=marker, linestyle=linestyle, ms=ms, color=color, alpha=alpha)
    xmin, xmax = subset.CLSTD.min(), subset.CLSTD.max()
    axs[0].plot([1,200], [0,0], lw=0.8, color='0.30')
    axs[0].axis([1, 200, -ylim, ylim])
    axs[0].set_xlabel('$R$ (km)')
    axs[0].set_ylabel('Residuals')
    #plt.figure('Resid vs Mw')
    axs[1].plot(subset.Eq_Mag.values[::10], resids[::10],
        marker=marker, linestyle=linestyle, ms=ms, color=color, alpha=alpha)
    xmin, xmax = subset.Eq_Mag.min(), subset.Eq_Mag.max()
    axs[1].plot([xmin,xmax], [0,0], lw=0.8, color='0.30')
    axs[1].axis([xmin, xmax, -ylim, ylim])
    axs[1].set_xlabel('$M_w$')
    axs[1].set_ylabel('Residuals')
    #plt.tight_layout()
    plt.subplots_adjust(wspace=0.2, hspace=0.55)
    plt.locator_params(axis='y', nbins=4)

# Write the results out
if kwargs.get('PrintOut', True):
    with open(fileout, 'a') as f:
        f.write(strftime('%d%b%Y', gmtime())+ ' 
')
        f.write('Data File: {}
'.format(infile))
        f.write('Number of Iterations: {}
'.format(N))
        f.write('Sample Size: {}
'.format(samplesize))
        #f.write('PI<{}

'.format(PIcutoff))
        f.write('z<{}m

'.format(Depthcutoff))
        f.write('Formula: {}:
'.format(funform))
        f.write('g: {}

'.format(g))
        #f.write(formula + ' 

')

f.write('Table: Regression Coefficients\n')
align = [('^','<')] + [ ('^','^') for j in range(lenresults)]
header = (['Database'] +
    [ '${a}_{}$'.format(j+1) for j in range(lenresults)])
database = 'CEUS' if CEUS else 'WUS'
data = [tuple([database] +
    ['{:10.4g}'.format(val) for val
    in np.nanmedian(mycoeffs, axis=0)])]
    #tuple([ ' ' for j in range(lenresults[1]+1)])
fields = range(lenresults+1)
pan.table(f, data, fields, header, align)
    f.write('\n
')

f.write('Table: Standard Deviations of Regression Coefficients\n')
    header = (['Database'] +
        ['${\sigma}_{a_{}'}'.format(j+1) + ']$ for j in range(lenresults))
    database = 'CEUS' if CEUS else 'WUS'
    data = [tuple([database] +
        ['{:10.4g}'.format(val) for val
        in np.nanstd(mycoeffs, axis=0)])]}
    #tuple([ ' ' for j in range(lenresults[1]+1)])
    fields = range(lenresults+1)
    pan.table(f, data, fields, header, align)
    f.write('\n
')
```

J.7 Fit of Limit-State Curves

The file CaseHistoriesv3.py calculates the dissipated energy for each case history in a database and fits a limit-state curve to the data. It also deals with the uncertainties and
compares with other prominent liquefaction evaluation procedures for SPT.

```python
import sys
import os
if os.name == 'posix':
    sys.path.append('/media/Storage/Documents/Python/Modules')
else:
    sys.path.append('E:\Documents\Python\Modules')

import matplotlib
matplotlib.rcParams.update({'font.size': 18, 'text.usetex': True, 'legend.fontsize': 16})
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D
from matplotlib.ticker import MaxNLocator
import numpy as np
import pandas as pd
from scipy.stats import norm
try:
    import ipdb as pdb
except:
    import pdb
from scipy.optimize import minimize, curve_fit
from scipy.interpolate import interp1d, RectBivariateSpline
import degrcurv as dc
import pandoctable as pan

def strip(text):
    try:
        return text.strip()
    except AttributeError:
        return text

def getDegrad(Degrad, PI, sigmeff, **kwargs):
    '''
    Outputs a 1D array (gam = shear strain (decimal) and 2- 2D arrays
    (Gratio = G/Gmax and damping (decimal)) that represent the shear
    modulus and damping degradation curves. It depends on the module
degrcurv, so use that if you want to customize it. Or, create your own
degradation curves.
    Right now, Degrad must equal 'IZ' for the Ishibashi and Zhang (1993) or
    'DS' for Darendeli and Stokoe (2001) curves.
    sigmeff must be in kPa
    '''
    #straindef = np.array([0.000001, 0.000003, 0.00001, 0.00003, 0.0001,
    #                      0.003, 0.01, 0.03, 0.01, 0.99,10,100])
    #straindef = np.logspace(-6, 0, 100) / 100.
    straindef = np.logspace(-5, 0., 300) / 100. # Darendeli (2001): pg.228 (258)
    if Degrad == 'IZ':
        if np.isscalar(PI):
            PI = np.array([PI])
```
OCR = kwargs.get('OCR', 1.)
soil = kwargs.get('soil', 1.)
N = kwargs.get('N', 10.)
freq = kwargs.get('freq', 1.)
Dmintype = kwargs.get('Dmintype', 1.)
if np.isscalar(OCR):
    OCR = np.ones(len(PI), dtype=float) * OCR
if np.isscalar(soil):
    soil = np.ones(len(PI), dtype=int) * soil
if np.isscalar(N):
    N = np.ones(len(PI), dtype=float) * N
if np.isscalar(freq):
    freq = np.ones(len(PI), dtype=float) * freq
if np.isscalar(sigmeff):
    sigmeff = np.ones(len(PI), dtype=float) * sigmeff
gam = kwargs.get('gam', straindef)
damping = np.zeros([len(PI), len(gam)], dtype=float)
Gratio = np.zeros([len(PI), len(gam)], dtype=float)
for i in xrange(len(PI)):
    if Degrad == 'IZ':
        gam, Gratio[i, :], damping[i, :] = dc.IZ_1993(gam=gam,
                                                  PI=PI[i],
                                                  sigm=sigmeff[i])
    elif Degrad == 'DS':
        gam, Gratio[i], damping[i] = dc.DS_2001(gam=gam,
                                                  PI=PI[i],
                                                  sigm=sigmeff[i],
                                                  OCR=OCR[i],
                                                  soil=soil[i],
                                                  N=N[i],
                                                  frq=freq[i])
return gam, Gratio, damping

def DobryIter(gam, Gratio, damping, Gmax, tau_avg, error=0.01):
    '''
    This function will estimate degraded damping and degraded modulus
    by iteration and using shear modulus and damping degradation curves:
    Inputs:
    gam An array of shear strains (decimal) of length n
    Gratio An array (matrix) of shear modulus degradation curves of
    shape m X n where m is the number of layers
    damping An array of damping degradation curves, also m X n
    Outputs: Two arrays: G and D, each of length m.
    '''
    try:
        len(tau_avg)
    except TypeError:
        tau_avg = [tau_avg]
    Gmax = [Gmax]
    G_ = np.zeros([len(tau_avg)], dtype=float)
    D_ = np.zeros([len(tau_avg)], dtype=float)
    gam_ = np.zeros([len(tau_avg)], dtype=float)
    for j in xrange(len(tau_avg)):
        if len(tau_avg) == 1:
Damp = np.ravel(damping)
Grat = np.ravel(Gratio)
else:
    Damp = np.ravel(damping[j,:])
    Grat = np.ravel(Gratio[j,:])
gamma = gam[0]
gamma0 = gamma + 0.0000001
Gratiocurv = interp1d(np.log10(gam), Grat,
                      kind='linear')
Dcurv = interp1d(np.log10(gam), Damp,
                 kind='linear')
thiserror = 1
count = 0
try:
    while thiserror > error:
        count += 1
        if count > 50:
            print('Layer %s did not converge!'%str(j))
            print('Error = {:.5f}'.format(thiserror))
            break
        G = Gmax[j] * Gratiocurv(np.log10(gamma))
        gamma = tau_avg[j] / G
        thiserror = abs(gamma - gamma0) / gamma0
        gamma0 = gamma
        D = Dcurv(np.log10(gamma))
        gam__ = gamma
except ValueError:
    if gamma > gam[-1]:
        G = Gmax[j] * Grat[-1]
        D = Damp[-1]
        gam__ = gam[-1]
    else:
        G = Gmax[j] * Grat[0]
        D = Damp[0]
        gam__ = gam[0]
    print('Interp error!')
G_[j] = G
D_[j] = D
gam_[j] = gam__
if len(tau_avg) == 1:
    return G_[0], D_[0], gam_[0]
else:
    return G_, D_, gam_

def TokimatsuSeedDirect(gam, Gratio, damping, Gmax, tau_avg, **kwargs):
    '''
    This function will estimate degraded damping and degraded modulus
    by iteration and using shear modulus and damping degradation curves:
    
    Inputs:
    gam An array of shear strains (decimal) of length n
    Gratio An array (matrix) of shear modulus degradation curves of
    shape m x n where m is the number of layers
    damping An array of damping degradation curves, also m x n
    Gmax The small strain shear modulus
    '''

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tau_avg The average shear stress

Outputs: Three arrays: G, D, and gamma each of length m.

```python
returnError = kwargs.get('returnError', False)
G_ = np.zeros(Gratio.shape[0], dtype=float)
D_ = np.zeros(Gratio.shape[0], dtype=float)
gam_ = np.zeros(Gratio.shape[0], dtype=float)
ErrorList = []
if np.isscalar(Gmax):
    Gmax = [Gmax]
if np.isscalar(tau_avg):
    tau_avg = [tau_avg]
for i in xrange(len(Gmax)):
    if i == 208: pdb.set_trace()
    Damp = np.ravel(damping[i, :])
    Grat = np.ravel(Gratio[i, :])
    gam_Grat = gam * Grat
    gamGratiocurv = interp1d(np.log10(gam_Grat), np.log10(gam),
                            kind='linear')
    Gratocurv = interp1d(np.log10(gam), Grat,
                         kind='linear')
    Dcurv = interp1d(np.log10(gam), Damp,
                     kind='linear')
    try:
        newgam = 10 ** (gamGratiocurv(np.log10(tau_avg[i] / Gmax[i])))
    except ValueError:
        if newgam > gam_[-1]:
            G_[i] = Gmax[i] * Grat[-1]
            D_[i] = Damp[-1]
            gam_[i] = gam[-1]
            print('Gamma exceeds range!, i={}'.format(i))
            ErrorList.append(i)
        else:
            switch=False
            G_[i] = Gmax[i] * Gratocurv(np.log10(newgam))
            D_[i] = Dcurv(np.log10(newgam))
            gam_[i] = newgam
    if returnError:
        if len(G_) == 1:
            return G_[0], D_[0], gam_[0], ErrorList
        else:
            return G_, D_, gam_, ErrorList
    else:
        if len(G_) == 1:
            return G_[0], D_[0], gam_[0]
        else:
            return G_, D_, gam_
```

```
CombinedWUS = ' 0.4208 | -0.3989 | 0.2457'
CombinedCEUS = ' 1.209 | -0.5448 | 0.1363'
SingleWUS = ' -0.3643 | -0.4105 | 0.2553'
```

---

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if Comb:
    if CEUS:
        a = [float(val) for val in CombinedCEUS.split('|')]
        sig = ErrorCombinedCEUS
    else:
        a = [float(val) for val in CombinedWUS.split('|')]
        sig = ErrorCombinedWUS
    return np.exp(a[0] + a[1] * np.log(PGA) + 0. * z + a[2] * Mw), sig
else:
    if CEUS:
        a = [float(val) for val in SingleCEUS.split('|')]
        sig = ErrorSingleCEUS
    else:
        a = [float(val) for val in SingleWUS.split('|')]
        sig = ErrorSingleWUS
    # Multiply by two for both components of motion
    return np.exp(a[0] + a[1] * np.log(PGA) + 0. * z + a[2] * Mw)*2, sig

class CaseHists(object):
    '''
    This object holds the information and performs all the initial calcs
    on the case history database file. It prepares it for the limit-state
    fitting.
    '''
    def __init__(self, **kwargs):
        self.kwargs = kwargs
        self.unit_wt_below = kwargs.get('unit_wt_below', 19.5)
        self.unit_wt_above = kwargs.get('unit_wt_above', 17)

        self.sigeffvlimit = kwargs.get('sigeffvlimit', 40.)  # kPa
        print('Lower limit of sigveff is {} kPa for Degrad Curves'.format(  
            self.sigeffvlimit))

        self.altDw= kwargs.get('altDw', False)# Applies an exponential to the sigveff
        self.altCycles = kwargs.get('altCycles', False) # divides vals by 2
        self.N_Gmaxtype = kwargs.get('N_Gmaxtype', 'Seedetal')
        if 'df' in kwargs.keys():
            self.df = kwargs.get('df')
        else:
            datafile = kwargs.get('infile', './Boulanger er al 2012.csv')
            if 'FCrange' in kwargs.keys():
                FCs = kwargs.get('FCrange')
                df0 = pd.read_csv(datafile)  
                self.df = df0[(df0.FC >= FC0) &  
                    (df0.FC < FCs[1])].copy()  
                self.df.index = np.arange(self.df.shape[0])
            else:
                self.df = pd.read_csv(datafile, converters = {'Liq' : strip})
        if 'sigv' not in self.df.columns:
            if 'FCrange' in kwargs.keys():
                FCs = kwargs.get('FCrange')
                df0 = pd.read_csv(datafile, converters = {'Liq' : strip})
                self.df = df0[(df0.FC >= FCs[0]) &  
                    (df0.FC < FCs[1])].copy()  
                self.df.index = np.arange(self.df.shape[0])
            else:
                self.df = pd.read_csv(datafile, converters = {'Liq' : strip})
        if 'sigv' not in self.df.columns:
self.df['sigv'], self.df['sigeffv'] = self.calcInsituStresses(**kwargs)

if kwargs.get('calcN160', True):
    print('Calculating N160cs...')
    Ncorrtype = kwargs.get('Ncorrtype', 'IB')
    self.df['N160cs'], self.df['delN160'], Cr, Ch, Cs = calcN160cs(
        self.df.Nm.values,
        self.df.sigeffv.values,
        self.df.FC.values, self.df.z.values,
        Ce=self.df.CE.values, Cs=self.df.CS.values,
        Cb=self.df.CB.values,
        returnall=True, Ncorrtype=Ncorrtype)
    self.df['N160'] = self.df['N160cs'] - self.df['delN160']
    self.df['N60'] = self.df['N160'] / Ch
    self.df['N160_Cetin'], Cr, Ch, Cs = calcN160cs(
        self.df.Nm.values,
        self.df.sigeffv.values,
        self.df.FC.values, self.df.z.values,
        Ce=self.df.CE.values, Cs=self.df.CS.values,
        Cb=self.df.CB.values,
        Cetin=True, returnall=True)
else:
    if 'N160cs' in self.df.columns:
        self.df['delN160'] = self.df['N160cs'] - self.df['delN160']
    else:
        self.df['delN160'] = calcDN160(self.df.FC.values)
    self.df['N160cs'] = self.df['delN160'] + self.df['N160']

def calcDissEn(**kwargs):
    self.df['Neq'], self.df['Neqerror'] = Neq_sl(self.df.amax.values,
        self.df.Mw.values, self.df.z.values, CEUS=False,
        Comb=False)#Degrad=self.Degrad)
    if self.altCycles:
        print('Using altCycles....... Dividing by 2')
        self.df['Neq'] = self.df['Neq'].values / 2.
    self.Degrad = kwargs.get('Degrad', 'DS')
    useVs = kwargs.get('useVs', False)
    self.useVs = useVs
    if kwags.get('rd') == 'Lasley':
        self.df['rd'] = self.calcrd()
    elif kwags.get('rd') == 'IB':
        self.df['rd'] = self.calcrd(type='IB')
        self.df['ko'], self.df['phi'] = self.calcKo()
        self.df['tauavg'] = self.calctauavg()
        self.df['sigmeff'] = self.calcSigmae( limit=False)
        self.df['sigmeff_alt'] = self.calcSigmae( limit=True)
        self.df['Gmax'] = self.calcGmax(limit=False)
        if self.Degrad == 'IZ':
            print('Ishibashi and Zhang Degrad Curves')
            self.gam, self.Gratio, self.damping = getDegrad('IZ',
                np.zeros(self.df['tauavg'].values.shape),
            )
self.df['sigmeff_alt'].values)

else:
    print('Darendeli and Stokoe Degrad Curves')
    FC = self.df.FC.values
    Soiltype = np.zeros(FC.shape)
    Soiltype[FC>10] = 2
    Soiltype[FC >= 50] = 3
    self.df['DS_soil'] = Soiltype
    self.gam, self.Gratio, self.damping = getDegrad('DS',
        np.zeros(self.df['tauavg'].values.shape),
        self.df['sigmeff_alt'].values,
        soil=Soiltype, N = 2. * self.df.Neq.values
    )
    if useVs:
        self.calcGmaxVs()
    if kwargs.get('GDtype', 'direct') == 'direct':
        print('TokiSeedDirect')
        self.df['G'], self.df['D'], self.df['gamma'], self.TS_Errors =
            TokimatsuSeedDirect(
                self.gam, self.Gratio, self.damping, self.df.Gmax.values,
                self.df.tauavg.values, returnError=True)
    else:
        print('DobryIter')
        self.df['G'], self.df['D'], self.df['gamma'] = DobryIter(self.gam,
            self.Gratio, self.damping, self.df.Gmax.values,
            self.df.tauavg.values)
        self.calcGDerror()
    self.df['dW'] = (2 * np.pi * self.df['D'] * self.df['tauavg'] ** 2
        * self.df['Neq'] / self.df['G'])

if 'Liq' in self.df.columns:
    # You need 'Liq' for fitting the curve, but not for forward analysis
    Liq = self.df['Liq'].values
    self.gsign = np.zeros(self.df.Liq.shape)
    self.ind1 = np.where(Liq == 'Yes')
    self.ind2 = np.where(Liq == 'No')
    self.ind3 = np.where(Liq == 'Marginal')
    self.Liq2 = np.zeros(Liq.shape, dtype=float)
    self.Liq2[self.ind2] = 0.
    self.Liq2[self.ind3] = 0.5
    self.gsign[self.ind1] = -1
    self.gsign[self.ind3] = 0
    self.gsign[self.ind2] = 1
    self.altwt = np.ones(self.df.Neq.values.shape)
    if useVs:
        self.update_altwt(kwvars.get('altwt', 0.3))
    self.dfVs = self.df[~np.isnan(self.df.Vs1.values)]
    self.dfVs.index = range(len(self.dfVs))
    self.calcVsError()
    if self.altdWn:
        print('using altdWn.......
        self.df['dWn'] = self.df['dW'] / self.df['sigeffv'] ** 1.11
    else:
        self.df['dWn'] = self.df['dW'] / self.df['sigeffv']

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#self.df['logdWn'] = np.log(2 * np.pi * 9.81 * 0.65 ** 2 *
#self.df['D'] * self.df['amax'] * self.df['sigv'] ** 2 *
#self.df['Neq'] / (np.exp(self.df['logVs']) *
#self.df['unit_wt_below'] * self.df['G'] / self.df['Gmax'])

self.df['logdWn'] = (np.log(2 * np.pi * 0.65 ** 2 * 9.81) + np.log(self.df['D']) + 2 * np.log(self.df['amax']) + 2 * np.log(self.df['sigv']) + 2 * np.log(self.df['rd']) + np.log(self.df['Neq']) - 2 * np.log(self.df['logVs']) - np.log(self.df['unit_wt_below']) - np.log(self.df['G']) / self.df['Gmax'])

self.df = self.calcUncertainty()

def calcInsituStresses(self, **kwargs):
    '''
    This function assumes that I am looking at a profile. Thus, it won't work for a case history database. If you have a case history database, you better calc your sigvs and sigeffvs before you input the dataframe into the CaseHists object.
    '''
    print('Calculating my total and effective overburden stresses...')
    if 'gwt' in kwargs.keys():
        gwt = kwargs['gwt']
    elif 'gwt' in self.df.columns:
        gwt = self.df.gwt.values[0]
    else: gwt = 0.

    unitwta = self.df.unit_wt_above
    unitwtb = self.df.unit_wt_below
    z = self.df.z.values
    sigv = (np.maximum(0.,(z-gwt)) * unitwta + np.minimum(z,gwt) * unitwtb)
    sigeffv = sigv - np.maximum(0, z-gwt) * 9.81
    return sigv, sigeffv

    def update_altwt(self, wt):
        '''
        This method allows me to update my weighting for case histories with measured shear wave velocities.
        '''
        self.altwt[np.isnan(self.df.Vs1pm.values)] = wt

    def calcGDerror(self):
        '''
        This returns the errors from the degradation curves. The D and S values are given in Chapter 11? of Darendeli's Dissertation.
        '''

    def calcGDerror(self):
if self.Degrad != 'DS':
    self.df['Derror'] = 1.
    self.df['Graterror'] = 0.1
    # These values are placeholders, I&Z don't give any values in their paper
else:
    gam = np.array([0.00001, 0.000022, 0.0000484, 0.0001, 0.00022, 0.000484, 0.01, 0.022, 0.0484, 0.1, 0.22, 0.484, 1])
    Gratio = np.array([0.01836, 0.01979, 0.02254, 0.02553, 0.03026, 0.03683, 0.04523, 0.05699, 0.07116, 0.08438, 0.09454, 0.09556, 0.08784, 0.07407, 0.05961, 0.04818])
    Damp = np.array([0.70766, 0.7093, 0.71422, 0.72232, 0.74132, 0.78058, 0.8525, 0.99402, 1.23299, 1.55606, 2.00485, 2.49242, 2.89875, 3.23658, 3.45147, 3.55137])
    Gratiocurv = interp1d(np.log10(gam), Gratio, kind='linear')
    Dcurv = interp1d(np.log10(gam), Damp, kind='linear')
    try:
        Derror = np.zeros(len(self.df))
        Graterror = np.zeros(len(self.df))
        gamma = self.df['gamma'].values*100 # gamma now in percent
        Derror[gamma <= gam[0]] = Damp[0]
        Graterror[gamma <= gam[0]] = Gratio[0]
        Derror[gamma >= gam[-1]] = Damp[-1]
        Graterror[gamma >= gam[-1]] = Gratio[-1]
        Derror[(gamma > gam[0]) & (gamma < gam[-1])] = Dcurv(np.log10(gamma[(gamma > gam[0]) & (gamma < gam[-1])]))
        Graterror[(gamma > gam[0]) & (gamma < gam[-1])] = Gratiocurv(np.log10(gamma[(gamma > gam[0]) & (gamma < gam[-1])]))
    except ValueError:
        pdb.set_trace()
    self.df['Derror'] = Derror / 100. # Convert into decimal
    self.df['Graterror'] = Graterror

def calcrd(self, **kwargs):
    '''
    Two options to calculate the stress reduction coefficient.
    You know you want to use mine. Just do it!
    '''
    Mw = self.df.Mw.values
    z = self.df.z.values
    if kwargs.get('type', 'Lasley') == 'IB':
        alpha = -1.012 - 1.126 * np.sin(np.minimum(z, 34.) / 11.73 + 5.133)
        beta = 0.106 + 0.118 * np.sin(np.minimum(z, 34.) / 11.28 + 5.142)
        return np.exp(alpha + beta * Mw)
    else:
        coeftext = ' -4.031 | 0.364 | -28.47 | 7.798'
        coeftext = ' -5.173 | 0.5094 | -16.81 | 5.591'
        coefs = [float(val) for val in coeftext.split(' | ')]
        alpha = np.exp(coefs[0] + coefs[1] * Mw)
        return np.exp((1 - alpha) * np.exp(-z / beta) + alpha, 1.)
def calctauavg(self):
    '''
    Average shear stress from PGA. Assumes a factor of 0.65
    '''
    df = self.df
    amax = df['amax'].values
    sigv = df['sigv'].values
    rd = df['rd'].values
    return 0.65 * amax * sigv * rd

def calcKo(self, **kwargs):
    which = kwargs.get('phitype', 'old')
    PhiVar = kwargs.get('PhiVar', 'N160cs')
    N = self.df[PhiVar].values
    sigeffv = self.df['sigeffv'].values
    if which == 'old':
        phi = np.sqrt(15.4 * N) + 20. # Hatanaka and Uchida, 1996, Sabatini et al. 2002
        # np.sqrt(20. * N1) + 20. originally # Hatanaka and Uchida, 1996
        # np.sqrt(15.4 * N) + 20. # Sabatini et al. 2002
    else:
        # Kulhawy and Wayne 1990, see Holtz et al. Eqn. 12.5, pg. 559
        # After Schmertmann 1975
        # I could never get this to work, plus, uses reg. N value, not corrected for
        # overburden pressures.
        phi = np.arctan((N / (12.2 + 20.3 * sigeffv / 101.325)) * np.pi / 180.)
    Ko = 1 - np.sin(phi * np.pi / 180.) # Jaky 1944, 1948
    return Ko, phi

def calcsigmeff(self, **kwargs):
    '''
    Calculates mean effective confining stress.
    Make sure your ko values are right.
    '''
    df = self.df
    ko = df['ko'].values
    if kwargs.get('limit', True):
        sigveff = np.maximum(self.sigeffvlimit, df['sigeffv'].values)
    else:
        sigveff = df['sigeffv'].values
    return (1 + 2 * ko) * sigveff / 3.

def calcGmax(self, **kwargs):
    '''
    Two options to calculate Gmax from SPT blow count.
    '''
    limit = kwargs.get('limit', False)
    if self.N_Gmaxtype == 'Seedetal':
        df = self.df
        GmaxVar = self.kwargs.get('GmaxVar', 'N160cs')
        # N = df['N160cs'].values # Seed et al. 1986 use N160
        # N = df['N160'].values
        # N = df['N60'].values # per Wair et al, you shouldn’t used overburden-corrected
        N = df['GmaxVar'].values
        print('Using {} for the Seed et al. Gmax Equation'.format(GmaxVar))
if limit:
    sigmeff = df['sigmeff_alt'].values
else:
    sigmeff = df['sigmeff'].values
return 440. * N ** (1/3.) * 101.325 * (sigmeff/101.325) ** 0.5 # Seed et al. 1986

if self.N_Gmaxtype == 'SeedetalALT':
    print('Using Seed et al. Alt Gmax equation...')
    beta = self.kwargs.get('SeedGmaxBeta', [249.6, 0.2779, 0.35198])
    df = self.df
    GmaxVar = self.kwargs.get('GmaxVar', 'N160')
    N = df[GmaxVar].values
    if limit:
        sigmeff = df['sigmeff_alt'].values
    else:
        sigmeff = df['sigmeff'].values
else: # Wair et al. (2012), PEER 2012/08
    df = self.df
    unit_wt = self.unit_wt_below
    if limit:
        sigeffv = np.maximum(df.sigeffv.values, self.sigeffvlimit)
    else:
        sigeffv = df.sigeffv.values
    N = df['N60'].values
    Vs = 30 * N ** 0.23 * sigeffv ** 0.23 # For Sand
    #Vs = 30 * N ** 0.215 * sigeffv ** 0.275 # For All Soils
    Gmax = Vs ** 2 * unit_wt / 9.81
    return Gmax

def calcGmaxVs(self):
    '''
    Calculating Gmax from the measured shear wave velocity.
    Notice that I have to have a value of unit weight.
    I'm using the same one as in the __init__ function
    '''
    df = self.df
    # From foundations 1:
    # Getting the Gmax from Vs1, but first I have to get the unit weight
    # of the soil.
    Vs = df.Vs.values
    N160cs = df.N160cs.values
    Gmax2 = np.copy(df.Gmax.values)
    sigv = df.sigv.values
    z = df.z.values
    if self.kwargs.get('myunitwt', 'assumed') == 'fromSPT':
        for i, vs in enumerate(Vs):
            if np.isnan(vs):
                pass
            else:
                N = N160cs[i]
                if N < 4:
                    pass
                elif N < 10:
elif N < 30:
    unitwt = 122.4 + (N - 10.) * (132.4 - 122.4) / (30. - 10.)
elif N < 50:
    unitwt = 127.4 + (N - 30.) * (147.4 - 127.4) / (50. - 30.)
else: # If it is above the range, I'll just use the Gmax calculated from
    # N160cs
    continue
Gmax2[i] = vs ** 2 * unitwt / 62.4 * 9.81 / 9.81
self.df['Gmax'] = Gmax2

# This might be a little messed up: how to apply cov?
# to the logVs or to Vs?

def calcVsError(self):
    Gmax = self.df.Gmax.values
    if self.useVs:
        Vs = self.df['Vs1'].values
        Vs[np.isnan(Vs)] = np.sqrt(Gmax[np.isnan(Vs)]) * 9.81 / 
        self.unit_wt_below
        #logVs = np.log(Vs)
        #logVsError = np.zeros(len(self.df))
        #logVsError[np.isnan(self.df.Vs1pm.values)] = logVs[
        #    np.isnan(self.df.Vs1pm.values)] * .25 #<<<<<<<<<<<<<<
        #logVsError[np.isnan(self.df.Vs1pm.values)] = (0.5 * logVs[np.isnan(
        #    self.df.Vs1pm.values)])
        VsError = np.zeros(len(self.df))
        VsError[np.isnan(self.df.Vs1pm.values)] = Vs[
            np.isnan(self.df.Vs1pm.values)] * .25 #<<<<<<<<<<<<<<
        VsError[np.isnan(self.df.Vs1pm.values)] = (0.5 * Vs[np.isnan(
            self.df.Vs1pm.values)])
    else:
        logVs = np.log(np.sqrt(Gmax * 9.81 / self.unit_wt_below))
        logVsError = 0.5 * logVs # From Brady Cox
        Vs = np.sqrt(Gmax * 9.81 / self.unit_wt_below)
        VsError = 0.5 * Vs # From Brady Cox

    self.df['logVs'], self.df['logVserror'] = transformToLog(Vs, VsError)
    self.df['Verror'] = VsError
    self.df['Vs'] = Vs

def to_pickle(self, **kwargs):
    # Allows me to send out my dataframe to a pickle.
    # To read it in, use pandas.read_pickle(...)
if self.useVs:
    fileout = kwvars.get('fileout', 
        '/media/Storage/Documents/00-VtResearch/Thesis/Markdown/+' 
        'Figures/LimitState/LimStDF_Vs.pickle')
else:
    fileout = kwvars.get('fileout', 
        '/media/Storage/Documents/00-VtResearch/Thesis/Markdown/+' 
        'Figures/LimitState/LimStDF.pickle')
# import pickle
# limitstatedata = {'N160cs':df.N160cs.values,
#                   'dW': df.dW.values,
#                   'dWn': df.dWn.values,
#                   'sigveff' : df.sigveffv.values,
#                   'Liq': df.Liq.values}
# pickle.dump(limitstatedata, open('limStatedata.p', 'wb'))
self.df.to_pickle(fileout)

def calcUncertainty(self, **kwvars):
    '''
    Estimates uncertainty in dWn and N160cs using the first order approx.
    '''
    df = self.df
    # N160cs first
    FC = df['FC'].values
    sigFC = kwvars.get('sigFC', 0.2 * FC) # Cetin (2000) pg. 65
    N160 = df['N160'].values
    delN160 = df['delN160'].values
    sigN = kwvars.get('sigN', np.minimum(3, 0.2 * N160)) # Cetin (2000) pg. 64
    sigN160cs = np.sqrt(sigN ** 2 +
           (delN160 * (492.883 - 9.7 * FC) / (FC + 0.01) ** 3) ** 2 *
           sigFC ** 2 )
    df['sigN160cs'] = sigN160cs
    # Now look at dWn
    unit_wt = kwvars.get('unit_wt', self.unit_wt_below)
    rho = np.eye(9)
    rho[0][1] = kwvars.get('rhoDamax', 0.)
    rho[0][2] = kwvars.get('rhoDsigv', 0.) # should be non-zero?
    rho[0][3] = kwvars.get('rhoDrd', 0.) # should be non-zero?
    rho[0][4] = kwvars.get('rhoDNeq', 0.)
    rho[0][5] = kwvars.get('rhoDVs', 0.)
    rho[0][6] = kwvars.get('rhoDunit_wt', 0.) # should be non-zero?
    rho[0][7] = kwvars.get('rhoDGrat', -0.5) # should be non-zero
    rho[0][8] = kwvars.get('rhoDsigeffv', 0.) # should be non-zero
    rho[1][2] = kwvars.get('rhoAmaxsigv', 0.)
    rho[1][3] = kwvars.get('rhoAmaxrd', 0.)
    rho[1][4] = kwvars.get('rhoAmaxNeq', 0.)
    rho[1][5] = kwvars.get('rhoAmaxVs', 0.)
    rho[1][6] = kwvars.get('rhoAmaxunit_wt', 0.)
    rho[1][7] = kwvars.get('rhoAmaxGrat', 0.)
    rho[1][8] = kwvars.get('rhoAmaxsigeffv', 0.)
    rho[2][3] = kwvars.get('rhoSigvrd', 0.)
    rho[2][4] = kwvars.get('rhoSigvNeq', 0.)
rho[2][5] = kwargs.get('rhoSigvVs', 0.)  
rho[2][6] = kwargs.get('rhoSigvunit_wt', 1.)  # Per Adrian's email 22 May 2015  
rho[2][7] = kwargs.get('rhoSigvGrat', 0.)  # should be non-zero  
rho[2][8] = kwargs.get('rhoSigvSigeffv', -1.)  # should be -1 if based on gwt alone  

rho[3][4] = kwargs.get('rhordNeq', -0.434)  # was -0.434, now 0.12 when logrderror is used  
rho[3][5] = kwargs.get('rhordVs', 0.)  
rho[3][6] = kwargs.get('rhordunit_wt', 0.)  
rho[3][7] = kwargs.get('rhordGrat', 0.)  # should be non-zero  
rho[3][8] = kwargs.get('rhordsigeffv', 0.)  

rho[4][5] = kwargs.get('rhoNeqVs', 0.)  
rho[4][6] = kwargs.get('rhoNequnit_wt', 0.)  
rho[4][7] = kwargs.get('rhoNeqGrat', 0.)  # should be non-zero???? - both estimated from amax  
rho[4][8] = kwargs.get('rhoNeqsigeffv', 0.)  

rho[5][6] = kwargs.get('rhoVsunit_wt', 0.)  
rho[5][7] = kwargs.get('rhoVsGrat', 0.)  
rho[5][8] = kwargs.get('rhoVssigeffv', 0.)  

rho[6][7] = kwargs.get('rhoUnitWtGrat', 0.)  
rho[6][8] = kwargs.get('rhoUnitWtsigeffv', 1.)  # Per Adrian's Email 22may 2015  

rho[7][8] = kwargs.get('rhoGratsigeffv', 0.)  # should be non-zero  
Rho = rho + rho.T - np.eye(9)  # To make it symmetric  

# Now get my means and standard deviations  
sig_amax = kwargs.get('sig_amax', 0.3*np.log(df.amax.values))  # Was 0.15, then 0.3  
# df['nonlog_amax'], df['sig_amax'] = transformFromLog(np.log(df['amax'].values), sig_amax)  
# df['logNeq'], df['sig_Neq'] = transformFromLog(np.log(df['Neq'].values), 
# df['logNeqerror'].values)  
sig_rd = kwargs.get('sig_rd', 0.15)  # From my rd functional form  
sig_sigv = kwargs.get('sig_sigv', 0.1 * df.sigv.values)  # See Uncertainties.ipynb  
sig_unit_wt = kwargs.get('sig_unit_wt', 0.1 * unit_wt)  # Changed to 0 per Adrian's email 22 may 2015  
sig_sigeffv = kwargs.get('sig_sigeffv', 0.1 * df.sigeffv.values)  # See Uncertainties.ipynb  

df['logD'], df['logDerror'] = transformToLog(df['D'].values, df['Derror'].values)  
df['logGrat'], df['logGraterror'] = transformToLog(df['G'].values, df['Gmax'].values, df['Graterror'].values)  
df['logsigv'], df['logsigverror'] = transformToLog(df['sigv'].values, sig_sigv)  # Need a sd for sigv here  
df['logrd'], df['logrderror'] = transformToLog(df['rd'].values, sig_rd)  # from rdStats-out25Apr2015.txt, 
# assumes constant with depth, mag  

df['logVs'], df['logVSError'] = transformToLog(df['Vs'].values, 
# df['Vserror'])  
df['logunit_wt'], df['logunit_wterror'] = transformToLog(unit_wt, df['unit_wt'].values, sig_unit_wt)  

df['logsigeffv'], df['logsigeffv_error'] = transformToLog(df['sigeffv'].values, sig_sigeffv)  # Need a sd for sigeffv here
rhosigsigeff = transformRhoToLog(df['sigv'].values, sigv, df['sigeffv'].values, sigeffv, -1.)

logdWnerror = np.zeros(len(df))
for i, row in df.iterrows():
    dels = np.array([1./row['D'],
                     2.,
                     2./row['sigv'],
                     2./row['rd'],
                     1.,
                     -2./row['logVs'], # Just added in this '/row['logVs']'
                     -1./self.unit_wt_below,
                     -1./row['G']/row['Gmax'],
                     -1./row['sigeffv'])
    # sigs is my array of standard deviations
    sigs = np.array([row['Derror'],
                     sig_amax[i],
                     sig_sigv[i],
                     sig_rd,
                     row['Neqerror'],
                     row['logVserror'],
                     sig_unit_wt,
                     row['Graterror'],
                     sig_sigeffv[i]])
    # Add in my correlation coefficients:
    Rho[2][8] = rhosigsigeff[i]
    Rho[8][2] = rhosigsigeff[i]
    # SIGMAdwn is a matrix with sig^2 on the diag, rhosigsig on off-diag
    SIGMAdWn = (Rho * sigs).T * sigs
    logdWnerror[i] = np.sqrt(np.dot(np.dot(dels, SIGMAdWn), dels))

#This is an aside to check my calcs. See checkFORM()
if len(df) == 1:
    self.SIGMA = SIGMAdWn
    #self.Rho = Rho
    self.MU = (np.log(2 * np.pi * 0.65 ** 2 * 9.81) + np.log(row['D']) # log D
               + 2 * np.log(row['amax']) # log amax
               + 2 * np.log(row['sigv']) # logsigv
               + 2 * np.log(row['rd']) # logrd
               + np.log(row['Neq']) # logNeq
               - 2 * row['logVs'] # logVs
               - np.log(unit_wt) # Unit wt
               - np.log(row['G']/row['Gmax']) # Grat
               - np.log(row['sigeffv']) # logsigeffv)
    self.MUs = np.array([np.log(row['D']), # log D
                         np.log(row['amax']), # log amax
                         np.log(row['sigv']), # logsigv
                         np.log(row['rd']), # logrd
                         np.log(row['Neq'])], # logNeq
def transformFromLog(mean, sig):
    '''
    For the mean and standard deviations of the distribution
    '''
    meanout = np.exp(mean + sig ** 2 / 2.)
    sigout = np.sqrt(np.exp(2 * mean + sig ** 2) * (np.exp(sig ** 2) - 1))
    return meanout, sigout

def transformRhoFromLog(mean1, sig1, mean2, sig2, rho):
    return (np.exp(rho * sig1 * sig2) - 1) / (np.sqrt(np.exp(sig1 ** 2) - 1) * np.sqrt(np.exp(sig2 ** 2) - 1))

def transformToLog(mean, sig):
    meanout = np.log(mean ** 2 / np.sqrt(sig ** 2 + mean ** 2))
    sigout = np.sqrt(np.log(1 + sig ** 2 / mean ** 2))
    return meanout, sigout

def transformRhoToLog(mean1, sig1, mean2, sig2, rho):
    return (1. / (sig1 * sig2) * np.log(1. + rho * np.abs((sig1 * sig2) / (mean1 * mean2))))

def calcDN160(FC, **kwargs):
    '''
    This is a hack for research purposes. Do not use for production;
    in the CaseHist object, don't give N160 but not N160cs in the
    input
    '''
    return np.exp(1.63 + 9.7 / (FC + 0.01) - (15.7 / (FC + 0.01)) ** 2)

def calcN160cs(Nm, sigveff, FC, z, **kwargs):
    '''
    Calculates N160cs using Cetins or Idriss and Boulanger's procedures
    '''
    if kwargs.get('Cetin', False):
        Cetin = True
        #Carr = np.array([0.7516507353, 0.7840220588, 0.8002095588, 0.8384742647,
        #0.8708602941, 0.892485294, 0.9165220588, 0.9356875, 0.9548566176,
        #0.9652132353, 0.9770551471, 0.9859926471, 0.9905183824, 0.9950441176,
        #0.9966176471, 0.9967279412, 0.9983845588, 0.9995880824])
        #zarr_cr = np.array([3.675, 4.05, 4.275, 4.875, 5.55, 6.15, 7.05, 8.025, 9.075,
        #10.35, 11.925, 14.25, 16.575, 18.9, 21, 23.25, 26, 29.85, 29.85])
        #f_cr = interp1d(zarr_cr, Carr, bounds_error=False, fill_value=0.7)
        #C = f_cr(z+1.2) # Cetin assumes a rod stick up length of 1.2
        #C[z+1.2 >= 29.5] = 1.
        # From Cetin's spreadsheet SiteK_KOC.xlsx
        Cr = np.maximum(0.6, np.minimum(1.0, 0.48 + 0.225 * np.log(z + 1.2)))
    else:
Cetin = False
Cr = np.ones(Nm.shape)
Cr[(z+1.5<3) & (z+1.5 > 3)] = 0.8
Cr[(z+1.5 >= 4) & (z+1.5 < 6)] = 0.85
Cr[(z+1.5 >= 6) & (z+1.5 < 10)] = 0.95
# Assuming a rod stick up length of 1.5 m
if 'Cb' in kwargs.keys():
    Cb = kwargs['Cb']
else:
    Bore_diam = kwargs.get('Bore_diam', 100 * np.ones(Nm.shape))
    Cb = np.ones(Nm.shape)
    Cb[Bore_diam <= 150] = 1.05
    Cb[Bore_diam > 150] = 1.15
    Ce = kwargs.get('Ce', 1.)
    Csopt = kwargs.get('Cs', 1.)

error = 1
n = Nm / 2.
N160 = n
i = 0
while error > 0.0001:
    i += 1
    if i > 25:
        pdb.set_trace()
    if Cetin:
        Cn = np.minimum(1.6, np.sqrt(101.325 / sigveff))
    else:
        alpha = 0.784 - 0.0768 * np.sqrt(np.minimum(n, 46))
        Cn = np.minimum(1.7, (101. / sigveff) ** alpha)
    if kwargs.get('calcCs', False):
        if Cetin:
            Cs = 1 + N160 / 100.
        else:
            Cs = np.maximum(1.1, np.minimum(1.3, 1 + n / 100.))
    else:
        Cs = Csopt
    if Cetin:
        N160 = Nm * Cn * Cs * Ce * Cb * Cr
        error = np.max(np.abs(n-N160)/N160)
        n = N160
    else:
        if kwargs.get('Ncorrtype', 'IB') == 'IB':
            DelN160 = np.exp(1.63 + 9.7 / (FC + 0.01) - (15.7 / (FC + 0.01)) **2 )
        else:
            N160 = Nm * Cn * Cs * Ce * Cb * Cr
            DelN160 = 0.025 * FC * N160
        N160cs = Nm * Cn * Cs * Ce * Cb * Cr + DelN160
        error = np.nanmax(np.abs(n-N160cs)/N160cs)
        n = N160cs
    if Cetin:
        if kwargs.get('returnall', False):
            return N160, Cr, Cn, Cs
        else:
            return N160, Cr, Cn, Cs
    else:
        return N160
if kwargs.get('returnall', False):
    return N160cs, DelN160, Cr, Cn, Cs
else:
    return N160cs

class CaseHistArtificial2(CaseHists):
    '''
    This provides an artificial case history object per Adrian’s suggestions.
    Notice that I create some fake data, then run it through the same
    CaseHists object as above.
    '''
    def __init__(self, **kwargs):
        #self.DetLiqAlt = kwargs.get('DetLiqAlt', False)
        self.thetas = kwargs.get('thetas', [0.7, -15, 7])
        self.N = kwargs.get('N', 1000)
        self.g = kwargs.get('g', g_2)
        gam_b = 19.5
        gam_a = 17.0

        # Populate Fake Data Frame
        if 'InputVars' in kwargs:
            pass
        else:
            amax = 10 ** np.random.uniform(-1, 0.01, self.N)
            Nm = np.random.uniform(2,45, self.N)
            z = np.random.lognormal(1.8, 0.5, self.N)
            zw = np.min((np.random.uniform(0,3, self.N), z-0.5), axis=0)
            FC = np.random.lognormal(1, 0.8, self.N)
            Mw = np.random.normal(6.5, 0.6, self.N)
            sigv = np.maximum(0.,(z-zw)) * gam_b + np.min((z,zw)) * gam_a
            sigveff = sigv - np.maximum(0,(z-zw)) * 9.81
            N160cs, DeltaN160cs, Cr, Cn, Cs = calcN160cs(Nm, sigveff, FC, z,
            returnall=True)

            Vs1 = np.ones(Nm.shape) * np.nan
            Liq = 'Yes'
            df = pd.DataFrame(dict(Mw=Mw,
                                    amax=amax,
                                    Liq=Liq,
                                    z=z,
                                    gwt=zw,
                                    sigv=sigv,
                                    sigeffv=sigveff,
                                    FC=FC,
                                    Nm=Nm,
                                    N160cs=N160cs,
                                    N160=N160cs - DeltaN160cs,
                                    delN160=DeltaN160cs,
                                    Vs1=Vs1,
                                    Vs1pm = Vs1))
        super(CaseHistArtificial2, self).__init__(df=df, rd='Lasley',
                                            Degrad = kwargs.get('Degrad', 'DS'),
                                            useVs=False,
                                            GDtype = kwargs.get('GDtype', 'direct'),
                                            calcN160=True)
self.gkwargs = kwargs.get('gkwargs',
    {'a': self.df.N160cs.values,
     'b': np.log(self.df.dWn.values),
     'g': self.g})
self.alpha = np.random.uniform(0, 1, self.N)
Pliq = norm.cdf(-self.g(self.thetas, self.gkwargs) / self.thetas[-1])
Liq = np.array(['Marginal' for i in range(self.N)])
Liq[self.alpha <= Pliq] = 'Yes'
Liq[self.alpha > Pliq] = 'No'
self.df['Liq'] = Liq
self.gsign = np.ones(self.df.Liq.shape)
self.ind1 = np.where(Liq == 'Yes')
self.ind2 = np.where(Liq == 'No')
self.ind3 = np.where(Liq == 'Marginal')
self.Liq2 = np.zeros(Liq.shape, dtype=float)
self.Liq2[self.ind2] = 0.
self.Liq2[self.ind3] = 0.5
self.gsign[self.ind1] = -1
self.gsign[self.ind3] = 0
self.gsign[self.ind2] = 1
self.altwt = np.ones(self.N)

def DetLiqAlt(self):
    '''
    This method incorporates input variable uncertainty into the
determination of whether or not the synthetic point liquefied.
    '''
    like = OtherLikelihood(df=self.df)
    Pliq = like(self.thetas, self.gkwargs, self.df, ReturnProb=True)
    #Pliqalt = norm.cdf(-g(self.thetas, self.gkwargs) / self.thetas[-1])
    Liq = np.array(['Marginal' for i in range(self.N)])
    Liq[self.alpha <= Pliq] = 'Yes'
    Liq[self.alpha > Pliq] = 'No'
    self.df['LiqOld'] = np.copy(self.df['Liq'].values)
    self.df['Liq'] = Liq

getPlot2D(beta, kwargs, df, **kwargs2):
    '''
    This plots the curve when I don’t have a regression coefficient for logDwn.
    '''
    paramlist = 'acdefhijk'
    no_params = 0
    for key in kwargs:
        if key in paramlist:
            no_params += 1
    norm = kwargs2.get('norm', True)
    logDW = kwargs2.get('logDW', True)
    logN = kwargs2.get('logN', False)
    label = kwargs2.get('label', 1)
    alpha = kwargs2.get('alpha', 1)
    invalues = kwargs2.get('invalues')
    xx = invalues.get('a', np.linspace(0, 28, 100))
y = np.zeros(xx.shape)
for i in range(no_params):
    if paramlist[i] == 'b':
        continue
    if invalues:
        y = y + beta[i] * invalues.get(paramlist[i])
    else:
        if i == 0:
            y = y + beta[i] * xx
        else:
            y = y + beta[i] * np.median(kwargs.get(paramlist[i]))
    y = y + np.ones(len(y)) * beta[i+1]
    #y = -y / beta[1]
    if logDW:
        y = np.exp(y)
    if norm:
        #y = y * 101.325#np.median(df.sigeffv.values)
        pass
    else:
        y = y / 50. #???

if logN:
    xx = np.exp(xx)
plt.figure(kwargs2.get('figname','limit-state'))
plt.plot(xx,y, label=label, lw=3.5)

def plotBase(df, **kwargs):
    Liq = df['Liq'].values
    ind1 = np.where(Liq == 'Yes')
    ind2 = np.where(Liq == 'No')
    ind3 = np.where(Liq == 'Marginal')
    plt.figure(kwargs.get('figname','limit-state'))
    x = kwargs.get('x', 'N160cs')
    xlabel = kwargs.get('xlabel', '$N_{1,60cs}$')

    plt.semilogy(df[x].values[ind1],df.dWn.values[ind1], 'ko')#, label='Liq.' )
    plt.plot(df[x].values[ind2],df.dWn.values[ind2], 'ws')#, label='No Liq.' )
    plt.plot(df[x].values[ind3],df.dWn.values[ind3], 'm*')#, label='Marginal')
    plt.xlabel(xlabel)
    plt.ylabel('$\Delta W / \sigma _{v}$')

def calcNashSutcliffe(Actual, Predicted):
    E = (1 - (np.sum((Actual - Predicted) ** 2) / np.sum((Actual - np.mean(Actual)) ** 2))) ** 100
    return E

def compareResults(g, inargs, gsign, **kwargs):
    
918
This calculates a few stats on the fit of the liquefaction curve, and
returns the results as a dictionary.

```
inargs refers to the input arguments of the limit state curve, g.
'''
sigma = kwargs.get('sig')
if sigma == None:
    try:
        sigma = inargs[0][-1]
    except:
        sigma = 1.
        print('Sigma = 1')
gout = g(*inargs)

#Pliq = kwargs.get('Pliq')
Pliq = 1 - norm.cdf(gout / sigma)
Pact = np.ones(len(Pliq))
Pact[gsign == 0] = 0.5
Pact[gsign > 0] = 0.

ind = np.where(np.sign(gout) != np.sign(gsign))[0]
indfn = np.where((np.sign(gout) != np.sign(gsign)) &
    (np.sign(gout) > 0))[0]
indfp = np.where((np.sign(gout) != np.sign(gsign)) &
    (np.sign(gout) <= 0))[0]

try:
    no_incorrect = len(ind)
except TypeError:
    pdb.set_trace()
    no_incorrect = 0
no_correct = len(gout) - no_incorrect

wrongs = gout[ind]

falneg = len(np.where(wrongs > 0)[0]) # Predicted no liq, but liquefied
falpos = len(np.where(wrongs < 0)[0]) # Predicted Liq, but did not liquefy

sumgwrong = np.sum(np.maximum(norm.cdf(wrongs/sigma)-0.5, 0))
sumgfn = np.sum(np.abs(norm.cdf(gout[indfn]/sigma)-0.5))
sumgfp = np.sum(np.abs(norm.cdf(gout[indfp]/sigma)-0.5))
if kwargs.get('UseProb', False):
    print('Using Probs to calc E.')
    E = calcNashSutcliffe(Pact, Pliq)
else:
    E = calcNashSutcliffe(gsign, np.sign(gout))
results = {
    'num_false_pos': falpos,
    'num_false_neg': falneg,
    'num_correct': no_correct,
    'num_incorrect': no_incorrect,
    'sum_g_err': sumgwrong,
    'sum_g_fn': sumgfn,
    'sum_g_fp': sumgfp,
    'NashSutcliffe_E': E
}
return results
def gIdrissBoul(df, **kwargs):
    '''
    Idriss and Boulanger limit state curve with input of a dataframe
    '''
    x = df['N160cs'].values
    y = df['CSRm7.5'].values
    co = 2.67 #2.8
    g = (x / 14.1 + (x / 126) ** 2 - (x / 23.6) ** 3 + (x / 25.4) ** 4 - co) - np.log(y)
    # This form of g is from Boulanger and Idriss 2012. However, you can make another g
    # that takes the exp of the first parens and subtracts y. This would yield a smaller
    # sum_g_erro
    return g

def gIdrissBoul2(N160cs, CSR, **kwargs):
    '''
    Idriss and Boulanger limit state function with inputs of N160cs and CSR
    '''
    co = kwargs.get('co', 2.67) #2.8
    g = (N160cs / 14.1 + (N160cs / 126) ** 2 - (N160cs / 23.6) ** 3 +
         (N160cs / 25.4) ** 4 - co) - np.log(CSR)
    # This form of g is from Boulanger and Idriss 2012. However, you can make another g
    # that takes the exp of the first parens and subtracts y. This would yield a smaller
    # sum_g_erro
    return g

def calcLS_IdrissBoul2(Pliq, N160cs, **kwargs):
    '''
    This returns the CSR values corresponding to a prob of liquefaction and
    a [range] of N160cs values, using Boulanger and Idriss/Idriss and boulangier
    curves
    '''
    co = kwargs.get('co', 2.67) #2.8
    siglnR = kwargs.get('siglnR', 0.17)
    out = np.exp(N160cs / 14.1 + (N160cs / 126) ** 2 - (N160cs / 23.6) ** 3 +
                (N160cs / 25.4) ** 4 - co + norm.ppf(Pliq) * siglnR)
    # This form of g is from Boulanger and Idriss 2012.
    return out

def gYoudEtal(df, **kwargs):
    '''
    Limit state given by Youd et al 2001
    '''
    x = df['N160cs'].values
    y = df['CSRm7.5'].values
    g = 1./(34 - x) + x/135 + 50 / (10*x + 45) ** 2 - 1./200. - y
    return g

def calcLS_Youdetal(N160cs):
    x = N160cs
    CRR = 1./(34 - x) + x/135 + 50 / (10*x + 45) ** 2 - 1./200.
    return CRR

def calcYoudCSR(amax, sigv, sigveff, Mw, z, N160, FC):
    '''
    
    920
Calculates the corrected CSR according to the Youd et al. 2001 procedure.

```python
# Liao and Whitman (1986):
rd = np.ones(len(z))
rd[z <= 9.15] = 1.0 - 0.00765 * z[z <= 9.15]
rd[(z > 9.15) & (z <= 23)] = 1.174 - 0.0267 * z[(z > 9.15) & (z <= 23)]
rd[z > 23] = 1.174 - 0.0267 * 23 # This is a hack for deep stuff
FC = np.float(FC)

alpha = np.zeros(N160.shape)
alpha[FC > 5] = np.minimum(5., np.exp(1.76 - 190./ FC[FC > 5] **2))
beta = np.ones(N160.shape)
beta[FC > 5] = np.minimum(1.2, 0.99 + FC[FC>5] ** 1.5 / 1000.)
N160cs = alpha + beta * N160

MSF = 10 ** 2.24 / Mw ** 2.56
Dr = 15 * np.sqrt(N160)

f = np.minimum(0.8, np.maximum(0.6, 1 - 0.005 * Dr))
Ksig = (sigveff / 101.325) ** (f - 1)
#Ksig = np.minimum(1.0, (sigveff / 101.325) ** (0.7 - 1))
CSR = 0.65 * amax * sigv * rd / (MSF * sigveff * Ksig)
```

```python
CRR = calcLS_Youdetal(N160cs)
FS = np.minimum(2., CRR / CSR) # To agree with IB 2008
return CSR, N160cs, FS
```

```python
def gCetindf(df, **kwargs):
    
    Cetin’s (2000 and maybe Cetin et al. 2004 or something) Limit-state curve
    
    beta = kwargs.get('beta',
    #[0.004, 13.79, 29.06, 3.82, 0.06, 44.29, 4.21]
    #[0.004, 13.32, 29.53, 3.70, 0.05, 44.97, 2.7] # Accounting for measurement errors
    #[0.004, 13.32, 29.53, 3.70, 0.05, 16.85, 2.7] # From Cetin et al. 2004
    )
    try:
        N = kwargs.get('N160', df.N160_Cetin.values)
    except:
        pdb.set_trace()
        N = kwargs.get('N160', df.N160.values)
    amax = df.amax.values
    sigv = df.sigv.values
    z = df.z.values
    F = df.FC.values
    M = df.Mw.values
    T = df.sigeffv.values
    rd = rd_Cetin1(amax, M, z)
    S = 0.65 * amax * sigv * rd / T
    g = (N * (1 + beta[0] * F) - beta[1] * np.log(S) - beta[2] * np.log(M) -
    return g
```

```python
def gCetin(CSR, N160, Mw, FC, sigeffv, **kwargs):
    
    Same as gCetindf, but not using a dataframe
```
```
1294  
1295  beta = kwargs.get('beta',
1296  # [0.004, 13.79, 29.06, 3.82, 0.06, 44.29, 4.21]
1297  # [0.004, 13.32, 29.53, 3.70, 0.05, 44.97, 2.7] # Accounting for measurement
1298  errors
1299  [0.004, 13.32, 29.53, 3.70, 0.05, 16.85, 2.7] # From Cetin et al. 2004
1300  )
1301  N = N160
1302  S = CSR
1303  F = FC
1304  M = Mw
1305  T = sigeffv
1306  g = (N * (1 + beta[0] * F) - beta[1] * np.log(S) - beta[2] * np.log(M) -
1308  return g
1309  
1310  def calcLS_Cetin(Pliq, N160, FC, Mw, sigveff):
1311  
1312  This is from Cetin et al. 2004
1313  Cetin, K. O., Seed, R. B., Der Kiureghian, A., Tokimatsu, K.,
1315  "Standard Penetration Test-Based Probabilistic and
1316  Deterministic Assessment of Seismic Soil Liquefaction
1317  Potential." Journal of Geotechnical and Geoenvironmental
1318  Engineering, 130(12), 1314-1340.
1319  
1320  Gives the CSR values of the limit state curve for the given input values.
1321  
1322  FC = np.minimum(35., FC)
1323  out = np.exp((N160 * (1 + 0.004 * FC) - 29.53 * np.log(Mw) - 3.70 *
1324  np.log(sigveff / 100.) + 0.05 * FC + 16.85 + 2.70 *
1325  norm.ppf(Pliq)) / 13.32)
1326  return out
1327  
1328  def g_1(beta, **kwargs):
1329  
1330  This does not assume the regression coefficient for dWn is -1
1331  
1332  # no_params = len(beta) - 1
1333  paramlist = 'abcdefhijk'
1334  no_params = 0
1335  for key in kwargs:
1336  if key in paramlist:
1337  no_params += 1
1338  a = kwargs.get('a')
1339  myones = np.ones(a.shape, dtype=float)
1340  res = np.array([beta[i] * kwargs.get(paramlist[i]) if i < (no_params)
1341  else beta[i]*myones for i in range(no_params+1)])
1342  return np.sum(res, axis=0)
1343  
1344  def g_2(beta, kwargs):
1345  
1346  Assumes the 'b' coefficient is -1
1347  
1348  # no_params = len(beta) - 1
1349  paramlist = 'acdefhijk'
```
no_params = 0
for key in kwargs:
    if key in paramlist:
        no_params += 1
a = kwargs.get('a')
myones = np.ones(a.shape, dtype=float)
res = np.array([beta[i] * kwargs.get(paramlist[i]) if i < (no_params)
                else beta[i]*myones for i in range(no_params+1)])
return np.sum(res, axis=0) - kwargs.get('b')

def calcLimStCurves(Prob, beta, kwargs, **this):
    '''
    Returns log dWn (or whatever) for a given limit state curve
    (see g_2). Assumes that regression coefficient 'b' is equal to -1.
    '''
    paramlist = 'acdefhijk'
    no_params = 0
    for key in kwargs:
        if key in paramlist:
            no_params += 1
    a = kwargs.get('a')
    myones = np.ones(a.shape, dtype=float)
    res = np.array([beta[i] * kwargs.get(paramlist[i]) if i < (no_params)
                    else beta[i]*myones for i in range(no_params+1)])
    cutoff = this.get('cutoff', 100.)
    out = np.sum(res, axis=0) + norm.ppf(Prob) * beta[-1]
    out[a>cutoff] = 100.
    return out

def log_like(beta, kwargs, df, wt=1.):
    '''
    Log-likelihood function for minimization. Deterministic.
    '''
    #df = kwargs.get('df')
    g = kwargs.get('g', g_1)
    #wt2 = kwargs.get('wt2',0.)
    sig = beta[-1]
    Liq = df['Liq'].values
    ind1 = np.where(Liq == 'Yes')
    ind2 = np.where(Liq == 'No')
    ind3 = np.where(Liq == 'Marginal')
    eps = g(beta, kwargs) / sig #~ wt2
    returnval = np.ones(Liq.shape, dtype=float) #= 0.95
    #returnval[ind1] = norm.cdf(0, loc=eps[ind1])
    #returnval[ind2] = (1. - norm.cdf(0, loc=eps[ind2]))
    #returnval[ind3] = norm.cdf(-eps[ind3])
    #returnval[np.abs(eps) > 2.5] = 1
    try:
        retval = -np.sum(np.log(np.maximum(returnval, 1e-10) ) * wt)
    except:
        pdb.set_trace()
    #return -np.sum(np.log(returnval))
    return retval
```python
class OtherLikelihood(object):
    '''
    Following Adrian’s guidance. This examines uncertainties
    in the input parameters.
    '''
    def __init__(self, **kwargs):
        self.df = kwargs.get('df')
        self.verbose = kwargs.get('verbose', False)
        self.voltype = kwargs.get('voltype', 'other')

        # Assign uncertainties if I have a dataset, otherwise...
        if 'df' in kwargs.keys():
            self.isdf = True
            #self.sigy = kwargs.get('sigy', np.abs(np.log(self.df.dWn.values)*0.5)) # in ln space
            self.sigy = kwargs.get('sigy') # in ln space
            if np.any(self.sigy) == None:
                self.sigy = self.df.logdWnerror.values
            self.sigx = kwargs.get('sigx') # Boulanger and Idriss used 0.15 and 0.2
            if np.any(self.sigx) == None:
                #self.sigx = np.minimum(self.df.N160.values * 0.2,3)# Per Cetin (2000), pg. 64
                self.sigx = self.df.sigN160cs.values
            self.liq = np.ones(len(self.df))
            self.liq[self.df.Liq.values == 'Yes'] = -1.
            self.speedup = kwargs.get('speedup', True)
        else:
            self.speedup = False
            self.isdf = False
            self.sigy = kwargs.get('sigy', 1.5) #* np.ones(len(self.df))
            self.sigx = kwargs.get('sigx', 7) # SPT blowcount error

        # This will ignore dx and dy keyword args, as well as ranges
        # Here I am creating a separate grid for each data point, instead of
        # one large grid for all datapoints.
        self.altgrid = kwargs.get('altgrid', True)
        if self.altgrid & self.isdf:
            # grid_x_sds is the number of standard deviations to extend in
            # each direction from the mean values.
            # The count is the number of spacings in grid
            self.grid_x_sds = kwargs.get('grid_x_sds', 4.5)
            self.grid_y_sds = kwargs.get('grid_y_sds', 4.5)
            self.grid_x_count = kwargs.get('grid_x_count', 35)
            self.grid_y_count = kwargs.get('grid_y_count', 35)
        elif self.isdf:
            # I’m assuming the variables here of logdWn and N160cs
            # Will need to be modified in other cases, CPT, for example
            xs = self.df.N160cs.values
            ys = self.df.logdWn.values
            if np.isscalar(self.sigy):
                sigy = np.ones(len(self.df)) * self.sigy
            else:
                sigy = self.sigy
            if np.isscalar(self.sigx):
                sigx = np.ones(len(self.df)) * self.sigx
            else:
```

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sigx = self.sigx
self.x_range = np.zeros((len(self.df),2))
self.y_range = np.zeros((len(self.df),2))
self.dx = np.zeros(len(self.df))
self.dy = np.zeros(len(self.df))
for i, (x, y) in enumerate(zip(xs, ys)):
    self.x_range[i, :] = [
        x - self.grid_x_sds * sigx[i],
        x + self.grid_x_sds * sigx[i]]
    self.dx[i] = (2 * self.grid_x_sds * sigx[i] /
        self.grid_x_count)
    self.y_range[i, :] = [
        y - self.grid_y_sds * sigy[i],
        y + self.grid_y_sds * sigy[i]]
    self.dy[i] = (2 * self.grid_y_sds * sigy[i] /
        self.grid_y_count)
grid = np.mgrid[
    self.x_range[i][0]:self.x_range[i][1]:self.dx[i],
    self.y_range[i][0]:self.y_range[i][1]:self.dy[i]]
xgrid, ygrid = grid[0], grid[1]
    if i == 0:
        self.xgrid = np.zeros((len(self.df), xgrid.shape[0],
            xgrid.shape[1]))
        self.ygrid = np.zeros((len(self.df), ygrid.shape[0],
            ygrid.shape[1]))
    try:
        self.xgrid[i, :
            self.grid_x_count, :
            self.grid_x_count] = xgrid[:, self.grid_x_count, :
            self.grid_x_count]
        self.ygrid[i, :
            self.grid_y_count, :
            self.grid_y_count] = ygrid[:, self.grid_y_count, :
            self.grid_y_count]
    except ValueError:
        pdb.set_trace()
else:
    # Grid spacing
    self.dx = kwargs.get('dx', .12)
    self.dy = kwargs.get('dy', .7)
    # Range of grid:
    self.x_range = kwargs.get('x_range', (0, 70))
    self.y_range = kwargs.get('y_range', (-15, 6))
    # Construct my grid
    self.grid = np.mgrid[self.x_range[0]:self.x_range[1]:self.dx,
        self.y_range[0]:self.y_range[1]:self.dy]
    self.xgrid, self.ygrid = self.grid[0], self.grid[1]

    # This is assuming x = N160cs, and y = DWn, to speed things up
    # If self.speedup is true, I calculate fxy once at the beginning
    # This will take a bit more memory, though.
    if self.isdf & self.speedup:
        if np.isscalar(self.sigy):
            self.sigy = np.ones(len(self.df)) * self.sigy
        if np.isscalar(self.sigx):
            self.sigx = np.ones(len(self.df)) * self.sigx
        y = self.df.logdWn.values

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sigx = self.sigx
sigy = self.sigy
for i, x in enumerate(self.df.N160cs.values):
    if len(self.xgrid.shape) > 2:
        xgrid = self.xgrid[i]
        ygrid = self.ygrid[i]
    else:
        xgrid = self.xgrid
        ygrid = self.ygrid
    sigx = self.sigx
    sigy = self.sigy
    #self.fxfy[i] = self.calcfxfy(x, y[i], sigx[i], sigy[i],
    #xgrid=xgrid, ygrid=ygrid)
    fxfy = self.calcfxfy(x, y[i], sigx[i], sigy[i],
                        xgrid=xgrid, ygrid=ygrid)
    if i == 0:
        self.fxfy = np.zeros((self.sigx.shape[0], xgrid.shape[0], xgrid.shape[1]))
    Vol = self.calcVol(fxfy, xgrid=xgrid, ygrid=ygrid,
                       dx=self.dx[i], dy=self.dy[i])
    #Vol = 1.
    try:
        self.fxfy[i] = fxfy / Vol
    except ValueError:
        pdb.set_trace()
        # This is one of my diagnostics: check if the vol == 1
        #print('Vol: {}'.format(Vol))
        #pdb.set_trace()

def __call__(self, beta, kwargs, df, wt=1., **otherkwargs):
    
    This is meant to mimic the other likelihood functions,
    and is supplied to the minimize function.
    By default it returns the negative sum of probabilities for a
    given set of regression coefficients.
    
    g = kwargs.get('g', g_2)
    EPS = g(beta, {'a': self.xgrid,
                   'b' : self.ygrid})
    sigy = self.sigy
    sigx = self.sigx
    x = kwargs['a']
    y = kwargs['b']
    if self.isdf:
        liq = self.liq
    else:
        if np.isscalar(sigy):
            sigy = np.ones(len(df)) * self.sigy
        if np.isscalar(sigx):
            sigx = np.ones(len(df)) * self.sigx
        Liq = df['Liq'].values
        liq = np.ones(len(x.shape))
        liq[Liq == 'Yes'] = -1.
        out = np.zeros(len(x.shape))
    plot = False
    plot = otherkwargs.get('plot', False)
    for i,xmean in enumerate(x):
        if self.verbose:
if i % 10 == 0:
    sys.stdout.write('-')
if i % 50 == 0:
    sys.stdout.write('{}
'.format(i))
sys.stdout.flush()
if len(EPS.shape) > 2:
    eps = EPS[i]
    xgrid = self.xgrid[i]
    dx = self.dx[i]
    ygrid = self.ygrid[i]
    dy = self.dy[i]
else:
    eps = EPS
    xgrid = self.xgrid
    dx = self.dx
    ygrid = self.ygrid
    dy = self.dy
if self.speedup:
    fxfy = self.fxfy[i]
else:
    fxfy = self.calcfxfy(xmean, y[i], sigx[i], sigy[i],
                        xgrid=xgrid, ygrid=ygrid)
Vol = self.calcVol(fxfy, xgrid=xgrid, ygrid=ygrid,
                   dx=dx, dy=dy)
if otherkwargs.get('ReturnProb', False):
    probsurf = norm.cdf(-eps / beta[-1]) * fxfy
else:
    probsurf = norm.cdf(liq[i] * eps/beta[-1]) * fxfy
if i == 0:
    probsurfall = probsurf
else:
    probsurfall += probsurf
out[i] = self.calcVol(probsurf, xgrid=xgrid, ygrid=ygrid,
                       dx=dx, dy=dy)
if otherkwargs.get('ReturnProb', False):
    return out
if plot:
    fig = plt.figure()
    ax = fig.add_subplot(111, projection='3d')
    ax.plot_surface(self.xgrid, self.ygrid, probsurfall)
    plt.show()
    pdb.set_trace()
    return fig
return -np.sum(np.log(np.maximum(out, 1e-10)) * wt)

def calcVol(self, surf, **kwargs):
    '''
    Calculates the volume under a two-dimensional surface.
    Surf is the n x m array of surface values.
    Optional keyword arguments allow you to specify the x and y grid.
    Otherwise it defaults to the single grid that was created in the
    __init__ function. However, if self.altgrid == True, that won't work.
Three options for self.voltype: 'bvs', 'quickndirty', and 'other'.
See below for details.

```python
self.voltype = kwargs.get('voltype', self.voltype)
xgrid = kwargs.get('xgrid', self.xgrid)
ygrid = kwargs.get('ygrid', self.ygrid)
dx = kwargs.get('dx', self.dx)
dy = kwargs.get('dy', self.dy)
x_range = kwargs.get('x_range', self.x_range)
y_range = kwargs.get('y_range', self.y_range)
if self.voltype == 'bvs':
    bvs = RectBivariateSpline(xgrid[:,0], ygrid[0,:], surf)
    #out = bvs.integral(x_range[0], x_range[1], y_range[0], y_range[1])
    out = bvs.integral(np.min(xgrid), np.max(xgrid),
                      np.min(ygrid), np.max(ygrid))
elif self.voltype == 'quickndirty':
    out = np.sum(surf[:-1, :-1]) * dx * dy
elif self.voltype == 'other':
    Ny = len(ygrid[0,:])
    interm = np.zeros(Ny)
    for i in range(Ny):
        try:
            interm[i] = np.trapz(surf[:,i], xgrid[:,0])
        except IndexError:
            pdb.set_trace()
    out = np.trapz(interm, ygrid[0,:])
return out

def calcfxfy(self, xmean, ymean, xsig, ysig, *args, **kwargs):
    '''
    This returns a two dimension array of the probability density function
    in both the x and y direction.
    Notice that you need to specify the xgrid and ygrid
    if self.altgrid == True
    '''
xgrid = kwargs.get('xgrid', self.xgrid)
ygrid = kwargs.get('ygrid', self.ygrid)
f = norm.pdf(xgrid, loc=xmean, scale=xsig)
f = norm.pdf(ygrid, loc=ymean, scale=ysig)
if np.min(xgrid) < 0:
    pdb.set_trace()
pass
out = f * f
return out

def MLEall(beta, kwargs, df, gsign, likefunc, method='Powell', wt=1, wt2=1):
    '''
    This is a small helper function to run the minimization of likelihood,
    and send the results to the compareResults function for summary
    '''
```

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results = minimize(likefunc, beta, args=(kwargs, df, wt),
                  method=method,
                  options={'maxiter': 5000, 'disp': True})
print(results.x)
print(results.x/np.abs(results.x[1]))
comres = compareResults(g1MLEalt, [results.x, kwargs], gsign)
print(comres)
return (results, comres)

def MLEmeta(mydict, plot=True):
    
    This is an attempt to make the minimization more straightforward.
    It is still pretty convoluted with dictionaries within dictionaries,
    but it works for now.
    
    def countargs(kwargs):
        count = 0
        for key in kwargs:
            if key in 'abcdefhijk':
                count += 1
        return count + 2

    def mydict.get(key, default):
        return default

    kwargs = mydict['kwargs']
    beta = mydict.get('beta', [1. for i in range(countargs(kwargs))])
    print(beta)
    method=mydict.get('method','TNC')
    bounds = mydict.get('bounds', ((None, None), (None, None), (0, None)))
    CH = mydict.get('CaseHist')
    df = CH.df
    wt = CH.altwt
    g = kwargs.get('g', g_1)
    likefunc = mydict.get('likefunc', log_like)
    gsign = CH.gsign
    results = minimize(likefunc, beta, args=(kwargs, df, wt),
                      method=method,
                      bounds=bounds,
                      options={'maxiter': 10000, 'disp': True})
    print(results.x)
    comres = compareResults(g, [results.x, kwargs], gsign, UseProb=UseProb)
    if plot:
        plotfunc = kwargs.get('plotfunc', plotFit2)
        plotfunc(results.x, kwargs, df, **mydict['plotkwargs'])
    print(comres)
    return (results, comres)

def run5(**kwargs):
    method = 'TNC'
    CSI = CaseHists(Degrad='DS', useVs=False, GDtype='direct', altwt=1.0,
                    myunitwt='assumed', rd='Lasley',
                    calcN160=True, # True is Default
                    Ncorrtype='Lasley',
                    N_Gmaxtype='SeededALT')

    results = minimize(likefunc, beta, args=(kwargs, df, wt),
                        method=method,
                        options={'maxiter': 5000, 'disp': True})
    print(results.x/np.abs(results.x[1]))
    comres = compareResults(g1MLEalt, [results.x, kwargs], gsign)
    print(comres)
    return (results, comres)
pdb.set_trace()

# Set CaseHists
CS1 = CaseHist(Degrad='DS', useVs=False, GDtype='direct', altwt=1.0, myunitwt='assumed', rd='Lasley', altDwn=False, altCycles=False, N_Gmaxtype='Wairetal')

CSVs = CaseHist(Degrad='DS', useVs=True, GDtype='direct', altwt=0.25, myunitwt='assumed', rd='Lasley', N_Gmaxtype='SeedetalALT')

CSVs.to_pickle()

plotBase(CS1.df)

plotBase(CSVs.df, figname='Vs')

df = CS1.df

gsign = CS1.gsign

Rtype = 'Rrup (km)'

Jafdf = df[~np.isnan(df[Rtype].values)].copy()

Jaf = LiqEvalJafarianetal(Jafdf, Rtype=Rtype)

JafResults = compareResults(Jaf.calc_g, [0.5], gsign[~np.isnan(df[Rtype].values)], sig=1)

print('Jafarian et al. 2014')

Jaf.plot()

plt.show()

pdb.set_trace()

beta = kwargs.get('beta', [0.4, -10.0, 1.0])

dict1 = dict(CaseHist=CS1, beta=beta, method=method, bounds=((None, None), (None, None), (0, None)), kwars=({'a': CS1.df.N160cs.values, 'b': np.log(CS1.df.dWn.values), 'g': g_2}),

plotkwars={
    'logDW': True,
    'norm': True,
    'label': 'DS-Regular',
    'invalues': {'a': np.linspace(0, 28, 60)}})

result1 = MLEmeta(dict1)

print('Regular^')

dictVs = dict(CaseHist=CSVs,

beta=[0.4, -10.0, 1.0], method=method, bounds=((None, None), (None, None), (0, None)), kwars=({'a': CSVs.df.N160cs.values, 'b': np.log(CSVs.df.dWn.values), 'g': g_2}),

plotkwars={
    'logDW': True,
    'norm': True,
    'label': 'Vs'},
resultVs = MLEmeta(dictVs)

print('With Vs and altwt = 0.25''

IBResults = compareResults(gIdrissBoul2, [df.N160cs.values, 
               df['CSRm7.5'].values], gsign, sig=0.13, UseProb=True) #Idriss and Boulanger 2010, pg. 100 (102)

print(IBResults)

YoudResults = compareResults(gYoudEtal, [df], gsign)

print(YoudResults)

CetResults = compareResults(gCetindf, [df], gsign, sig=2.7, UseProb=True)

print(CetResults)

like2 = OtherLikelihood(df=df)

dict2 = dict(CaseHist=CS1, 
             likefunc = like2, 
             beta = result[0].x, 
             kwargs = {'a': CS1.df.N160cs.values, 
                       'b': np.log(CS1.df.dWn.values), 
                       'g' : g_2}, 
             method=method, 
             plotkwars ={ 
                          'logDW' : True, 
                          'norm' : True, 
                          'label' : 'No Vs, Uncert', 
                          'invalues' : {'a' : np.linspace(0, 28, 60)}})

result2 = MLEmeta(dict2)

likeVs = OtherLikelihood(df=CSVs.df)

dict2Vs = dict(CaseHist=CSVs, 
               likefunc = likeVs, 
               beta = resultVs[0].x, 
               method=method, 
               kwargs = {'a': CSVs.df.N160cs.values, 
                         'b': np.log(CSVs.df.dWn.values), 
                         'g' : g_2}, 
               plotkwars ={ 
                          'logDW' : True, 
                          'norm' : True, 
                          'figname' : 'Vs', 
                          'label' : 'Vs & Uncert', 
                          'invalues' : {'a' : np.linspace(0, 28, 60)}})

result2Vs = MLEmeta(dict2Vs)
labels = ['#1 - $G_{\text{max}} = f(N_{1,60cs})$','
#2 - $G_{\text{max}} = f(V_s, N_{1,60cs})$','
#3 - $G_{\text{max}} = f(N_{1,60cs})$, with Uncertainties','
#4 - $G_{\text{max}} = f(V_s, N_{1,60cs})$, with Uncert.'],

mixedbeta = np.copy(result2[0].x)
mixedbeta[-1] = result1[0].x[-1]
mixedkwargs = {'a': CS1.df.N160cs.values,
'b': np.log(CS1.df.dWn.values),
'g': g_2}
mixed = compareResults(g_2, [mixedbeta, mixedkwargs], gsign, UseProb=True)
print(mixedbeta)
print(mixed)

df = CS1.df
printCoefTable(result1[0].x, resultVs[0].x,
result2[0].x, result2Vs[0].x,
labels=labels)

df = CS1.df
def run4():
    method = 'Nelder-Mead'
g=g_2
CS1 = CaseHistArtificial2(N=200, thetas=[0.4, -14, 1.2], g=g)
plotBase(CS1.df)
pdb.set_trace()

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'logDW' : True,
'norm' : True,
'label' : 'Deterministic-Old',
'invalues' : {'a' : np.linspace(0, 35, 60)}
result1 = MLEmeta(dict1)
like = OtherLikelihood(df=df)
#outval = like([0.7, -1, 15, 3.], dict1['kwargs'], df)
dict2 = dict(CaseHist=CS1,
likefunc = like,
beta = result1[0].x,
method=method,
kwgars = {'a': CS1.df.N160cs.values,
'b': np.log(CS1.df.dWn.values),
'g': g},
plotkwars ={
'logDW' : True,
'norm' : True,
'label' : 'Deterministic-Old',
'invalues' : {'a' : np.linspace(0, 35, 60)}}
result2 = MLEmeta(dict2)
plt.figure('limit-state')
plt.legend(loc='lower right')
plt.savefig('Limit-state-old.pdf')
plt.close('all')
# Alt method
CS1.DetLiqAlt()
#CS1a = CaseHistArtificial2(N=1000, thetas= [0.4, -15, 1.2], g=g, 
#DetLiqAlt=True)
CS1a = CS1
plotBase(CS1a.df#,figname='Limit-State-New' )
gsign = CS1a.gsign
dict1a = dict(CaseHist=CS1a,
beta=[1.,-10.,1.],
method=method,
kwgars = {'a': CS1a.df.N160cs.values,
'b': np.log(CS1a.df.dWn.values),
'g': g},
plotkwars ={
'logDW' : True,
'norm' : True,
'figname' : 'Limit-State-New',
'label' : 'Deterministic-New',
'invalues' : {'a' : np.linspace(0, 35, 60)}}
result1a = MLEmeta(dict1a)
#plotFit2(results1a.x,{'a': CS1a.df.N160cs.values, 'b' : np.log(CS1a.df.dWn.values),
'g' : g, df, figname='Limit-State-New')
likea = OtherLikelihood(df=df)
#pdb.set_trace()
#outval = like([0.7, -1, 15, 3.], dict1['kwargs'], df)
dict2a = dict(CaseHist=CS1a,
likefunc = likea,
1972 beta = result1a[0].x,
1973 method=method,
1974 kwars = {'a': CS1a.df.N160cs.values,
1975    'b': np.log(CS1a.df.dWn.values),
1976    'g': g},
1977 plotkwars ={
1978    'logDW': True,
1979    'norm': True,
1980    '#filename': 'Limit-State-New',
1981    'label': 'Probabilitistic-New',
1982    'invalues': {'a': np.linspace(0, 35, 60)}})
1983 result2a = MLEmeta(dict2a)
1984
1985 printCompareTable(result1[1], result2[1],
1986     result1a[1],
1987     result2a[1],
1988     labels=['Det.- Old', 'Prob. - Old',
1989         'Det. - New',
1990         'Prob. - New'])
1991
1992 printCoefTable(result1[0].x, result2[0].x,
1993     result1a[0].x,
1994     result2a[0].x,
1995     labels=['Det.- Old', 'Prob. - Old',
1996         'Det. - New',
1997         'Prob. - New'])
1998 #plt.figure('Limit-State-New')
1999 plt.legend(loc='lower right')
2000 plt.savefig('Limit-state-new.pdf')
2001 plt.show()
2002 pdb.set_trace()
2003
def LiqEvalEnergy(df, **kwars):
2004     '''
2005     This function will calculate the probability of liquefaction
2006     '''
2007     g = kwars.get('g', g_2)
2008     gkwars = kwars.get('gkwars', {'a': df.N160cs.values,
2009         'b': np.log(df.dWn.values}))
2010     gbeta = kwars.get('gbeta',
2011         [0.2897, -1.0, -9.3443, 0.9188]
2012         [0.91626033, -4.15771179, -45.2238767, 4.1210432]
2013         [0.4754, -13.471, 6.277e-4] #1 May 15
2014         [0.2912, -11.18, 1.272])
2015     gout = g(gbeta, gkwars)
2016     Pliq = norm.cdf(-gout / gbeta[-1])
2017     LSC = calcLimStCurves(0.15, gbeta, gkwars)
2018     #FSscale = np.minimum(np.min(np.log(df.dWn.values)),
2019     #kwars.get('FSscale', gbeta[1]))
2020     FSscale = kwars.get('FSscale', gbeta[1])
2021     if kwars.get('FSalt', False):
2022         FS = np.minimum(2.,
2023             np.maximum(LSC / df.dWn.values, 0.1))
2024 else:
FS = np.minimum(2., np.maximum((LSC - FSscale) / (np.log(df.dWn.values) - FSscale), 0.1))

FS[df.gamma.values * 1.543 < 1e-4] = 2.  # Won't liq. if doesn't exceed threshold. The 1.534 converts from the average strain to a max value.

FS[np.log(df.dWn.values) < FSscale] = 2.

#otherL = calcLimStCurves(0.15, gbeta,
#  {'a':np.linspace(0,30, 100)})

# plt.figure('mine')
# plt.semilogy(np.linspace(0, 30, 100), np.exp(otherL), '-k')

# plt.plot(df.N160cs.values[Pliq>=0.15], df.dWn.values[Pliq>=0.15], 'ro')
# plt.plot(df.N160cs.values[Pliq<0.15], df.dWn.values[Pliq<0.15], 'bo')
# plt.plot(df.N160cs.values[FS>=1], df.dWn.values[FS<1], 'gx')
# plt.plot(df.N160cs.values[FS<1], df.dWn.values[FS<1], 'rx')

# plt.figure('LS-log(dWn) values')
# print(LSC)

# plt.figure('Demand dWn vals (log of)')
# print(np.log(df.dWn.values))
# #f_ls = interp1d(np.linspace(0, 30,100), np.exp(otherL))
# #print(np.log(f_ls(df.N160cs.values)))

# plt.figure('FS')
# plt.plot(FS, df.z.values)
# plt.show()

pdb.set_trace()

if kwargs.get('plot', False):
    indLiq = np.where(gout<= 0)
    indNo = np.where(gout> 0)
    print(len(indLiq[0]))
    print(len(indNo[0]))
    plt.semilogy(N160cs[indLiq], dWn[indLiq], 'ko')
    plt.plot(N160cs[indNo], dWn[indNo], 'ws')
    plt.show()

pdb.set_trace()

return Pliq, gout, FS

def LiqEvalBoulangerIdriss(df, **kwargs):
    returnall = kwargs.get('returnall', False)
    calcN160 = kwargs.get('calcN160', True)
    Mw = df.Mw.values
    N160cs = df.N160cs.values
    z = df.z.values
    PGA = df.amax.values
    sigveff = df.sigeffv.values
    sigv = df.sigv.values
    MSF = np.minimum( 6.9 * np.exp(-Mw / 4.) - 0.058, 1.8)
    if calcN160:
        N160cs, DN160, Cr, Ch, Cs = calcN160cs(df.Nm.values, df.sigeffv.values,
                                               df.FC.values, df.z.values, Ce=df.CE.values, Cs=df.CS.values,
                                               returnall=True)
        N160 = N160cs - DN160
    else:
        N160 = df.N160.values
    if 'Ksig' in kwargs.keys():
        Ksig = kwargs['Ksig']
    else:
Csig = np.minimum(1 / (18.9 - 2.55 * np.sqrt(np.minimum(37,N160))), 0.3)
Ksig = np.minimum(1 - Csig * np.log(sigveff / 101.325), 1.1)

# Stress reduction coefficient. Notice that I am cheating here with
# the depth; it says not to use below 34 meters (or even 20 m)
alpha = -1.012 - 1.126 * np.sin(np.minimum(z, 34.) / 11.73 + 5.133)
beta = 0.106 + 0.118 * np.sin(np.minimum(z, 34.) / 11.28 + 5.142)
rd = np.exp(alpha + beta * Mw)

#CSR M=7.5, sigveff = 1 atm
CSR = 0.65 * sigv * PGA * rd / (sigveff * MSF * Ksig)
go = gIdrissBoul2(N160cs, CSR, co=co, siglnR=siglnR) #Deterministic curve at Pl=15%???
gout = gIdrissBoul2(N160cs, CSR, co=co)
FS = np.minimum(2, CRR / CSR)
Plq = norm.cdf(-gout / siglnR)

if kwargs.get('plot', False):
    indLiq = np.where(gout<= 0)
    indNo = np.where(gout> 0)
    print(len(indLiq[0]))
    print(len(indNo[0]))
    plt.plot(N160cs[indLiq], CSR[indLiq], 'ko')
    plt.plot(N160cs[indNo], CSR[indNo], 'ws')
    plt.show()
Pliq, gout, FS, CSR*Ksig, CRR*Ksig, rd, N160cs

def rd_Cetin1(amax, Mw, z, **kwargs):
    beta = [-9.147, -4.173, 0.652, 10.567, 0.089, 0.089, -7.76, 78.576, 0.0014, 19.8, 0.1, 0.0072]
d = z
g = np.empty(d.shape, dtype=float)
        )
        )
        )
g[d<beta[9]] = (numerator1 / denominator)[d<beta[9]]
return g

def rd_Cetin2(amax, Mw, z, Vs12):
d=z
beta = [-23.013, -2.949, 0.999, 0.0525, 16.258,
        0.201, 0.341, 0.0785, 7.586, 0.0046,]
```python
20, 0.85, 0.0072]
g = np.empty(d.shape, dtype=float)
g[d<beta[10]] = (numerator1 / denominator)[d<beta[10]]
g[d>=beta[10]] = (numerator2 / denominator - beta[9] * (d - beta[10]))[d>=beta[10]]
return g

def LiqEvalCetin(df, **kwargs):
  
  Evaluates liquefaction using Cetin's procedure
  
  returnall = kwargs.get('returnall', False)
calcN160 = kwargs.get('calcN160', True)

  def calcDWF(Mw):
    CetinM = [5.50,6.00,6.50,7.00,7.50,8.00,8.50]
    CetinMSF = [1.61,1.41,1.25,1.12,1.00,0.91,0.83]
    f_MSF = interp1d(CetinM, CetinMSF)
    MSF = f_MSF(Mw)
    MSF = (7.5 / Mw) ** 2.217 #From Cetin's Spreadsheet SIteX_KOC.xlsx
    return MSF

def calcKsig(sigv, N160cs):
  f = 0.6 + 0.005714 * (40 - (np.maximum(5, np.minimum(40, N160cs))))
  ksiq = np.minimum(1.5, (sigv/101.325) ** (f-1))
  ksiq = (100. / sigv) ** 0.278 #From Cetin's Spreadsheet SIteX_KOC.xlsx
  return ksiq

  FC = df.FC.values
  z = df.z.values
  amax = df.amax.values
  Mw = df.Mw.values
  if 'Vs12' in df.columns:
    rd = rd_Cetin2(amax, Mw, z, df.Vs12.values)
  else:
    rd = rd_Cetin1(amax, Mw, z)
sigy = df.sigy.values
sigeffv = df.sigeffv.values

  # N Correction
  N = df.Nm.values
  if calcN160:
    N160, Cr, Cn, Cs = calcN160cs(N, sigeffv, FC, z, Ce=df.CE.values, Cn=df.CN.values, Cb=df.CB.values, Cetin=True, calcCs=True, returnall=True)
  N160 = df.N160.values
  FC_lim = np.minimum(35, FC)
```

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FC_lim[FC<5] = 0.
C_fines = (1 + 0.004 * FC_lim) + 0.05 * (FC_lim / N160)
N160cs = N160 * C_fines
CSR_eq = 0.65 * amax * sigv / sigeffv
DWF = calcDWF(Mw)
Ksig = calcKsig(sigeffv, N160)
CSR_eq_75 = CSR_eq / DWF
CSR_eq_str = CSR_eq_75 / Ksig

gout = gCetin(CSR_eq, N160, Mw, FC_lim, sigeffv)
Pliq = norm.cdf(-gout / 2.7)
CRR = calcLS_Cetin(0.15, N160, FC_lim, Mw, sigeffv) # Uses 0.5 for deterministic? See SiteX_KOC.xlsx

FS = np.minimum(2., CRR / CSR_eq) # From SiteX_KOC.xlsx
if returnall:
    return Pliq, gout, FS, CSR_eq, CRR, rd, N160
return Pliq, gout, FS

---

class LiqEvalJafarianetal(object):
    '''
    "Simplified Soil Liquefaction Assessment Based on Cumulative Kinetic
    Energy Density: Attenuation Law and Probabilistic Analysis."
    '''
    def __init__(self, df, **kwargs):
        self.df = df
        if 'rhoeff' in kwargs.keys():
            self.df['rhoeff'] = kwargs['rhoeff']
        elif 'rhoeff' in df.columns:
            pass
        else:
            self.df['rhoeff'] = 1400. #kg/m^3, This is a guess, maybe up to 1800
        self.Rtype = kwargs.get('Rtype', 'Rrup (km)')
        self.df['rsed'] = self.calc_rSED(**kwargs)
        self.df['SEDsurf'] = self.calc_SED_surf()
        self.df['CKED'] = self.calc_CKED()
        self.df['g'] = self.calc_g()
        self.Rtype = kwargs.get('Rtype', 'Rrup (km)')
        self.df['rsed'] = self.calc_rSED(**kwargs)
        self.df['SEDsurf'] = self.calc_SED_surf()
        self.df['CKED'] = self.calc_CKED()
        self.df['g'] = self.calc_g()
        def calc_CKED(self, **kwargs):
            rhoeff = self.df['rhoeff'].values
            SEDsurf = self.df['SEDsurf'].values
            rsed = self.df['rsed'].values
            return rhoeff * rsed * SEDsurf * 0.0001 # in N*s/M^2 or kg / (s *m)
        def calc_SED_surf(self, **kwargs):
            Vs30 = self.df['Vs30'].values
            if 'Vs30' in self.df.columns:
                Vs30 = self.df['Vs30']
            else:
                Vs30 = 273.* np.ones(self.df.shape[0])
if 'faulttype' in self.df.columns:
    faulttype = self.df.faulttype
elif 'faulttype' in kwargs.keys():
    faulttype = kwargs['faulttype']
else:
    faulttype = ['unspecified' for val in xrange(self.df.shape[0])]

f1 = (76.37e-7 * (R + 24.83) ** 2 * (1 + 0.026348 * M +
    (0.040161 * R + np.log(Vs30) + 1.45626)) +
    1.17971 * M - 0.01443 * R - 0.82029 * np.log(Vs30) -
    0.39071)

f2 = np.zeros(self.df.shape[0])

f2[faulttype == 'normal'] = (97.3e-5 * M[faulttype == 'normal'] ** 2 + 0.10408 * M[faulttype == 'normal'] - 0.89195) +

f2[faulttype == 'strikeslip'] = ((0.12595 * M[faulttype == 'strikeslip'] - 0.64) * (-0.14572 * M[faulttype == 'strikeslip'] ** 2 + M[faulttype == 'strikeslip'] + 0.91072)) +

f2[faulttype == 'reverse'] = (-5.857e-6 * M[faulttype == 'reverse'] ** 3 * (M[faulttype == 'reverse'] - 3.4631) * (M[faulttype == 'reverse'] ** 3 - 8.56458 * M[faulttype == 'reverse'] ** 2 + 8.19733 * M[faulttype == 'reverse'] + 5.93354))

fb = -0.0024 * R + 0.0005 * Vs30 + 0.0054

fb[faulttype == 'normal'] = (-0.125 * M[faulttype == 'normal'] - 0.0054 * R[faulttype == 'normal'] + 0.0002 * Vs30[faulttype == 'normal'] + 0.9772) +

fb[faulttype == 'strikeslip'] = (0.0003 * Vs30[faulttype == 'strikeslip'] - 0.1067) -

fb[faulttype == 'reverse'] = (0.0043 * R[faulttype == 'reverse'] + 0.0006 * Vs30[faulttype == 'reverse'] - 0.6259) +

SEDsurf = 10 ** (f1 + f2 + fb) # in cm^2 /s?
return SEDsurf

def calc_rSED(self, **kwargs):
    z = self.df.z.values
    M = self.df.Mw.values
    rsed = (1 - ((-0.2361663 * M + 2.263352) * z ** 1.958192) / ((-0.2361663 * M + 2.263352) * z ** 1.958192 + (0.4487404 * M + 1.959488) * z ** 1.316766 + (14.39358 * M - 56.22128)))
    #self.df.rsed = rsed
    return rsed

def calc_g(self, P1=0.5, sig=1.):
    sigeffv = self.df.sigeffv.values
    N160 = self.df.N160.values
    FC = self.df.FC.values
    CKED = self.df.CKED.values
    # not sure, but may need to take negative of g
    g = (np.log(1/P1 - 1) - 0.80908 * np.log(sigeffv / 101.325) -

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def calc_CKED_liq(self, N160, **kwargs):
    Pl = kwargs.get('Pl', 0.5)
    FC = kwargs.get('FC', 0.)
    sigeffv = kwargs.get('sigeffv', 50.)
    return np.exp((np.log(1./Pl - 1) - 0.80908 * np.log(sigeffv / 101.325) -
                   0.38610 * N160 - 0.0236 * FC - 0.16946) / -1.40241)

def plot(self, **kwargs):
    fig, ax = plt.subplots(num=kwargs.get('figname', 'Jafarian'))
    ax.plot(self.df.N160[self.df.Liq == 'Yes'],
            self.df.CKED[self.df.Liq == 'Yes'], 'ok')
    ax.plot(self.df.N160[self.df.Liq == 'No'],
            self.df.CKED[self.df.Liq == 'No'], 'sw')
    N160 = np.linspace(2, 40, 50)
    CKED = self.calc_CKED_liq(N160)
    ax.plot(N160, CKED, 'b', lw=3)
    ax.set_xlabel('$N_{1,60}$')
    ax.set_ylabel('CKED ($N s/m^2$)')
    ax.set_yscale('log')
    return fig

def calcKsigFactory(**kwargs):
    '''
    Calcs Ksigs and compares
    '''

def calc_dWone(sigveff, Degrad, PI, tau, N160, **kwargs):
    '''
    Calculates the dissipated energy in one equivalent cycle
    '''
    soil = kwargs.get('soil', 1)
    phi = np.sqrt(20 * N160) + 20
    ko = 1. - np.sin(phi * np.pi / 180.)
    sigme = (1 + 2 * ko) * sigveff / 3.
    Gmax = 440. * N160 ** (1./3.) * 101.325 * (sigme / 101.325) ** 0.5
    gam, Gratio, damping = getDegrad('DS', PI, sigme, N=10, soil=soil)
    G, D, gamma = TokimatsuSeedDirect(gam, Gratio, damping, Gmax, tau)
    dw1 = 2 * np.pi * D * tau ** 2 / G
    return dw1, G, D, gamma

def calc_KsigEn(sigveff, dw1, tau1, **kwargs):
    '''
    Calculates Ksig using the Darendeli and Stokoe curves
    and energy principles
    '''
    verbose = kwargs.get('verbose', False)
    sigveff1 = kwargs.get('sigveff1', 101.325)
    Degrad = kwargs.get('Degrad', 'DS')
    PI = kwargs.get('PI', [0.])
    soil = kwargs.get('soil', 0)
    normd = kwargs.get('normd', True)
dW1n = dW1 / sigveff
numtrials = kwargs.get('numtrials', 200)
#pdb.set_trace()

for i, sigve in enumerate(sigveff):
    #print(i)
    tau = CSR * sigve
    dw, G, D, gamma = calcdWone(sigve, Degrad, PI, tau, N160,
                              soil=soil)
    dwn = dw / sigve
    mytau = tau

    trialtaus = kwargs.get('trialtaus', np.linspace(0.35 * tau,
                              tau * np.maximum(3, 1.7 * sigve / 101.325), numtrials))
    theseerrors = np.zeros(trialtaus.shape)
    theseDWs = np.zeros(trialtaus.shape)

    count = -1
    if verbose:
        print('


 Sigveff: {}'.format(sigve))
    if normd:
        error = np.abs(dW1n - dwn) / dW1n
    else:
        error = np.abs(dW1 - dw) / dW1
    while np.abs(error) > 0.01:
        count += 1
        if error < -10:
            break
        if count > (numtrials - 1):
            dw = np.nan
            mytau = np.nan
            break
        if normd:
            mytau = np.sqrt(dW1n * G * sigve / (2 * np.pi * D))
        else:
            mytau = np.sqrt(dW1 * G / (2 * np.pi * D))
        mytau = trialtaus[count]
        dw, G, D, gamma = calcdWone(sigve, Degrad, PI, mytau, N160,
                                  soil=soil)
        if normd:
            dwn = dw / sigve
            #error = np.abs(dW1n - dwn) / dW1n
            theseerrors[count] = (dW1n - dwn) / dW1n
            theseDWs[count] = dwn
        else:
            error = np.abs(dW1 - dw) / dW1
        if verbose:
            print('Count: {}, Error: {:.4f}, tau: {:.2f}'.format(
                count, error, mytau))
        if np.abs(error) < 0.01:
            dWone[i] = dwn
            tau[i] = mytau

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else:
    f_tau = interp1d(theseerrors[:count-1], trialtaus[:count-1])
    f_dW = interp1d(theseerrors[:count-1], theseDWs[:count-1])
    try:
        dWone[i] = f_dW(0.)
        taus[i] = f_tau(0.)
    except ValueError:
        pdb.set_trace()
    #errors[i] = error
    #dWone[i] = dw
    #taus[i] = mytau
    Ksig = (taus / sigveff) / (tau1 / sigveff1)
return Ksig, taus, dWone

#ko=0.5
normd = True
verbose = True
PI = [0.]
Drs = np.array([30., 40., 50.])#
N160s = Drs ** 2 / 15 ** 2
x = np.linspace(0, 50, 100)
IBCSR = np.exp(x / 14.1 + (x / 126) ** 2 -
            (x / 23.6) ** 3 + (x / 25.4) ** 4 - 2.67)
f_csr = interp1d(x, IBCSR)
CSRs = f_csr(N160s)
lws = [1.5, 2.3, 3.5]
colors = ['0.3', '0.1', '0.0']
Degrad = 'DS'
labels = ['$D_r = {:.0f}\%$, $CSR={:.2f}$:'.format(Drs[0], CSRs[0]),
          'Darendeli and Stokoe (2001)',
          'Boulanger and Idriss (2004)',
          'Hynes and Olsen (1999)',
          '#',
          '$D_r = {:.0f}\%$, $CSR={:.2f}$:'.format(Drs[1], CSRs[1]),
          'Darendeli and Stokoe (2001)',
          'Boulanger and Idriss (2004)',
          'Hynes and Olsen (1999)',
          '#',
          '$D_r = {:.0f}\%$, $CSR={:.2f}$:'.format(Drs[2], CSRs[2]),
          'Darendeli and Stokoe (2001)',
          'Boulanger and Idriss (2004)',
          'Hynes and Olsen (1999)',
          '#',
          'Dissipated-Energy-Derived:',
          'Darendeli and Stokoe (2001) - Clean Sand',
          'Darendeli and Stokoe (2001) - Sand with High Fines',
          ]
HOdashes = (15,5)
LegLines = [
            plt.Line2D([], [], color='0.0', linestyle='-', lw=lws[0], alpha=0),
            #plt.Line2D([], [], color=colors[0], linestyle='--', lw=lws[0]),
            plt.Line2D([], [], color=colors[1], linestyle='--', lw=lws[0]),
            #plt.Line2D([], [], color=colors[2], linestyle='--', lw=lws[0], dashes=HOdashes),
            #plt.Line2D([], [], color='0.0', linestyle='--', lw=lws[0], alpha=0),]
plt.Line2D([], [], color='0.0', linestyle='-', lw=lws[0], alpha=0),
#plt.Line2D([], [], color=colors[0], linestyle='-', lw=lws[1]),
plt.Line2D([], [], color=colors[1], linestyle='--', lw=lws[1]),
plt.Line2D([], [], color=colors[2], linestyle='-', lw=lws[2], dashes=HOdashes),
#plt.Line2D([], [], color='0.0', linestyle='-', lw=lws[0], alpha=0),
plt.Line2D([], [], color='0.0', linestyle='-', lw=lws[0], alpha=0),
#plt.Line2D([], [], color=colors[0], linestyle='-', lw=lws[2]),
plt.Line2D([], [], color=colors[1], linestyle='--', lw=lws[2]),
plt.Line2D([], [], color=colors[2], linestyle='-', lw=lws[2], dashes=HOdashes),
#plt.Line2D([], [], color='0.0', linestyle='-', lw=lws[0], alpha=0),
plt.Line2D([], [], color='0.0', linestyle='-', lw=lws[0], alpha=0),
plt.Line2D([], [], color=colors[0], linestyle='-', lw=lws[1]),
plt.Line2D([], [], color=colors[0], linestyle='-', lw=lws[1]),
plt.Line2D([], [], color=colors[0], linestyle='-', lw=lws[2]),

]  

sigveff1 = np.array([101.325])
sigveff = np.linspace(40, 900, 45)  
errors = np.zeros(sigveff.shape)

plt.figure('Main Event', figsize=(8.5, 5.))

for Dr, CSR, lw in zip(Drs, CSRs, lws):
    print('Dr = {}
'.format(Dr))
    N160 = Dr ** 2 / 15. ** 2
    dWone = np.zeros(sigveff.shape)
    taut = np.zeros(sigveff.shape)
    soil = 0
    tau1 = CSR * 101.325
    dW1, G1, D1, gam1 = calcdWone(sigveff1, Degrad, PI, tau1, N160, soil=soil)
    dW1n = dW1 / sigveff1[0]

    Ksig, tau, dW = calcKsigEn(sigveff, dW1, tau1, PI=PI, soil=soil, Degrad='DS', verbose=verbose, normd=normd)
    #Ksig2 = (taus / sigveff) / (tau1 / sigveff1)
    #pdb.set_trace()

    Csig = np.minimum(1 / (18.9 - 17.3 * Dr/100.), 0.3)
    KsigIB = np.minimum(1 - Csig * np.log(sigveff / 101.325), 1.1)

    plt.figure('Main Event')
    #plt.plot(sigveff/101.325, Ksig, 'r-', lw=lw, color=colors[0],
    #label=labels[1])
    #plt.plot(sigveff/101.325, KsigIB, 'b--', lw=lw, color=colors[1],
    #label=labels[2])
    plt.plot(sigveff/101.325, KsigIB, 'r-', lw=lw, color=colors[0],
     label=labels[1])
    plt.plot(sigveff/101.325, Ksig, 'r-', lw=lw, color=colors[1],
     label=labels[2])
    #plt.plot(sigveff/101.325, KsigIB, 'r-', lw=lw, color=colors[0],
    #label=labels[1])
    if Dr >= 40:
        f = np.minimum(0.8, np.maximum(0.6, 1 - 0.005 * Dr))
        plt.plot(sigveff/101.325, np.minimum(1.,
        (sigveff / 101.325) ** (f - 1)), 'r-',
        lw=lw, label=labels[3], color=colors[2], dashes=HOdashes)
    plt.figure('CSR')
    plt.plot(sigveff, taud/sigveff, 'r-', lw=2, label='$D_r = {}$'.format(Dr))

plt.figure('Main Event')
plt.grid('on', alpha=0.5)
plt.xlabel(r'$\sigma\prime_{v0} / P_a$')
plt.ylabel(r'$K_\sigma$')
leg1 = plt.legend(LegLines, labels,
    bbox_to_anchor=(0.5, 1.05), loc='lower center',
    bbox_to_anchor=(1.05, 1.), loc='upper left',
    ncol=1, mode='expand',
    fontsize=13,
    borderaxespad=0., handlelength=4.5)

if normd:
    plt.axis([xmin, xmax, 0.4, 1.2])
else:
    plt.axis([xmin, xmax, 0, 1.2])

fig, ax = plt.subplots(num='Soil types')
dashes = [(1000,1), (35,5), (20,7.5), (10,10)]
for soil, dash, label, color in zip([1, 0, 2, 3], dashes, labels,
    colors2):
    print('Soil Type: {}'.format(soil))
    N160 = Drs[1] ** 2 / 15. ** 2
    dWone = np.zeros(sigveff.shape)
    taus = np.zeros(sigveff.shape)
    tau1 = CSRs[1] * 101.325
    dW1, G1, D1, gam1 = calcdWone(sigveff1, Degrad, PI, tau1, N160,
        soil=soil)
    dW1n = dW1 / sigveff1[0]
    Ksig, tau, dW = calcKsigEn(sigveff, dW1, tau1, PI=PI, soil=soil,
        Degrad='DS', verbose=verbose, normd=normd)
    ax.plot(sigveff, Ksig, dashes=dash, lw=2.5, color=color,
        label=label)
    if soil == 1:
        plt.figure('Main Event')
        plt.plot(sigveff/101.325, Ksig, '-', lw=lws[1], color=colors[0],
            label=labels[1])
    if soil == 2:
        plt.figure('Main Event')
        plt.plot(sigveff/101.325, Ksig, '-', lw=lws[2], color=colors[0],
            label=labels[1])

ax.grid('on', alpha=0.5)
ax.set_xlabel(r'$\sigma\prime_{v} / P_a$')
ax.set_ylabel(r'$K_\sigma$')
leg2 = ax.legend(
    bbox_to_anchor=(0.5, 1.), loc='upper left',
    fontsize=12,
    bbox_to_anchor=(0.5, 1.02), loc='lower center',
    ncol=1, mode='expand',
    ncol=1, mode='expand',
    bbox_to_anchor=(0.5, 1.05), loc='lower center',
    bbox_to_anchor=(1.05, 1.), loc='upper left',
    ncol=1, mode='expand',
    fontsize=13,
    borderaxespad=0., handlelength=4.5)
J.8 Data Reduction of CSS Lab Data

The file gcts-cv-css.py takes the output files from CV-CSS tests on the GCTS equipment and reduces the data.

```python
import os
import sys
if os.name == 'posix':
sys.path.append('/media/Storage/Documents/Python/Modules')
sys.path.append('/media/Storage/Documents/Python/CaseHistories/')
else:
sys.path.append('/../../Documents/Python/Modules')
sys.path.append('/../../Documents/Python/CaseHistories/
try:
```
import ipdb as pdb

except:
    import pdb
import glob
import csv
import numpy as np
import matplotlib
matplotlib.rcParams.update({'font.size': 18, 'text.usetex': True,
    'legend.fontsize': 16})
matplotlib.rcParams.update({'font.size': 18, 'font.family': 'STIXGeneral',
    'mathtext.fontset': 'stix',
    'legend.fontsize': 16})
import matplotlib.pyplot as plt
from matplotlib.ticker import MaxNLocator
import statsmodels.api as sm
import pandas as pd
import pickle as p
import qtfiledialog as fd
import tables as pt
from time import strftime
import datetime as dt
from scipy.interpolate import interp1d
import degrcurv as dc
from CaseHistoriesv3 import getDegrad, DobryIter, TokimatsuSeedDirect

# Makes the code okay to use in Python3, not fully tested.
try: # xrange(10)
    # raw_input('This is Python 2, press "Enter"')
    basestring
except NameError:
    xrange = range
    raw_input = input
    basestring = str

class SumTable(pt.IsDescription):
    '''
    PyTables summary table format for stress-controlled soil tests.
    '''
    File = pt.StringCol(itemsize=32,pos=1)
    eo = pt.Float32Col(pos=2)
    Dr = pt.Float32Col(pos=3)
    CSR = pt.Float32Col(pos=4)
    Sigveff = pt.Float32Col(pos=5)
    Cycles = pt.Float32Col(pos=6)
    DE = pt.Float32Col(pos=7)
    DE_corr = pt.Float32Col(pos=8)
    DE_b = pt.Float32Col(pos=9)
    DE_m = pt.Float32Col(pos=10)
    DE_1 = pt.Float32Col(pos=11)
    Gs = pt.Float32Col(pos=12)
    mass = pt.Float32Col(pos=13)
    hi = pt.Float32Col(pos=14)
    di = pt.Float32Col(pos=15)
    PEC = pt.Float32Col(pos=16)
```python
LoadCorr = pt.BoolCol(pos=17)
LoadCorrType = pt.StringCol(itemsize=32, pos=18)
WaterTestName = pt.StringCol(itemsize=32, pos=19)
Modified = pt.StringCol(itemsize=32, pos=20)
Date_of_Test = pt.Int64Col(pos=21)
failuretype = pt.StringCol(itemsize=32, pos=22)
DE_corralt = pt.Float32Col(pos=8)
MaxStrain = pt.Float32Col(pos=23)
MaxStress = pt.Float32Col(pos=24)
r_u_fin = pt.Float32Col(pos=25)
r_u_fin_zero_stress = pt.Float32Col(pos=26)

class StrainSumTable(pt.IsDescription):
    '''
    PyTables summary table format for strain-controlled soil tests.
    '''
    File = pt.StringCol(itemsize=32, pos=1)
eo = pt.Float32Col(pos=2)
Dr = pt.Float32Col(pos=3)
CSR = pt.Float32Col(pos=4)
Gamma = pt.Float32Col(pos=4)
Sigveff = pt.Float32Col(pos=5)
Cycles = pt.Float32Col(pos=6)
DE = pt.Float32Col(pos=7)
DE_corr = pt.Float32Col(pos=8)
DE_b = pt.Float32Col(pos=9)
DE_m = pt.Float32Col(pos=10)
DE_1 = pt.Float32Col(pos=11)
Gs = pt.Float32Col(pos=12)
mass = pt.Float32Col(pos=13)
hi = pt.Float32Col(pos=14)
di = pt.Float32Col(pos=15)
PEC = pt.Float32Col(pos=16)
LoadCorr = pt.BoolCol(pos=17)
LoadCorrType = pt.StringCol(itemsize=32, pos=18)
WaterTestName = pt.StringCol(itemsize=32, pos=19)
Modified = pt.StringCol(itemsize=32, pos=20)
Date_of_Test = pt.Int64Col(pos=21)
failuretype = pt.StringCol(itemsize=32, pos=22)
DE_corralt = pt.Float32Col(pos=8)
MaxStrain = pt.Float32Col(pos=23)
MaxStress = pt.Float32Col(pos=24)
r_u_fin = pt.Float32Col(pos=25)
r_u_fin_zero_stress = pt.Float32Col(pos=26)

class EQSumTable(pt.IsDescription):
    '''
    PyTables summary table format for soil tests with earthquake loading functions.
    '''
    File = pt.StringCol(itemsize=32, pos=1)
eo = pt.Float32Col(pos=2)
Dr = pt.Float32Col(pos=3)
CSR = pt.Float32Col(pos=4)
Sigveff = pt.Float32Col(pos=5)
Sigveff_fin = pt.Float32Col(pos=6)
```

r_u_fin = pt.Float32Col(pos=7)
DE = pt.Float32Col(pos=7)
DE_corr = pt.Float32Col(pos=8)
DE_b = pt.Float32Col(pos=9)
DE_m = pt.Float32Col(pos=10)
DE_1 = pt.Float32Col(pos=11)
Ar = pt.Float32Col()
PTRatio = pt.Float32Col()
ElapsedTime = pt.Float32Col()
Gs = pt.Float32Col(pos=12)
mass = pt.Float32Col(pos=13)
hi = pt.Float32Col(pos=14)
di = pt.Float32Col(pos=15)
PEC = pt.Float32Col(pos=16)
LoadCorr = pt.BoolCol(pos=17)
LoadCorrType = pt.StringCol(itemsize=32, pos=18)
WaterTestName = pt.StringCol(itemsize=32, pos=19)
Modified = pt.StringCol(itemsize=32, pos=20)
Date_of_Test = pt.Int64Col(pos=21)
failuretype = pt.StringCol(itemsize=32, pos=22)
Cycles = pt.Float32Col(pos=23)
Total_Pts = pt.Float32Col(pos=24)
CSR_calcd = pt.Float32Col(pos=25)
EQ = pt.StringCol(itemsize=32, pos=26)
Neq = pt.Float32Col(pos=27)
Gmax = pt.Float32Col(pos=28)
DE_corralt = pt.Float32Col(pos=8)

class EQCSR_stuff(pt.IsDescription):
    '''
    PyTable formats for a summary table of eqs
    '''
    File = pt.StringCol(itemsize=32, pos=1)
    CSR_nom = pt.Float32Col(pos=2)
    EQ = pt.StringCol(itemsize=32, pos=3)

class WaterSumTable(pt.IsDescription):
    '''
    Format of output table for friction tests without a surcharge
    '''
    File = pt.StringCol(itemsize=32, pos=1)
    Modified = pt.StringCol(itemsize=32, pos=2)
    posm = pt.Float32Col(pos=3)
    posb = pt.Float32Col(pos=4)
    negm = pt.Float32Col(pos=5)
    negb = pt.Float32Col(pos=6)
    Load_unit = pt.StringCol(itemsize=16, pos=7)
    Disp_unit = pt.StringCol(itemsize=16, pos=8)
    Date_of_Test = pt.Int64Col(pos=9)
    Gmax = pt.Float32Col(pos=10)
    G2 = pt.Float32Col(pos=11)
    gamr = pt.Float32Col(pos=12)
    voffset = pt.Float32Col(pos=13)
    hypa = pt.Float32Col(pos=14)
    hypb = pt.Float32Col(pos=15)
class SurchargeSumTable(pt.IsDescription):
    
    Format of output table for friction tests with a surcharge
    
    File = pt.StringCol(itemsize=32,pos=1)
    Modified = pt.StringCol(itemsize=32,pos=2)
    posm = pt.Float32Col(pos=3)
    posb = pt.Float32Col(pos=4)
    negm = pt.Float32Col(pos=5)
    negb = pt.Float32Col(pos=6)
    surcharge = pt.Float32Col(pos=7)
    DE = pt.Float32Col(pos=7)
    DE_corr = pt.Float32Col(pos=8)
    Load_unit = pt.StringCol(itemsize=16,pos=9)
    Disp_unit = pt.StringCol(itemsize=16,pos=10)
    Date_of_Test = pt.Int64Col(pos=11)

def moviemaker((t,x,y), **kwargs):
    
    This will create a movie of the friction test hysteresis loops.
    
    Deprecated because ‘mencoder’ isn’t available anymore
    
    numy = kwargs.get('num_y', 1)
    syms = kwargs.get('syms',['ro','b', 'g', '.k'])
    no_frames = kwargs.get('no_frames', 100)
    frames_stay = kwargs.get('frames_stay', 1)
    xlabel = kwargs.get('xlabel','x')
    ylabel = kwargs.get('ylabel','y')
    tlabel = kwargs.get('tlabel','Time')
    moviename = kwargs.get('moviename', 'Movie1')
    fixedaxes = kwargs.get('fixedaxes', False)
    
    if fixedaxes == True:
        xmax = np.max(x) + 0.05 * (np.max(x) - np.min(x))
        xmin = np.min(x) - 0.05 * (np.max(x) - np.min(x))
        ymax = np.max(y) + 0.05 * (np.max(y) - np.min(y))
        ymin = np.min(y) - 0.05 * (np.max(y) - np.min(y))

    fps = kwargs.get('fps',5)
    step = len(t) / no_frames
    files = []
    
    fig, ax = plt.subplots(figsize=(5,5))
    for i in range(no_frames):
        im1 = max(0,i-frames_stay)
        ind = step * (i + 1)
        indm1 = step * (im1)
        plt.cla()
        if numy == 1:
            plt.plot(x[indm1:ind], y[indm1:ind], syms[0])
        else:
            for j,yy in enumerate(y):
                plt.plot(x[indm1:ind], yy[indm1:ind], syms[j])
        if fixedaxes != True:
            try:
                xmin = np.min(x[indm1:ind])
                xmax = np.max(x[indm1:ind])
                ymin = np.min(yy[indm1:ind])
                ymax = np.max(yy[indm1:ind])
            except:
                xmin = np.min(x[indm1:ind])
                xmax = np.max(x[indm1:ind])
                ymin = np.min(yy[indm1:ind])
                ymax = np.max(yy[indm1:ind])
except ValueError:
    pdb.set_trace()
plt.xlabel(xlabel)
plt.ylabel(ylabel)
plt.title('{}: {}-{}'.format(tlabel,t[ind-1], t[ind]))
plt.axis([xmin,xmax,ymin,ymax])
fname = '_tmp%03d.png'%i
print('Saving frame', fname)
plt.savefig(fname)
files.append(fname)

print('Making movie animation.mpg - this make take a while')
o.s.system("mencoder 'mf://_tmp*.png' -mf type=png:fps={} -ovc lavc -lavcopts vcodec=wmv2 -oac copy -o {}.mpg".format(fps,moviename))
#os.system("convert _tmp*.png animation.mng")

# cleanup
for fname in files: os.remove(fname)

def nextpow2(i):
    '''
    Returns the the log-base-2 of the next power of 2 greater than the input value.
    Example:
    >>> y = nextpow2(5)
    >>> print y
    3
    >>> 2 **nextpow2(5)
    8
    '''
    n = 2
    while n < i:
        n = n * 2
    return int(round(np.log2(n)))

def datetimeconvert(datestr,timestr):
    '''
    Convenience function for working with dates
    Example:
    >>> date = dt.datetime.strptime(datestr+timestr, '%m/%d/%y%H:%M:%S')
    >>> int(date.strftime('%Y%m%d%H%M%S'))
    '''
    motionpool = ['NGA_no_87_SAD273',
    'NGA_no_45_DCF090',
    'NGA_no_283_A=ARI000',
    'NGA_no_2658_TCU129-N',
    'NGA_no_1060_CUC090',
    'NGA_no_1060_CUC180',
    'NGA_no_23_GGP010',
    'NGA_no_45_DCF090_inv',
    'NGA_no_87_SAD273_inv',
    'NGA_no_87_SAD273_INV',
    'NGA_no_45_DCF090_INV',
    'NGA_no_87_SAD273_INV']
'NGA_no_1060_CUC090_inv',
'NGA_no_283_A-ARI000_inv']

print('What is the ground motion for {}:'.format(basename))
for i, val in enumerate(motionpool):
    print(' [{0}]. {}'.format(i+1, val))
print(' [0]: Input the motion yourself.')

choice = int(input('Choose: >>> '))
if choice == 0:
    name_of_motion = input('Motion Name (Ex. NGA_no_87_SAD273) >>> ')  
else:
    name_of_motion = motionpool[choice-1]

return name_of_motion

def unit_lookup(header1, header2, Label):
    '''
    Returns the unit of a given variable (Label).
    header1 is an array of labels: Shear Load, Shear Displacement, etc
    header2 is an array of units corresponding to the labels: kN, mm, etc
    Label is label for which a unit is desired.
    '''
    for i, label in enumerate(header1):
        if Label == label:
            return header2[i]
    break

def getsign(sign):
    '''
    Should use np.sign() instead of this
    '''
    i = 0
    mys = sign[i]
    if mys != 0:
        return mys
    else:
        while mys == 0:
            i += 1
            if i > 30:
                pdb.set_trace()
            mys = np.sign(np.mean(sign[:i]))
        return mys

def calcDissEnergy(stress, strain, **kwargs):
    '''
    Calculates the dissipated energy from a stress and strain time history.
    Output is the same length as the input time history.
    '''
    area = kwargs.get('area', np.ones(stress.shape, dtype=float))
    ht = kwargs.get('ht', np.ones(stress.shape, dtype=float))
    stress = stress / area
    strain = strain / ht
    dissEn = np.zeros(stress.shape, dtype=float)
    dissEn = np.cumsum((stress[1:] + stress[:-1]) * 
                    (strain[1:] - strain[:-1])) * 0.5
    return dissEn
def PeakFromP2P(th, **kwargs):
    
    Returns the index of peaks using the peak to peak method.
    This is the Simple-Range Counting Method from Section 5.3 of ASTM
    1049 - 85 (2011) where both positive and negative ranges are counted.
    Optional Keyword arguments:
    thrshld = 0 [default]. Threshold load under which no cycles are
    counted.
    
    thrshld = kwargs.get('thrshld', 0.0005)
    if thrshld == None:
        print('You\'ve got to specify the threshold!!!')
        thrshold = float(input('What will it be? >>> '))
    zero = 0.
    load = th
    dLoad = np.diff(load)
    ind = np.where(((dLoad[:-1] >= zero) & (dLoad[1:] < zero)) |
        ((dLoad[:-1] < zero) & (dLoad[1:] >= zero)) )
    ind2 = ind[0] + 1
    peaks = load[(ind2)]
    Amp = np.abs(peaks[1:] - peaks[:-1]) / 2
    indout = ind2[np.where((Amp!=0) & (Amp >= thrshld))[0]+1]
    if indout[0] == 0 or indout[0] == 1:
        return indout[1:]
    else:
        return indout

def PeakFromZC(th, **kwargs):
    
    Returns the index of the peak using zero crossings.
    
    calcZero = kwargs.get('calcZero', True)
    if calcZero:
        lenth = len(th)
        zero = np.mean(th[:lenth/2])
    else:
        zero = kwargs.get('zero', 0.)
    ind = np.where(((th[:-1] >= zero) & (th[1:] < zero)) |
        ((th[:-1] < zero) & (th[1:] >= zero)) )
    indout = np.zeros((len(ind[0]),), dtype=int)
    for i,ind2 in enumerate(ind[0]):
        if i == 0:
            if ind2 == 0:
                indout[i] = 0.
            continue
        else:
            indout[i] = (ind[0][i-1] +
            np.abs(th[ind[0][i-1]:ind2] - zero).argmax(axis=0))
        
    # plt.figure('yeahyeah')
    # plt.plot(th)
    # plt.plot(indout, th[indout], 'o')
    # plt.show()
```python
# pdb.set_trace()
if indout[0] == 0:
    return indout[1:]
else:
    return indout

def calcAriasRatio(motion, dt, **kwargs):
    '''
    Calculates the following:
    a_rms / (max(abs(motion)) )
    It should be unitless.
    '''
    if 1 in motion.shape or len(motion.shape) == 1:
        NumMotions = 1
    else:
        NumMotions = np.min(motion.shape)
    Ar = np.zeros([NumMotions,], dtype=float)
    if NumMotions == 1:
        Ar = (calcRmsAccel(motion, dt, **kwargs) / np.max(np.abs(motion))) # Assume data is in rows
    else:
        for i in xrange(NumMotions):
            Ar[i] = (calcRmsAccel(motion[i,:], dt, **kwargs) / np.max(np.abs(motion[i,:]))) # Assume data is in rows
    return Ar

def calcRmsAccel(motion, dt, **kwargs):
    '''
    Calculates the rms acceleration.
    
    Keyword Arguments:
    duration Sto95 [default] Uses the duration from 5-95% of 
    the area under the motion squared
    total Uses the entire time of the input motion
    '''
    motion = np.ravel(motion)
    durationtype = kwargs.get('duration','Sto95')
    NPTS = len(motion)
    if len(dt) > 1:
        time = np.cumsum(dt)
        asqr = np.cumsum(motion ** 2) * np.max(dt)
    else:
        time = np.linspace(0,(NPTS-1) * dt,NPTS)
        asqr = np.cumsum(motion ** 2) * dt
    if durationtype == 'Sto95':
        int1 = interp1d( asqr, time, kind='linear' )
        T = int1(0.95 * asqr[-1]) - int1(0.05 * asqr[-1])
    else:
        T = time[-1]
    return np.sqrt(asqr[-1] / T)
```

953
class hyperbolic(object):
    '''
    To handle hyperbolic stress-strain relationships.
    Equations taken from Hardin, B. O., and Drnevich, V. P. (1972).
    "Shear modulus and damping in soils." Journal of the Soil Mechanics and Foundations
    Division, 98(7), 667-692.
    This wasn't really working last time I tried it.
    '''
    def __init__(self, Gmax, taumax, **kwargs):
        '''
        Initializes the object to prepare for calculating values.
        '''
        self.Gmax = Gmax
        self.taumax = taumax
        self.gamr = taumax / Gmax
        self.a = kwargs.get('a', -0.5)
        self.b = kwargs.get('b', 0.16)
        self.voffset = kwargs.get('voffset', 0.)
    def __call__(self, gam, **kwargs):
        '''
        Calculate your tau from your gam
        '''
        Gmax = kwargs.get('Gmax', self.Gmax)
        taumax = self.taumax
        gamr = self.gamr
        a = kwargs.get('a', self.a)
        b = kwargs.get('b', self.b)
        mottype = kwargs.get('mottype', 'sine')
        window_len = kwargs.get('window_len', 11)
        if kwargs.get('smooth', True) == True:
            from smooth import smooth
            gam_sm = np.zeros(gam.shape, dtype=float)
            gam_sm[1:] = smooth(gam, window='flat',
                                window_len=window_len)[window_len/2:-window_len/2]
            ind = PeakFromZC(gam_sm)
        else:
            gam_sm = gam
            ind = PeakFromZC(gam_sm)
        for i in xrange(len(ind)):
            if i == 0:
                gambase = gam_sm[0]
                taubase = 0.
                mysign = np.sign(np.mean(np.diff(gam_sm[:ind[1]])))
            val = gam_sm[ind[i]]
tau[ind[i]] = (taubase + mysign*np.abs(val - gambase) / ((1. / Gmax) + np.abs(val - gambase) * (1. + a * np.exp(-b * (np.abs(val - gambase) / gam_r))) / tau_max))

gam_r = 2 * gamr
tau_max = 2 * taumax
gambase = gam_sm[ind[i]-1]
taubase = tau[ind[i]-1]

else:
    val = gam_sm[ind[i-1]:ind[i]]
    mysign = np.sign(np.mean(np.diff(gam_sm[ind[i-1]:ind[i]])))
    taubase = tau[ind[i]-1]
    gambase = gam_sm[ind[i]-1]

    if printer:
        plt.plot(gam_sm,tau)
        plt.show()
        pdb.set_trace()

    return tau + self.voffset

def findab(self, gam, tau, **kwargs):
    '''
    Tries to calculate a and b from the data
    '''
    from scipy.optimize import curve_fit
    returns = kwargs.get('True', True)

    def finder1(x,a,b,Gmax):
        return self.__call__(gam, a=a, b=b, Gmax=Gmax)

    def finder2(x,a,b):
        return self.__call__(gam, a=a, b=b)

    if kwargs.get('Gmax', True) == True:
        p0 = kwargs.get('p0', [self.a, self.b, self.Gmax])
        self.popt, self.pov = curve_fit(finder1,gam, tau, p0=p0)
        self.a, self.b, self.Gmax = self.popt[0], self.popt[1], self.popt[2]
        if returns:
            return self.a, self.b, self.Gmax

    else:
        p0 = kwargs.get('p0', [self.a, self.b])
        self.popt, self.pov = curve_fit(finder2,gam, tau, p0=p0)
        self.a, self.b = self.popt[0], self.popt[1]
        if returns:
return self.a, self.b

class bilinear(object):
    '''
    To handle bi-linear stress-strain relationships.
    Also not really working last time I tried it.
    Needs some serious love. "Will you adopt me?!?"
    '''
    def __init__(self, Gmax, G2, gamr, **kwargs):
        '''
        Initializes the object to prepare for calculating values.
        '''
        self.Gmax = Gmax
        self.G2 = G2
        self.gamr = gamr
        self.voffset = kwargs.get('voffset', 0.)

def __call__(self, gam, **kwargs):
    '''
    Calculate your tau from your gam
    '''
    Gmax = kwargs.get('Gmax',self.Gmax)
    m = self.G2
    gamr = self.gamr
    voffset = self.voffset
    motype = kwargs.get('motype','sine')
    window_len = kwargs.get('window_len',11)
    if kwargs.get('smooth', True) == True:
        from smooth import smooth
        gam_sm = np.zeros(gam.shape, dtype=float)
        gam_sm[1:] = smooth(gam, window='flat',
                            window_len=window_len)[window_len/2:-window_len/2]
    else:
        gam_sm = gam
        # find the stress reverses:
        if motype == 'sine':
            ind = PeakFromZC(gam_sm)
        else:
            ind = PeakFromP2P(gam_sm)
    tau = np.zeros(gam.shape, dtype=float)
    printer = False
    # Do my calcs
    gam_r = gamr
    for i in range(len(ind)):
        if i == 0:
            mysign = np.sign(np.mean(np.diff(gam_sm[:ind[i]])))
            if np.isnan(mysign):
                mysign = 0.
            gambase = gam_sm[0]
            taubase = 0.
            val = gam_sm[:ind[i]]
            diff = np.abs(val - gambase)
            pt1 = np.min([diff, np.ones(diff.shape) * gam_r], axis=0)
            pt2 = np.max([diff - gam_r, np.zeros(diff.shape)], axis=0)
            tau[:ind[i]] = taubase + mysign * (pt1 + Gmax + pt2 * m)
            gam_r = 2 * gamr
gambase = gam_sm[ind[i]-1]
taubase = tau[ind[i]-1]

else:
    mysign = np.sign(np.mean(np.diff(gam_sm[ind[i-1]:ind[i]])))
    if np.isnan(mysign):
        mysign = 0.
    val = gam_sm[ind[i-1]:ind[i]]
    diff = np.abs(val - gambase)
    pt1 = np.min([diff, np.ones(diff.shape) * gam_r], axis=0)
    pt2 = np.max([diff - gam_r, np.zeros(diff.shape)], axis=0)
    tau[ind[i-1]:ind[i]] = taubase + mysign * (pt1 * Gmax + pt2 * m)
    gambase = gam_sm[ind[i]-1]
    taubase = tau[ind[i]-1]
    mysign = np.sign(np.mean(np.diff(gam_sm[ind[i]:])))
    val = gam_sm[ind[i]:]
    diff = np.abs(val - gambase)
    pt1 = np.min([diff, np.ones(diff.shape) * gam_r], axis=0)
    pt2 = np.max([diff - gam_r, np.zeros(diff.shape)], axis=0)
    tau[ind[i]:] = taubase + mysign * (pt1 * Gmax + pt2 * m)

if printer:
    plt.plot(gam_sm,tau)
    plt.show()
    pdb.set_trace()
return tau + voffset

class HDF5saver(object):
    '''
    This object will save the data to a pytable HDF5 file.
    Setup to accept all test types.
    '''
    def __init__(self,**kwargs):
        testtype = kwargs.get('testtype','sand')
        self.strain = kwargs.get('strain', False)
        if testtype == 'sand':
            filename = kwargs.get('filename','SummaryResults.h5')
            # Check to see if the output table exist, if not, create it.
            self.outfile = pt.openFile(filename,mode='a',
                                       title='CV-CSS Lab Testing Results')
            # Check if the internal summary table exists
            if self.outfile.__contains__('Summary'):
                self.summtable = self.outfile.root.Summary
            else:
                self.summtable = self.outfile.createTable('/', 'Summary',
                                                           StrainSumTable)
        else:
            self.summtable = self.outfile.createTable('/', 'Summary',
                                                           SumTable)
        elif testtype == 'EQ':
            filename = kwargs.get('filename','EQSummaryResults.h5')
            # Check to see if the output table exist, if not, create it.
            self.outfile = pt.openFile(filename,mode='a',
                                       title='EQ CV-CSS Lab Testing Results')
            # Check if the internal summary table exists
            if self.outfile.__contains__('Summary'):
                self.summtable = self.outfile.root.Summary
            else:
                self.summtable = self.outfile.createTable('/', 'Summary',
                                                           SumTable)
        """
self.summtable = self.outfile.root.Summary

else:
    self.summtable = self.outfile.createTable('/', 'Summary', EQSumTable)

elif testtype == 'water':
    filename = kwargs.get('filename', 'WaterSummary.h5')

    # Check to see if the output table exist, if not, create it.
    self.outfile = pt.openFile(filename, mode='a',
                               title='CV-CSS Lab Testing Results')
    # Check if the internal summary table exists
    if self.outfile.__contains__('/WaterSummary'):
        self.summtable = self.outfile.root.WaterSummary
    else:
        self.summtable = self.outfile.createTable('/',
                                                   'WaterSummary',
                                                   WaterSumTable)

elif testtype == 'surcharge':
    filename = kwargs.get('filename', 'SurchargeSummary.h5')

    # Check to see if the output table exist, if not, create it.
    self.outfile = pt.openFile(filename, mode='a',
                               title='CV-CSS Surcharge Lab Testing Results')
    # Check if the internal summary table exists
    if self.outfile.__contains__('/SurchargeSummary'):
        self.summtable = self.outfile.root.SurchargeSummary
    else:
        self.summtable = self.outfile.createTable('/',
                                                   'SurchargeSummary',
                                                   SurchargeSumTable)

self.filename = filename
def input(self, ResultObj, **kwargs):
    '''
    This is the mechanism whereby data is input into the table.
    '''
    # Check to see if an entry already exists
    name = ResultObj.name
    name = str(os.path.basename(name))
    if self.testtype == 'sand':
        self.delete(name)
        entry = self.summtable.row
        entry['File'] = name
        entry['eo'] = ResultObj.e_o
        entry['Dr'] = ResultObj.Dr
        entry['CSR'] = ResultObj.CSR
        if self.strain:
            entry['Gamma'] = ResultObj.gamma
            entry['Sigveff'] = ResultObj.sigveff
            entry['Cycles'] = ResultObj.cycles
            entry['DE'] = ResultObj.DE
            entry['DE_corr'] = ResultObj.DE_corr
            entry['DE_b'] = ResultObj.DE_b
            entry['DE_m'] = ResultObj.DE_m
            entry['DE_1'] = ResultObj.DE_1

    self.testtype = testtype

    return entry

    # Check to see if an entry already exists
    name = ResultObj.name
    name = str(os.path.basename(name))
    if self.testtype == 'sand':
        self.delete(name)
        entry = self.summtable.row
        entry['File'] = name
        entry['eo'] = ResultObj.e_o
        entry['Dr'] = ResultObj.Dr
        entry['CSR'] = ResultObj.CSR
        if self.strain:
            entry['Gamma'] = ResultObj.gamma
            entry['Sigveff'] = ResultObj.sigveff
            entry['Cycles'] = ResultObj.cycles
            entry['DE'] = ResultObj.DE
            entry['DE_corr'] = ResultObj.DE_corr
            entry['DE_b'] = ResultObj.DE_b
            entry['DE_m'] = ResultObj.DE_m
            entry['DE_1'] = ResultObj.DE_1

    self.testtype = testtype

    return entry
entry['Gs'] = ResultObj.Gs
entry['mass'] = ResultObj.mass
entry['hi'] = ResultObj.hi
entry['di'] = ResultObj.di
entry['PEC'] = ResultObj.PEC
entry['LoadCorr'] = ResultObj.loadcorr
if ResultObj.loadcorr:
  entry['LoadCorrType'] = ResultObj.loadcorr_type
  entry['WaterTestName'] = ResultObj.WaterTestName
entry['Modified'] = strftime("%Y-%m-%d %H:%M:%S")
entry['Date_of_Test'] = ResultObj.date_of_test
entry['failuretype'] = ResultObj.cycletype
entry['DE_corralt'] = ResultObj.dW_corralt
entry.append()
self.summtable.flush()

if self.testtype == 'EQ':
  rowdata = self.delete(name, returns=True)
  if rowdata == []:
    try:
      CSR, EQ = self.EQExtradata(name)
    except:
      CSR, EQ = eqCSR(ResultObj.name, table=self.EQExtraTable, returns=True)
    else:
      try:
        CSR, EQ = self.EQExtradata(name)
      except:
        CSR, EQ = eqCSR(ResultObj.name, table=self.EQExtraTable, returns=True)
      
      ResultObj.CSR = 
      # extract the old CSR and EQ data
      entry = self.summtable.row
      entry['File'] = name
      entry['eo'] = ResultObj.e_o
      entry['Dr'] = ResultObj.Dr
      entry['CSR'] = CSR
      entry['Sigveff'] = ResultObj.sigveff
      entry['Sigveff_fin'] = ResultObj.sigveff_fin
      entry['r_u_fin'] = ResultObj.r_u_fin
      entry['DE'] = ResultObj.DE
      entry['DE_corr'] = ResultObj.DE_corr
      entry['DE_b'] = ResultObj.DE_b
      entry['DE_m'] = ResultObj.DE_m
      entry['DE_1'] = ResultObj.DE_1
      entry['Ar'] = ResultObj.Ar
      entry['PTratio'] = ResultObj.PTratio
      entry['ElapsedTime'] = ResultObj.cyc['Time'].values[-1]
      entry['Gs'] = ResultObj.Gs
      entry['mass'] = ResultObj.mass
      entry['hi'] = ResultObj.hi
      entry['di'] = ResultObj.di
      entry['PEC'] = ResultObj.PEC
      entry['LoadCorr'] = ResultObj.loadcorr
      if ResultObj.loadcorr:
entry['LoadCorrType'] = ResultObj.loadcorr_type
entry['WaterTestName'] = ResultObj.WaterTestName
entry['Modified'] = strftime("%Y-%m-%d %H:%M:%S")
entry['Date_of_Test'] = ResultObj.date_of_test
entry['FailureType'] = ResultObj.cycletype
entry['Cycles'] = ResultObj.cycles
entry['Total_Pts'] = ResultObj.total_pts
entry['CSR_calcd'] = ResultObj.CSR
entry['EQ'] = EQ
entry['Neq'] = ResultObj.Neq
entry['Gmax'] = ResultObj.Gmax
entry['DE_corralt'] = ResultObj.dW_corralt
entry.append()
self.summtable.flush()

if self.testtype == 'water':
    # pdb.set_trace()
    entry = self.summtable.row
    entry['File'] = name
    entry['Modified'] = strftime("%Y-%m-%d %H:%M:%S")
    entry['posm'] = ResultObj.poscoeff[0]
    entry['posb'] = ResultObj.poscoeff[1]
    entry['negm'] = ResultObj.negcoeff[0]
    entry['negb'] = ResultObj.negcoeff[1]
    entry['Load_unit'] = unit_lookup(ResultObj.headerlabel,
                                     ResultObj.units,
                                     'Internal Shear Load')
    entry['Disp_unit'] = unit_lookup(ResultObj.headerlabel,
                                      ResultObj.units,
                                      'Internal Shear LVDT')
    entry['Date_of_Test'] = ResultObj.date_of_test
    entry['Gmax'] = ResultObj.Gmax
    entry['gamr'] = ResultObj.gamr
    entry['voffset'] = ResultObj.voffset
    entry['hypa'] = ResultObj.hypa
    entry['hypb'] = ResultObj.hypb
    entry.append()
    self.summtable.flush()

if self.testtype == 'surcharge':
    entry = self.summtable.row
    entry['File'] = name
    entry['Modified'] = strftime("%Y-%m-%d %H:%M:%S")
    entry['posm'] = ResultObj.poscoeff[0]
    entry['posb'] = ResultObj.poscoeff[1]
    entry['negm'] = ResultObj.negcoeff[0]
    entry['negb'] = ResultObj.negcoeff[1]
    entry['surcharge'] = ResultObj.surcharge
    entry['DE'] = ResultObj.PDE
    entry['DE_corr'] = ResultObj.PDE_corr
    entry['Load_unit'] = unit_lookup(ResultObj.headerlabel,
                                     ResultObj.units,
                                     'Shear Load')
    entry['Disp_unit'] = unit_lookup(ResultObj.headerlabel,
                                     ResultObj.units,
                                     'Shear Displacement')
entry['Date_of_Test'] = ResultObj.date_of_test
entry.append()
self.summtable.flush()

def read(self):
    
    Results in the result of the Summary Table.
    
results = self.summtable.read()
return results

def plot(self, **kwargs):
    if kwargs.get('latex', True):
        fs = kwargs.get('fs', 18)
        import matplotlib
        matplotlib.rcParams.update({'font.size': 18, 'text.usetex': True,
          '#legend.fontsize': 16})
        matplotlib.rcParams.update({'font.size': 18, 'font.family': 'STIXGeneral',
          'mathtext.fontset': 'stix',
          'legend.fontsize': 16, 'text.usetex': False})
    else:
        pdb.set_trace()
        import matplotlib
        matplotlib.rcParams.update({'font.size': 18, 'font.family': 'sans',
          'text.usetex': False})
        cmap = kwargs.get('cmap', 'Set1')
        interval = kwargs.get('interval', 24.)
        from mpl_toolkits.mplot3d import axes3d
        CSR = self.summtable.read(field='CSR')
        Dr = self.summtable.read(field='Dr')
        N = self.summtable.read(field='Cycles')
        DE = self.summtable.read(field='DE')
        DE_corr = self.summtable.read(field='DE_corr')
        Sigveff = self.summtable.read(field='Sigveff')
        datefield = kwargs.get('datefield', 'Modified')
        Date = self.summtable.read(field=datefield)
        delta = np.ones(Date.shape, dtype=float) * 1000.
        separator = kwargs.get('separator', 'delta<interval')
        separator = kwargs.get('separator', 'Sigveff<75.')
        separator = kwargs.get('separator', 'sigvcolormap')
        for i in xrange(len(Date)):
          t1 = dt.datetime.now()
          if datefield == 'Modified':
            t2 = dt.datetime.strptime(Date[i].decode('utf-8'),
              'XY-%m-%d %H:%M:%S')
          elif datefield == 'Date_of_Test':
            t2 = dt.datetime.strptime(str(Date[i].decode('utf-8')),
              'Ym%d%H%M%S')
          delt = t1-t2
          delta[i] = delt.total_seconds() / 3600.
          if separator == 'sigvcolormap':
            fig1 = plt.figure(1)
            ax1 = fig1.add_subplot(111, projection='3d')
            st1 = ax1.scatter(CSR,Dr,zs=np.log10(N), c=Sigveff, cmap=cmap)
            ax1.set_zlabel(r'$\log10(No. of cycles to liq)$')
ax1.set_ylabel('Dr (%)')
ax1.set_xlabel('CSR')
plt.colorbar(st1)

fig2 = plt.figure(2)
ax2 = fig2.add_subplot(111, projection='3d')
st2 = ax2.scatter(CSR, Dr, zs=DE_corr, c=Sigveff, cmap=cmap)
plt.colorbar(st2)
ax2.set_zlabel(r'$\Delta W_{corrected}$')
ax2.set_ylabel('Dr (%)')
ax2.set_xlabel('CSR')

fig4 = plt.figure(4)
ax4 = fig4.add_subplot(111, projection='3d')
st4 = ax4.scatter(CSR, Dr, zs=np.log10(DE), c=Sigveff, cmap=cmap)
plt.colorbar(st4)
ax4.set_zlabel(r'$log(\Delta W)$')
ax4.set_ylabel('Dr (%)')
ax4.set_xlabel('CSR')

fig5 = plt.figure(5)
ax5 = fig5.add_subplot(111, projection='3d')
st5 = ax5.scatter(CSR, Dr, zs=(DE / N), c=Sigveff, cmap=cmap)
plt.colorbar(st5)
ax5.set_zlabel(r'$\Delta W / N$')
ax5.set_ylabel('Dr (%)')
ax5.set_xlabel('CSR')

fig6 = plt.figure(6)
ax6 = fig6.add_subplot(111, projection='3d')
DEn = DE / Sigveff
st6 = ax6.scatter(CSR, Dr, zs=DEn, c=Sigveff, cmap=cmap)
plt.colorbar(st6)
ax6.set_zlabel(r'$\Delta W / \sigma_v$')
ax6.set_ylabel('Dr (%)')
ax6.set_xlabel('CSR')

plt.figure(3)
ax3 = plt.scatter(N, CSR, color=Sigveff, cmap=cmap)
plt.xlabel(r'$N$')
plt.ylabel('CSR')
plt.colorbar(ax3)
ax = plt.gca()
ax.set_xscale('log')

else:
    ind2 = np.where(eval(separator))
    ind1 = np.where(~eval(separator))
    fig = plt.figure(1)
    ax = fig.add_subplot(111, projection='3d')
    ax.scatter(CSR[ind1], Dr[ind1], zs=np.log10(N[ind1]), facecolor='b')
    ax.scatter(CSR[ind2], Dr[ind2], zs=np.log10(N[ind2]), facecolor='r')
    ax.set_zlabel(r'$log10(No. of cycles to liq)$')
    ax.set_ylabel('Dr (%)')
    ax.set_xlabel('CSR')
fig = plt.figure(2)
ax = fig.add_subplot(111, projection='3d')
ax.scatter(CSR[ind1], Dr[ind1], zs=np.log10(DE_corr[ind1]), facecolor='b')
ax.scatter(CSR[ind2], Dr[ind2], zs=np.log10(DE_corr[ind2]), facecolor='r')
ax.set_zlabel(r'$\log(\Delta W_{corrected})$')
ax.set_ylabel('Dr (%)')
ax.set_xlabel('CSR')

fig = plt.figure(4)
ax = fig.add_subplot(111, projection='3d')
ax.scatter(CSR[ind1], Dr[ind1], zs=np.log10(DE[ind1]), facecolor='b')
ax.scatter(CSR[ind2], Dr[ind2], zs=np.log10(DE[ind2]), facecolor='r')
ax.set_zlabel(r'$\log(\Delta W)$')
ax.set_ylabel('Dr (%)')
ax.set_xlabel('CSR')

fig = plt.figure(5)
ax = fig.add_subplot(111, projection='3d')
ax.scatter(CSR[ind1], Dr[ind1], zs=(DE[ind1] / N[ind1]), facecolor='b')
ax.scatter(CSR[ind2], Dr[ind2], zs=(DE[ind2] / N[ind2]), facecolor='r')
ax.set_zlabel(r'$\Delta W / N$')
ax.set_ylabel('Dr (%)')
ax.set_xlabel('CSR')

syms = ['o','x','+']
# color=['r','b']
Drs = [0,60, 85, 100]
for i in xrange(len(Drs)-1):
    ind1 = np.where((delta>interval) & (Dr >= Drs[i]) & (Dr < Drs[i+1]))
    plt.semilogx(N[ind1], CSR[ind1],'b'+syms[i],
                label=r'$\Delta_r (\%)$ <{} <{} $\Delta_r (\%)$'.format(Drs[i],Drs[i+1]))
    ind2 = np.where((delta<=interval) & (Dr >= Drs[i]) & (Dr < Drs[i+1]))
    plt.semilogx(N[ind2], CSR[ind2],'r'+syms[i])

plt.xlabel(r'$N$')
plt.ylabel('CSR')
plt.legend(loc='upper right')

more = True
if more:
    ind100 = np.where((Sigeff >90) & (Sigeff<150))
    ind50 = np.where(Sigeff <90)
    ind250 = np.where(Sigeff > 150)
    plt.figure('Dr-DE')
    plt.plot(Dr[ind100], DE[ind100], 'bo', label=r'$\sigma _v =$ 100 kPa')
    plt.plot(Dr[ind50], DE[ind50], 'ro', label=r'$\sigma _v =$ 60 kPa')
    plt.plot(Dr[ind250], DE[ind250], 'go', label=r'$\sigma _v =$250 kPa')
    plt.xlabel('Relative Density (%)')
    plt.ylabel('Dissipated Energy (kPa)')
    plt.legend(loc='best')

plt.figure('Dr-nDE')
plt.plot(Dr[ind100], DE[ind100]/Sigeff[ind100], 'bo', label=r'$\sigma _v =$ 100 kPa')
plt.plot(Dr[ind50], DE[ind50]/Sigeff[ind50], 'ro', label=r'$\sigma _v =$ 60 kPa')
plt.plot(Dr[ind250], DE[ind250]/Sigeff[ind250], 'go', label=r'$\sigma _v =$
plt.xlabel('Relative Density (%)')
plt.ylabel('Normalized Dissipated Energy')
plt.legend(loc='best')

plt.figure('N-CSR')
plt.semilogx(N[ind100], CSR[ind100], 'bo', label=r'$\sigma \prime _v =$ 100 kPa')
plt.plot(N[ind50], CSR[ind50], 'ro', label=r'$\sigma \prime _v =$ 60 kPa')
plt.plot(N[ind250], CSR[ind250], 'go', label=r'$\sigma \prime _v =$250 kPa')
plt.xlabel('Cycles to Liquefaction')
plt.ylabel('Cyclic Stress Ratio')
plt.legend(loc='best')

plt.figure('DE-CSR')
plt.plot(CSR[ind100], DE[ind100], 'bo', label=r'$\sigma \prime _v =$ 100 kPa')
plt.plot(CSR[ind50], DE[ind50], 'ro', label=r'$\sigma \prime _v =$ 60 kPa')
plt.plot(CSR[ind250], DE[ind250], 'go', label=r'$\sigma \prime _v =$250 kPa')
plt.ylabel('Dissipated Energy (kPa)')
plt.xlabel('Cyclic Stress Ratio')
plt.legend(loc='best')
plt.show()

```
def delete(self,*arg, **kwargs):
    '''
    Deletes an entry from an H5 Table.
    '''
    filters = 'csv (*.csv)' # for qtfiledialog
    # filters = 'csv |*.csv' # for wxfiledialog
    returnkwarg = kwargs.get('returns', False)
    infilelist = []
    if len(arg) == 0:
        # if kwargs.get('filelist',None) == None:
        filelist=fd.fileopen(
            message='Select the files you want to remove from the table:',
            filters=filters,
            defaultDir=(u'/media/Storage/Documents/Python' +
            '/GCTS/ConstantVolume'))
    print('Files to remove from {}:

'.format(self.summtable))
    for file1 in filelist:
        infilelist.append(file1)
        print(file1 + '
')
        del filelist
print('Files to remove from {}:

'.format(self.summtable))
    for file1 in filelist:
        infilelist.append(file1)
        print(file1 + '
')
    del filelist
    print('Files to remove from {}:

'.format(self.filename))

    selection = raw_input('Are you sure you want to remove these ' +
    'files from {}? [y]/n: '.format(self.filename))
    if selection.lower() == 'n':
        return
    elif selection.lower() == 'y':
        pass
    elif selection == ''
pass
else:
    return
else:
    for val in arg:
        infilelist.append(val)
rowdata = []
for name in infilelist:
    name = str(os.path.basename(name)).split('.')[0]
try:
    row1 = self.summtable.getWhereList('File == name')
except NameError:
    row1 = self.summtable.get_where_list('File == name')
except AttributeError:
    pdb.set_trace()
if len(row1) == 0:
    pass
else:
    for i, val in enumerate(row1):
        if kwargs.get('returns') == True:
            rowdata.append(self.summtable.read(val, val+1))
        try:
            self.summtable.remove_row(val)
        except NameError:
            self.summtable.removeRows(val-i)
        except IndexError, NotImplementedError:
            pdb.set_trace()
if returns == True:
    return rowdata

def EQExtradata(self, name, **kwargs):
    '''
    Gets the input CSR and Earthquake motion name from EQExtra.h5.
    '''
    try:
        self.EQExtraTable
    except AttributeError:
        filename = 'EqExtra.h5'
        outfile = pt.openFile(filename, mode='a')
        # Check if the internal summary table exists
        self.EQExtraTable = outfile.root.Data
        testnames = table.read(field='File')
        try:
            row1 = self.EQExtraTable.getWhereList('File == name')
        except NameError:
            row1 = self.EQExtraTable.get_where_list('File == name')
        CSR = self.EQExtraTable.read(row1, row1+1, field='CSR_nom')[0]
        EQ = self.EQExtraTable.read(row1, row1+1, field='EQ')[0]
    if EQ == 'None' or EQ == None:
        CSR, EQ = eqCSR(name, table=self.EQExtraTable,
                        returns=True)
        EQ = getMotionName(name)
    return CSR, EQ
def table2Latex(self, **kwargs):
    '''
    Prints out a table for use in Latex.
    keyword:
    cols = ['File', 'Dr', ...]
    The tables library would probably work better.
    '''
    defaultcols = ['File', 'Dr', 'CSR', 'Sigveff', 'Cycles', 'DE']
    cols = kwargs.get('cols', defaultcols)
    line = r''
    for i, val in enumerate(cols):
        line += r' {} &'.format(val)
    line = line[:-1] + r'\'
    print(line)
    
    for row in self.summtable:
        line = r''
        for val in cols:
            if val == 'Dr':
                line += r' {:.1f} &'.format(row[val])
            elif val == 'CSR':
                line += r' {:.2f} &'.format(row[val])
            elif val == 'Sigveff':
                line += r' {:.0f} &'.format(row[val])
            elif val == 'Cycles':
                line += r' {:.1f} &'.format(row[val])
            elif val == 'DE':
                line += r' {:.2f} &'.format(row[val])
            elif val == 'CSR_calcd':
                line += r' {:.2f} &'.format(row[val])
            else:
                line += r' {} &'.format(row[val])
        line = line[:-1] + r'\' + r'\n'
        print(line)

    def close(self):
        self.outfile.close()

class SoilTest(object):
    '''
    This object controls all the calcs and i/o for each test.
    Keyword Definition
    file name/path of the GCTS data file for the test.
    '''

    def __init__(self, **kwargs):
        self.Error = False
        infile = kwargs.get('infile')
        self.emin = kwargs.get('emin', 0.53)
        self.emax = kwargs.get('emax', 0.845)
        selfstrainfailval = kwargs.get('strainfailval', '03')
        srufailval = kwargs.get('rufailval', '98')
        self.loadcorr = kwargs.get('loadcorr', True)
if self.loadcorr:
    self.loadcorr_type = kwargs.get('loadcorr_type', 'bilinear')
self.waterfile = kwargs.get('waterfile')
verbose = kwargs.get('verbose', True)
if verbose: print('


')
self.testtype = kwargs.get('testtype', 'sine')
self.extrafigs = kwargs.get('extrafigs', False)
self.cycletype = kwargs.get('cycletype', 'wu_etal')
self.strain = kwargs.get('strain', False)
self.PaperFigs = kwargs.get('PaperFigs', False)
if self.testtype == 'EQ':
    self.path = './EQ/
else:
    if self.strain:
        self.path = './StrainControlled/
    else:
        self.path = './Sine/
if not os.path.exists(self.path):
    os.makedirs(self.path)
if 'infile' == None:
    infile = raw_input('Nothing to do. Specify an input file:
else:
    self.csvimport(infile)
self.calcs1(verbose=verbose, **kwargs)
self.DiscreteCycles()
errcode = self.dissen(verbose=verbose, **kwargs)
if self.Error:
    return
if self.testtype == 'EQ':
    self.EQcalcs()
    self.calcdW_Alt()
    self.plotter()
if kwargs.get('THout', False):
    self.fileout(**kwargs)

# if self.Error:
#    return 1
#else:
#    #return 0

def csvimport(self, infile):
    '''
    This function pulls in the data from the GCTS output file.
    The GCTS file should not have the data separated into stages.
    '''
    self.data=[]
    self.label=[]
    self.name=[]
    self.Gs=[]
    self.mass=[]
    self.cyc_header=[]
    self.pist_area=[]
datasection=0
datafile = csv.reader(open(infile, 'rU'))
rowcount = -1
for row in datafile:
    rowcount += 1
    if datasetion==0:
        if self.Gs:
            pass
        elif 'Specific Gravity: ' in row:
            self.Gs = float(row[1])
            self.Gs = 2.66  # Because sometimes I forget to change the value in the GCTS software
        if self.name:
            pass
        elif 'Specimen: ' in row:
            self.name = row[1]
    if self.mass:
        pass
    elif 'Dry Mass of Specimen: ' in row:
        self.mass = float(row[1]); self.mass_unit = row[2]
        if self.mass==0:
            self.mass = float(input('Input the dry mass (g) for specimen %s:' % self.name))
    if 'Type:' and 'Universal' in row:
dimsec=1
    if 'Starting Date: ' in row:
        testdate = row[1]
    if 'Starting Time: ' in row:
        testtime = row[1]
    if dimsec==1:
        if 'Height: ' in row:
            self.hi = float(row[3]) * 25.4
            if self.hi > 40:
                self.hi = self.hi - 25.4 * 3.337
                print('Changed the height to {} mm !!!'.format(self.hi))
                self.hi_unit = 'mm'  # Convert to mm
            if 'Diameter: ' in row:
                self.di = float(row[3]) * 25.4
                if self.di / 25.4 == 4.04:
                    print('Changed diameter from {:.3f} mm to 102.36 mm'.format(self.di))
                    self.di = 102.362
                    self.di_unit = 'mm'  # Convert to mm
                self.area = (self.di / 1000 / 2) ** 2 * np.pi  # in m^2
            if len(row) > 17:
                if row[0] == 'Time':
                    self.headerlabel = rowcount
                elif row[0] == 'sec':
                    self.units = row
                    break
df = pd.read_csv(infile, names=self.headerlabel, skiprows=header+2)

df = df.convert_objects(convert_numeric=True)

select = df.apply(lambda r : any([isinstance(e, basestring)
    for e in r]), axis=1)

df = df[~select]
df = df.dropna()

df['dt'] = df['Time'].diff()

if self.strain:
    sheardisp = df['Shear Displacement'].values
    sheardisp = sheardisp - sheardisp[0]
    for i, disp in enumerate(sheardisp):
        if np.abs(disp) >= 0.02:
            if i > 35:
                ind = i - 35
            else:
                ind = i
            break
else:
    shearload = df['Shear Load'].values
    shearload = shearload - shearload[0]
    for i, load in enumerate(shearload):
        if np.abs(load) >= 0.02:
            if i > 35:
                ind = i - 35
            else:
                ind = i
            break

dt = df['dt'][ind:].values
for i, d in enumerate(dt):
    if d < 0.1:
        ind2 = i + ind
    break

# Create a new dataframe that contains only the cyclic portion

columns = ['Time', 'Cycles', 'Shear Load', 'Shear Displacement',
    'Normal Load', 'Normal Displacement',
    'Internal Shear Load', 'Internal Shear LVDT',
    'Internal Normal LVDT', 'dt']

self.cyc = df.loc[ind2:, columns].reset_index(drop=True)
self.date_of_test = datetimeconvert(testdate, testtime)

def calcs1(self, **kwargs):
    
    # Performs the first calculations on the data obtained from the csv file.
    
    verbose = kwargs.get('verbose', True)
    self.cycletype = kwargs.get('cycletype', 'strain01')

    self.cyc['ndisp_ext'] = (self.cyc['Normal Displacement'] -
        self.cyc['Normal Displacement'][0])
    self.cyc['ndisp_int'] = (self.cyc['Internal Normal LVDT'] -
        self.cyc['Internal Normal LVDT'][0])

    # Calculate strains
    self.b_cyc = self.hi - self.cyc['Internal Normal LVDT'][0]
self.cyc['nstrain_int'] = self.cyc['ndisp_int'] / self.h_cyc
self.cyc['nstrain_ext'] = self.cyc['ndisp_ext'] / self.h_cyc
self.cyc['sstrain_ext'] = (self.cyc['Shear Displacement'] / self.h_cyc)
self.cyc['sstrain_int'] = (self.cyc['Internal Shear LVDT'] / self.h_cyc)

# Calculate stresses
if 'lbf' in self.units:
    for i, unit in enumerate(self.units):
        if unit == 'lbf':
            if self.headerlabel[i] == 'Normal Load':
                self.cyc['nload'] = (self.cyc['Normal Load'] * 0.0044482216)  # Convert from lbf to kN
            else:
                self.cyc['nload'] = self.cyc['Normal Load']
        break
self.cyc['nstress'] = self.cyc['nload'] / self.area  # in kPa

# Correct the loads by subtracting out the friction
if self.loadcorr == True:
    loadcorrf = self.loadcorrection()
    friction = loadcorrf(self.cyc['Internal Shear LVDT'].values)
else:
    friction = np.zeros(self.cyc['nload'].values.shape, dtype=float)
frictionplots = kwargs.get('frictionplots', False)
if frictionplots:
    plt.figure(1)
    plt.plot(self.cyc['Internal Shear LVDT'].values, label='LVDT')
    for typ in ['old', 'hyperbolic', 'bilinear']:
        lc = self.loadcorrection(type=typ, motype=self.testtype)
        fric = lc(self.cyc['Internal Shear LVDT'].values)
        DE = calcDissEnergy(fric, self.cyc['Internal Shear LVDT'].values, area=self.area, h=self.h_cyc)
    plt.figure(2)
    plt.plot(fric*100, label='{}Frict*100'.format(typ[:3]))
    plt.legend(loc='best')
    plt.figure('DE')
    plt.plot(DE, label='{}'.format(typ))
    plt.legend(loc='best')
plt.plot(self.cyc['Shear Load'] / self.area)  # Convert to kPa
self.cyc['sstress_ext'] = ((self.cyc['Shear Load'] - friction) / self.area)  # Convert to kPa
self.cyc['sstress_int'] = ((self.cyc['Internal Shear Load'] - friction) / self.area)  # Convert to kPa
self.cyc['G'] = self.cyc['sstress_int'] / self.cyc['sstrain_int']

# Calculate Volumes, Void Ratios and Relative Densities
self.V_cyc = self.area * self.h_cyc / 1000.  # cu m
V_s = self.mass / 1000. / (self.Gs * 1000)  # cu m
self.e_o = (self.V_cyc - V_s) / V_s
self.Dr = (self.emax - self.e_o) / (self.emax - self.emin) * 100.

# Calculate the pore pressures
self.sigveff = self.cyc['nstress'].values[0]
self.sigveff_fin = self.cyc['nstress'].values[-1]
self.cyc['Pore Pressure'] = self.sigveff - self.cyc['nstress']

# Calculate the apparent Residual Excess Pore Pressure, \(r_u\)
self.cyc['Ru'] = self.cyc['Pore Pressure'] / self.sigveff

# Get the index of zero stress
sstress_int = self.cyc['sstress_int'].values
self.ZeroStressInd = np.where(np.sign(sstress_int[:-1]) !=
                           np.sign(sstress_int[1:]))[0]

# Calculate the number of cycles, determine the point of liquefaction
if self.cycletype == 'modulus':  # Not working?
    self.cycles, self.cycind = self.mod_liq_crit()
elif self.cycletype == 'strain01':
    ss = self.cyc['sstrain_int'].values
    ind = np.where((ss > 0.01) | (ss < -0.01))
    try:
        self.cycles = self.cyc['Cycles'][ind[0][0]]
        self.cycind = ind[0][0]
    except:
        self.cycles = -1  #self.cyc['Cycles'].values[-1]
        self.cycind = -1  #len(ns)
        print('Shear strain criteria didn\'t work!')
        pdb.set_trace()
elif self.cycletype == 'strain03SA':
    ss = self.cyc['sstrain_int'].values
    ind = np.where((ss > 0.03) | (ss < -0.03))
    try:
        self.cycles = self.cyc['Cycles'][ind[0][0]]
        self.cycind = ind[0][0]
    except:
        self.cycles = -1  #self.cyc['Cycles'].values[-1]
        self.cycind = -1  #len(ns)
        print('Shear strain criteria didn\'t work!')
elif self.cycletype == 'strainSA':
    failval = float('0.' + self.strainfailval)
    ss = self.cyc['sstrain_int'].values
    ind = np.where((ss > failval) | (ss < -failval))
    try:
        self.cycles = self.cyc['Cycles'][ind[0][0]]
        self.cycind = ind[0][0]
    except:
        self.cycles = -1000  #self.cyc['Cycles'].values[-1]
        self.cycind = -1  #len(ns)
        print('Shear strain criteria didn\'t work!')
elif self.cycletype == 'strainSAZS':
    self.cycletype = 'strain{}SAZS'.format(self.strainfailval)
    failval = float('0.' + self.strainfailval)
    ss = self.cyc['sstrain_int'].values
    ind = np.where((ss > failval) | (ss < -failval))
    try:
        self.cycles = self.cyc['Cycles'][ind[0][0]]
        self.cycind = ind[0][0]
    except:
        self.cycles = -1000  #self.cyc['Cycles'].values[-1]
        self.cycind = -1  #len(ns)
        print('Shear strain criteria didn\'t work!')
    failval = float('0.' + self.strainfailval)

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sszs = self.cyc['sstrain_int'].values[self.ZeroStressInd]

ind = np.where((sszs > failval) | (sszs < -failval))
ind2 = self.ZeroStressInd[ind[0]]

try:
    self.cycles = self.cyc['Cycles'][ind2[0]]
    self.cycind = ind2[0]
except:
    self.cycles = -1000 # self.cyc['Cycles'].values[-1]
    self.cycind = -1 # len(ns)
    print('Shear strain criteria didn\'t work!')

elif self.cycletype == 'normstress':
    ns = self.cyc['nstress'].values
    minval = 1. # Adjust the add value as needed
    ind = np.where(ns < (minval)) # old way
    ss = self.cyc['sstress_int'].values
    stressind = np.where((np.sign(ss[:-1]) != np.sign(ss[1:])) &
                         (ns[:-1] < minval))
    try:
        # self.cycles = self.cyc['Cycles'][ind[0][0]] # old way
        self.cycles = self.cyc['Cycles'][stressind[0][0]]
        self.cycind = ind[0][0]
    except:
        self.cycles = -1 # self.cyc['Cycles'].values[-1]
        self.cycind = -1 # len(ns)
        print('Normal Stress criteria didn\'t work!\n
\' Or the sample did not liquefy!\')

elif self.cycletype == 'ru':
    #self.rufailval = '99'
    self.cycletype = 'ru' + self.rufailval
    failval = float('0.'+self.rufailval)
    ruzs = self.cyc['Ru'].values[self.ZeroStressInd]
    ind = np.where(ruzs >= failval)
    ind2 = self.ZeroStressInd[ind[0]]
    try:
        self.cycles = self.cyc['Cycles'][ind2[0]]
        self.cycind = ind2[0]
    except:
        self.cycles = -1000 # self.cyc['Cycles'].values[-1]
        self.cycind = -1 # len(ns)
        print('r_u failure criteria didn\'t work!')

elif self.cycletype == 'wu_etal':
    self.cycles, self.cycind = self.wu_etal_liq_crit()

elif self.cycletype == 'strainDAZS':
    self.cycletype = 'strainDAZS.format(self.strainfailval)
    failval = float('0.' + self.strainfailval)
    strain = self.cyc['strain_int'].values[self.ZeroStressInd]
    stress = self.cyc['sstress_int'].values[self.ZeroStressInd]
    # ind = np.where((np.sign(stress[1:]) != np.sign(stress[:-1]))[0]
    cycles = -1000
    cycind = -1
    for i, val in enumerate(self.ZeroStressInd):
        if (i == 0) or (i == 1):
            continue
        else:
            try:
                val0 = self.ZeroStressInd[i-2]
diff = np.abs(strain[val] - strain[val0])
except IndexError:
    pdb.set_trace()
if diff >= failval:
    cycles = self.cyc['Cycles'].values[val]
    cycind = val
    break
self.cycles = cycles
self.cycind = cycind
if self.cycles < 0.:
    print('Failure criteria didn\t work: DA {}%'.format(failval))
elf self.cycletype = 'strainDA':
    self.cycletype = 'strain(DA'.format(self.stainfailval)
failval = float('0.' + self.stainfailval)
strain = self.cyc['strain_int'].values
stress = self.cyc['stress_int'].values
ind = np.where(np.sign(stress[1:]) != np.sign(stress[:-1]))[0]
cycles = -1000
break
for i, val in enumerate(ind):
    if (ind[i] == 0) or (i == 0) or (i == 1):
        continue
    else:
        try:
            mycycle = strain[ind[i-2]:ind[i]]
            diff = np.max(mycycle) - np.min(mycycle)
        except IndexError:
            pdb.set_trace()
        if diff >= failval:
            cycles = self.cyc['Cycles'].values[ind[i]]
            cycind = np.argmax(np.abs(mycycle)) + ind[i-2]
            #plt.plot(self.cyc['Time'].values[ind[i-2]:ind[i]],
            #plt.plot(self.cyc['Time'].values[ind[i-2]:ind[i]],
            #mycycle)
            #pdb.set_trace()
            break
self.cycles = cycles
self.cycind = cycind
if self.cycles < 0.:
    print('Failure criteria didn\t work: DA {}%'.format(failval))
elf self.cycletype = 'backcalc':
gbeta = [ 0.2747 , -11.34 , 1.303 ]
print(gbeta)
self.DWliqbc = self.sigveff * np.exp(gbeta[0] *
    (self.Dr / 15.) ** 2 + gbeta[1])
self.cycles = self.cyc['Cycles'].max() #May need to be adjusted
self.cycind = len(self.cyc.index) - 2
else:
    self.cycles = self.cyc['Cycles'].max() #May need to be adjusted
    self.cycind = len(self.cyc.index) - 2
self.r_u_fin = self.cyc['Ru'].values[self.cycind]
self.total_pts = self.cyc['Cycles'].values[-1]
# Calculate the CSR
if self.strain:
    self.CSRcalc(strain=True)
self.CSRcalc()

if verbose:
    print('Test: %s, Dr=%.2f%%, CSR: %.3f, Cycles: %.1f, sigv: %.0f kPa'
          % (self.name, self.Dr, self.CSR, self.cycles, self.sigveff))
    if self.strain:
        print('Gamma (SA): {:.4f}'.format(self.gamma))

def EQcalcs(self, **kwargs):
    
    This will calculate Neq_computed for the earthquake tests.
    
    from smooth import smooth
    
    # Get my gam, G and D degradation curves:
    sigmeff = (1. + 2. * 0.45) * self.sigveff / 3.  # <== Assuming a ko here.
    gam, Gratio, damping = getDegrad('DS', 0., sigmeff, N=self.cycles,
                                     soil=1., freq=0.1)
    tau_avg = np.max(np.abs(self.cyc['sstress_int'].values)) * 0.65

    strain = smooth(self.cyc['sstrain_int'].values)
    stress = smooth(self.cyc['sstress_int'].values)
    runningS = (np.abs(stress - stress[0]) / np.abs(strain - strain[0]))

    Gmax = (440 * (self.Dr / 15.) ** (2/3.) * 101.325 *
           np.sqrt(sigmeff/101.325))

    G, D, gamout = TokimatsuSeedDirect(gam, Gratio, damping, self.Gmax, tau_avg)
    Gstr = G * (1 - D ** 2 + 1j * 2 * D)  #<== Simplified

    NPTS = len(stress)
    NFFT = 2 ** nextpow2(NPTS)

    newstrain = np.fft.irfft(np.fft.rfft(stress, NFFT) / Gstr)[::NPTS]

    DissEntotalstress = np.cumsum((stress[1:] + stress[:-1]) *
                                   (newstrain[1:] - newstrain[:-1])) *
                                   0.5
    dWone = 2 * np.pi * D * tau_avg * 2 / G
    self.Neq = DissEntotalstress[self.maxind] / dWone

def calcdW_Alt(self, **kwargs):
    
    This will calculate a dissipated energy in a manner more consistent
    with equivalent-linear results.
    
    N160 = (self.Dr / 15.) ** 2
    phi = np.sqrt(20 * N160) + 20
    ko = 1 - np.sin(phi * np.pi / 180.)
    sigmeff = (1. + 2. * ko) * self.sigveff / 3.  # <== Assuming a ko here.
    gam, Gratio, damping = getDegrad('DS', 0., sigmeff, N=self.cycles,
                                      soil=0, freq=0.1)

    if self.testtype == 'EQ':
        tau_avg = np.max(np.abs(self.cyc['sstress_int'].values)) * 0.65
    else:
        tau_avg = self.CSR * self.sigveff

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G, D, gamout = TokimatsuSeedDirect(gam, Gratio, damping, self.Gmax, tau_avg)
self.dWone = 2 * np.pi * D * tau_avg ** 2. / G
if self.testtype == 'EQ':
  self.dW_corralt = self.dWone * self.Neq
else:
  self.dW_corralt = self.dWone * self.cycles
print(' G/Gmax: {:.3f}, D: {:.3f}, gam: {:.4g}, DE_alt: {}'.format(G/self.Gmax, D, gamout, self.dW_corralt ))
print('dWone/Gmax: {}, sigmeff: {}'.format(self.dWone/self.Gmax, sigmeff))

def DiscreteCycles(self, **kwargs):
  
  Modifies the cycle count so that partial cycles are given, and saved as 'CyclesD' in the dataframe.
  
  cycles = self.cyc['Cycles'].values
time = self.cyc['Time'].values
ind = np.where((cycles[:-1] != cycles[1:]))
cyclesD = np.zeros(cycles.shape, dtype=float)
  
  for i, val in enumerate(ind[0]):
    if i == 0:
      in1 = 0
      in2 = val + 1
      prevyc = 0.
    else:
      in1 = ind[0][i-1] + 1
      in2 = val + 1
      prevyc = cycles[in1] - 1.
      time2 = time[in1:in2] - time[in1]
      cyclesD[in1:in2] = prevyc + time2 / time2[-1]
      in1 = ind[0][i-1] + 1
      in2 = len(time)
    prevyc = cycles[in1] - 1.
    time2 = time[in1:in2] - time[in1]
    cyclesD[in1:in2] = prevyc + time2 / time2[-1]
  self.cyc['CyclesD'] = cyclesD
  self.cyc['CycleRatio'] = cyclesD / self.cycles

def CSRcalc(self, **kwargs):
  
  Calculates the average CSR over the majority of the cyclic portion, or, for a strain controlled tests, the SA shear strain.

  strain = kwargs.get('strain', False)
  if self.testtype == 'sine':
    cycrange = kwargs.get('cycrange',75)
    # Get the zero crossings
    if strain:
      stress = self.cyc['sstress_int'].values
else:
    stress = self.cyc['sstress_int'].values
    cycles = int(self.cyc['Cycles'].values[-1] * cycrange / 100)
    # Calc the max and min in each cycle
    maxs = np.zeros([cycles,],dtype=float)
    mins = np.zeros([cycles,],dtype=float)
    for i in xrange(cycles):
        ind2 = np.where(self.cyc['Cycles'].values == i+1)
        maxs[i] = np.max(stress[ind2])
        mins[i] = np.min(stress[ind2])
    sigd = np.mean(maxs - mins) / 2
    if strain:
        self.gamma = sigd
    else:
        self.CSR = sigd / self.sigveff
        if self.strain:
            self.CSR = self.CSR * -1.
        else:
            self.ElapsedTime = self.cyc['Time'].values[-1]
            stress = self.cyc['sstress_int'].values
            peakval = np.amax(np.abs(stress[:self.cycind]))
            self.CSR = 0.65 * peakval / self.sigveff
            ind = np.argmax(np.abs(stress))
            peaktime = self.cyc['Time'].values[ind]
            dt1 = self.cyc['dt'].values[ind2[0][1]:self.cycind]
            stress1 = stress[ind2[0][1]:self.cycind]
            ind3 = np.where(dt1 > 0)
            dt2 = dt1[ind3]
            stress2 = stress1[ind3]
            self.PTratio = peaktime / self.ElapsedTime
            self.Ar = calcAriasRatio(stress2,
            print('dt= {} sec'.format(np.max(dt2)))

    def dissen(self,**kwargs):
    '''
    Calculates the dissipated energy from the test
    '''
    verbose = kwargs.get('verbose',True)
    stresses = self.cyc['sstress_int'].values
    strains = self.cyc['sstrain_int'].values
    cycles = self.cyc.Cycles.values
    if self.cycletype == 'backcalc':
        try:
            disseEn = np.cumsum((stresses[1:] + stresses[:-1]) *
            (strains[1:] - strains[:-1])) * 0.5
            disseEnZS = disseEn[self.ZeroStressInd
            mylen = int(len(self.ZeroStressInd) / 2)
            mydf = pd.DataFrame(dict(MyIndex = self.ZeroStressInd[:mylen],
            DW=dissEnZS[:mylen]))
            fit = sm.formula.ols('MyIndex ~ DW', data=mydf).fit()
params = fit.params

#ind = np.where(dissEnZS > self.DWliqbc)[0]
#self.maxind = self.ZeroStressInd[ind[0]]
ind0 = int(params[0] + params[1] * self.DWliqbc)
ind = np.where(self.ZeroStressInd <= ind0)[0]
self.maxind = self.ZeroStressInd[ind[-1]]
if self.maxind == 0 : self.Error = True; return 1
except:
    self.Error = True
    return 1
    #pdb.set_trace()
maxind = self.maxind
self.cycind = maxind
self.Cycles = cycles[self.cycind]
self.r_u_fin = self.cyc['Ru'].values[self.cycind]
else:
    #maxind = self.cycind
    # In this section, I get the index of the beginning of the cycle
    # in which the sample has liquefied.
    cycstartind = np.where((cycles[:-1] != cycles[1:]))[0]
    zerostrainind = np.where(np.sign(strains[:-1]) != np.sign(strains[1:]))[0]
    try:
        #maxind = cycstartind[np.where(self.cycind >= cycstartind)[-1]]
        # Finds where the strain was last zero for DE calcs
        #maxind = zerostrainind[np.where(self.cycind >= zerostrainind)[-1]]
        # Finds where the stress was last zero for DE calcs
        maxind = self.ZeroStressInd[np.where(self.cycind >=
            self.ZeroStressInd)[-1]]
        self.maxind = maxind
        except IndexError:
            self.Error = True
            return 1
    try:
        dissEn = np.cumsum((stresses[1:] + stresses[:-1]) *
            (strains[1:] - strains[:-1])) * 0.5
        except ValueError:
            pdb.set_trace()
            if np.abs(np.mean(stresses)) > 1:
                ('Adjusting the internal shear stresses based on the externals!!')
            stresses = stresses + np.mean(self.cyc['sstress_ext'].values -
                stresses)
    try:
        dissEn2 = np.zeros([len(self.cyc.index),],dtype=float)
        dissEn2[1:] = dissEn
        self.DE = dissEn[maxind]
        #dissEn2[maxind:] = self.DE
        self.cyc['DE'] = dissEn2
        except IndexError:
            self.DE = 0.
            self.DE_corr = 0.
            self.DE_b = 0.
            self.DE_m = 0.
            self.PEC = 0.
            self.DE_x = 0.
self.DE_y = 0.
self.DE_1 = 0.
self.cyc['DE'] = np.zeros(len(self.cyc.index))
self.Error = True
return 1

# Calculate the liquefaction-corrected dissipated energy
#ind = np.where((stresses[:maxind-1] < 0) &
#(stresses[1:maxind] >= 0))
x = self.cyc['CycleRatio'].values[self.ZeroStressInd]
y = self.cyc['DE'].values[self.ZeroStressInd]
alen = int(0.15 * len(x))
if alen < 4:
    alen = int(0.25 * len(x))
elen < 4:
    alen = int(0.35 * len(x))
elen < 4:
    alen = int(0.55 * len(x))
A = np.vstack([x[:alen],np.zeros([alen,])]).T
A = np.vstack([x[:alen],np.zeros([alen,])]).T
try:
m, b = np.linalg.lstsq(A, y[:alen])[0]
b = 0.
except ValueError:
    self.DE_corr = 0.
    self.DE_b = 0.
    self.DE_m = 0.
    self.PEC = 0.
    self.DE_x = 0.
    self.DE_y = 0.
    self.DE_1 = 0.
return

self.DE_corr = m + b
self.DE_m = m
self.DE_b = b
self.DE_x = x
self.DE_y = y
self.DE_1 = 1.0 / float(self.cycles) * m + b

# Calculate the PEC (Green's Dissertation, eq. 4-15)
Ru = self.cyc['Ru'].values
ind = np.where(Ru > 0.65)
try:
    self.PEC = self.cyc['DE'].values[ind[0][0]] / 0.4225
except IndexError:
    self.PEC = -1
if verbose:
    print(' Total DE: %.4f, Corrected DE: %.4f, DE/N: %.4f' %
          (self.DE,self.DE_corr,self.DE/self.cycles))

def plotter(self, **kwargs):
    '''
    Produces plots of interest.
    Keyword     Definition
    save         True [default] or False
    savetype     png or pdf, etc

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show  Should the figures be shown? True or False
''
save = kwarg.get('save',True)
savetype = kwarg.get('savetype','png')
show = kwarg.get('show',False)

# Time plot
useTime = False
if self.testtype == 'EQ': useTime = True
if useTime:
    xcol = 'Time'
    xlabel = 'Time (s)'
else:
    #xcol = 'CycleRatio'
    xcol = 'Cycles'
    xlabel = 'Cycles, $N$'
myalt = True
if myalt:
    fig1, (ax1, ax2, ax3, ax4) = plt.subplots(nrows=4, ncols=1, sharex=False,
        sharey=False, num='Results of %s'%self.name, figsize=(8,11))
else:
    fig1, (ax1, ax2, ax3) = plt.subplots(nrows=3, ncols=1, sharex=False,
        sharey=False, num='Results of %s'%self.name, figsize=(8,8))
if self.testtype == 'EQ':
    ax1.set_title(r'$D_r$={:.1f} \%, $CSR$={:.2f}, $\sigma\prime_{v0}$={:.0f} kPa'.format(self.Dr,self.CSR+0.0f)
else:
    ax1.set_title(r'$D_r$={:.1f} \%, $CSR$={:.2f}, $N_{liq}$={:.1f}, $\sigma\prime_{v0}$={:.0f} kPa'.format(self.Dr,self.CSR+0.0f))
ax1.plot(self.cyc[axcol], self.cyc.nstress, label='Normal Stress')
ax1.plot(self.cyc[axcol], self.cyc.sstress_int, label='Internal Shear Stress')
ax1.plot(self.cyc[axcol].values[self.cycind],0.,'or')
ax1.plot(self.cyc[axcol].values[self.maxind],0.,'og')
ax1.yaxis.set_major_locator(MaxNLocator(nbins=4))
ax1.legend(loc='best')
ax1.set_ylabel('Stress, $\tau$ (kPa)')
ax1.set_xlabel(xlabel)
ax1.grid(True)

#plt.subplot(312)
ax2.plot(self.cyc[axcol], self.cyc.nstrain_int*100.)
ax2.set_ylabel(r'Normal Strain, $\varepsilon_v$ (%)')
ax2.set_xlabel(xlabel)
ax2.yaxis.set_major_locator(MaxNLocator(nbins=4))
ax2.grid(True)

ax1.plot(self.cyc[axcol], self.cyc.mstress, label='Normal Stress')
ax1.plot(self.cyc[axcol], self.cyc.sstress_int, label='Internal Shear Stress')
ax1.plot(self.cyc[axcol].values[self.cycind],0.,'or')
ax1.plot(self.cyc[axcol].values[self.maxind],0.,'og')
ax1.xaxis.set_major_locator(MaxNLocator(nbins=4))
ax1.legend(loc='best')
ax1.set_ylabel('Stress, $\tau$ (kPa)')
ax1.set_xlabel(xlabel)
ax1.grid(True)

#plt.subplot(313)
ax2.plot(self.cyc[axcol], self.cyc.mstrain_int*100.)
ax2.set_ylabel(r'Normal Strain, $\varepsilon_v$ (%)')
ax2.set_xlabel(xlabel)
ax2.grid(True)

#ax2.legend(loc='best')
ax2.plot(self.cyc[axcol], self.cyc.nstress, label='Normal Stress')
ax2.plot(self.cyc[axcol], self.cyc.sstress_int, label='Internal Shear Stress')
ax2.plot(self.cyc[axcol].values[self.cycind],0.,'or')
ax2.plot(self.cyc[axcol].values[self.maxind],0.,'og')
ax2.xaxis.set_major_locator(MaxNLocator(nbins=4))
ax2.legend(loc='best')
ax2.set_ylabel('Stress, $\tau$ (kPa)')
ax2.set_xlabel(xlabel)
ax2.grid(True)
if myalt:
    ax3.plot(self.cyc[xcol], self.cyc.Ru,
     )
    ax3.plot(self.cyc[xcol].values[self.ZeroStressInd],
    self.cyc['Ru'].values[self.ZeroStressInd], 'ws')
    ax3.plot(self.cyc[xcol].values[self.cycind],
    self.cyc['Ru'].values[self.cycind],
    'or')
    ax3.plot(self.cyc[xcol].values[self.maxind],
    self.cyc['Ru'].values[self.maxind],
    'og')
    [xmin, xmax, ymin, ymax] = ax3.axis()
    ax3.plot([xmin, xmax], [1., 1.], 'k--', lw=0.5, color='0.5')
    ax3.yaxis.set_major_locator(MaxNLocator(nbins=4))
    ax3.axis((xmin, xmax, 0, 1.1))
    ax3.set_ylabel(r'$r_u$')
    ax3.set_xlabel(xlabel)
    #ax3.autoscale(True)
    ax3.grid(True)
    ax4.plot(self.cyc.sstrain_ext * 100., self.cyc.sstress_ext,
    label=r'Shear Strain, $\gamma$')
    ax4.plot(self.cyc['sstrain_ext'].values[self.cycind] * 100.,
    self.cyc['sstress_ext'].values[self.cycind],
    'or')
    ax4.plot(self.cyc['sstrain_ext'].values[self.maxind] * 100.,
    self.cyc['sstress_ext'].values[self.maxind],
    'og')
    ax4.yaxis.set_major_locator(MaxNLocator(nbins=4))
    ax4.set_xlabel(r'Shear Strain, $\gamma$ (%)')
    ax4.autoscale(True)
    ax4.grid(True)
else:
    ax3.plot(self.cyc.sstrain_ext, self.cyc.sstress_ext,
    label=r'Shear Strain, $\gamma$')
    ax3.plot(self.cyc['sstrain_ext'].values[self.cycind],
    self.cyc['sstress_ext'].values[self.cycind],
    'or')
    ax3.plot(self.cyc['sstrain_ext'].values[self.maxind],
    self.cyc['sstress_ext'].values[self.maxind],
    'og')
    ax3.yaxis.set_major_locator(MaxNLocator(nbins=4))
    ax3.set_xlabel(r'Shear Strain, $\gamma$ (kPa)')
    ax3.autoscale(True)
    ax3.grid(True)
fig1.subplots_adjust(hspace=0.47, left=0.16)
#plt.show()
#pdb.set_trace()
fig2 = plt.figure('Shear-Normal strains')
plt.plot(self.cyc.nstress,self.cyc.sstress_int)
plt.xlabel('Normal Stress (kPa)')
plt.ylabel('Shear Stress (kPa)')
plt.autoscale()
plt.grid(True)

# Dissipated Energy
fig3, (ax13, ax23, ax33) = plt.subplots(nrows=3, ncols=1,
    sharex=False, sharey=False,
    num='Dissipated Energy-%s'%self.name)
fig3.suptitle(r'$\Delta W = %.3f, \Delta W_{corr}= %.3f, PEC = %.3f$
    %(self.DE,self.DE_corr,self.PEC))

ax13.plot(self.cyc.Time, self.cyc.DE)
ax13.set_ylabel(r'$\Delta W$')
ax13.set_xlabel('Time (sec)')
ax13.grid(True)

#plt.subplot(312)
ax23.plot(self.DE_x,self.DE_y,'o')
ax23.set_xlabel(r'$\frac{N}{N_{liq}}$')
ax23.set_ylabel(r'$\Delta W$')
ax23.plot(self.DE_x,self.DE_m*self.DE_x+self.DE_b)
ax23.plot(self.DE_x, self.DE_x * self.cycles * self.dWone,'sw')
ax23.grid(True)

#plt.subplot(313)
DEsqr = np.sqrt(self.cyc['DE'].values)
Ru = self.cyc['Ru'].values
ax33.plot(DEsqr,Ru,'o')
ax33.set_xlabel(r'$\sqrt{\Delta W}$')
ax33.set_ylabel(r'$r_u$')
ax33.plot([0,np.sqrt(self.PEC)],[0,1.],'-')
ax33.grid(True)

plt.figure('DE-Ru')
plt.plot(self.cyc['DE'].values, Ru,'o')
plt.xlabel(r'$\Delta W$')
plt.ylabel(r'$r_u$')
plt.grid(True)
# plt.show()

if show:
    plt.show()
if save:
    import matplotlib
    figures=[manager.canvas.figure for manager in
        matplotlib._pylab_helpers.Gcf.get_all_fig_managers()]
    for i, figure in enumerate(figures):
        figure.savefig(self.path +
            self.name+'-'+str(i+1)+'.'+savetype)
plt.close('all')
DEplot = False
if DEplot == True:
    self.cyc.plot(x='sstrain_ext',y='sstress_ext',
        label=r'Shear Strain, $\gamma$')
    plt.ylabel(r'Shear Stress, $\tau$ (kPa)')

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If self.extrafigs:
    plt.close('all')
    plt.figure('s-s')
    self.cyc.plot(x='sstrain_ext', y='sstress_ext',
                  label=r'Shear Strain, $\gamma$')
    plt.xlabel(r'Shear Stress, $\tau$ kPa')
    plt.ylabel(r'Shear Strain, $\gamma$')
    plt.title(r'$D_r$=%.1f %%, $CSR$= %.2f, $N$=%.1f, $\sigma_v$'\=%.0f (kPa)'
              %(self.Dr, self.CSR, self.cycles, self.sigveff))
    plt.savefig('./ExtraFigs/+self.name +'~'+'tau-gam'+'.png')

    plt.figure('PP-N')
    EquivalentPorePress = (self.cyc['nstress'].values[0] -
                           self.cyc['nstress'].values)
    plt.plot(self.cyc['CyclesD'].values,
             EquivalentPorePress)
    plt.xlabel(r'Cycles')
    plt.ylabel(r'Equivalent Pore Pressure (kPa)')
    plt.title(r'$D_r$=%.1f %%, $CSR$= %.2f, $N$=%.1f, $\sigma_v$'\=%.0f (kPa)'
              %(self.Dr, self.CSR, self.cycles, self.sigveff))
    plt.savefig('./ExtraFigs/+self.name +'~'+'PP-N'+'.png')

    plt.figure('Ru-DE')
    stresses = self.cyc['sstress_int'].values
    ind = np.where((stresses[:-1] < 0) &
                    (stresses[1:] >= 0))
    plt.plot(self.cyc['DE'].values[ind], Ru[ind], '-o')
    plt.xlabel(r'Dissipated Energy')
    plt.ylabel(r'Pore Pressure Ratio')
    plt.title(r'$D_r$=%.1f %%, $CSR$= %.2f, $N$=%.1f, $\sigma_v$'\=%.0f (kPa)'
              %(self.Dr, self.CSR, self.cycles, self.sigveff))
    plt.savefig('./ExtraFigs/+self.name +'~'+'Ru-DE'+'.png')
    plt.close('all')

if self.PaperFigs:
    color = '0.35'
    lw=1.2
    alpha = 0.9
    fig1, (ax1, ax2) = plt.subplots(nrows=1, ncols=2,
                                    sharex=False, sharey=True,
                                    num='PaperFig1-%s'%self.name, figsize=(9,5))
    ax1.plot(self.cyc.sstrain_int * 100., self.cyc.sstress_int, lw=lw,
             color='0.15', alpha=alpha)
    ax1.set_xlabel(r'Shear Strain, $\gamma$ (%)')
    ax1.set_ylabel('Shear Stress (kPa)')
    ax1.xaxis.set_major_locator(MaxNLocator(nbins=4, prune='both')) # added
    ax1.grid(True)

    ax2.plot(self.cyc.nstress, self.cyc.sstress_int, lw=lw, color=color,
             alpha=alpha)
    ax2.set_xlabel('Vertical Stress (kPa)')
    ax2.grid(True)
    fig1.subplots_adjust(bottom=0.12, wspace=0)
    if os.name == 'posix':
sys.path.append('/media/Storage/Documents/00-VtResearch/Thesis/Markdown/Figures/SeismicCompression')
else:
sys.path.append('/..../Documents/00-VtResearch/Thesis/Markdown/Figures/SeismicCompression')

from SCplots import dimlines

fig2, ax3 = plt.subplots(num='PaperFig2-%s'%self.name,
figsize=(10, 8.33))
ax3.plot(self.DE_x,self.DE_y,'o', color=color, label='Data')
ax3.plot(1.,self.DE*1.1,'k',
label=r'$\Delta W_{\mathrm{Effect.}}$')
ax3.set_xlabel(r'Cycles / Cycles to Liquefaction, $N/N_{liq}$')
ax3.set_ylabel(r'$\Delta W$ $(kPa)$')
ax3.plot(self.DE_x,self.DE_m*self.DE_x+self.DE_b, '--', lw=lw,
color='0.2', alpha=0.7)
ax3.plot(1., self.DE_m, '*k', ms=6, label=r'$\Delta W_{\mathrm{Total}}$')
[xmin, xmax, ymin, ymax] = ax3.axis()
ax3.plot([1.0,1.0],[0,ymax * 1.2], '-', color='0.5', lw=0.7,
alpha=0.7)
dimlines(ax3, [1., self.DE_m], [1.,self.DE*1.1],
'\$\Delta W_{\mathrm{Effect.}} - \Delta W_{\mathrm{Total}}$', 0.5,
side='left', textscale=0.5)
ax3.legend(loc='upper left', numpoints=1)
ax3.grid(True)
fig2.subplots_adjust(bottom=0.15)
# plt.show()
# pdb.set_trace()
fig1.savefig('./Sine/PaperFigs/{}-1.pdf'.format(self.name), dpi=100)
fig1.savefig('./Sine/PaperFigs/{}-1.png'.format(self.name), dpi=100)
fig2.savefig('./Sine/PaperFigs/{}-2.pdf'.format(self.name), dpi=100)
fig2.savefig('./Sine/PaperFigs/{}-2.png'.format(self.name), dpi=100)
plt.close('all')

def loadcorrection(self, **kwargs):
    
    Uses the water test files to correct the loads.
    
    loadcorr_type = kwargs.get('type', self.loadcorr_type)
    friction = HDF5saver(testtype='water')
    #atable = friction.read()
    if self.waterfile == None:
        dates = friction.summtable.read(field='Date_of_Test')
        ind = np.argmin(np.abs(dates-self.date_of_test))
        self.WaterTestName = friction.summtable.read(ind,field='File')[0]
    if loadcorr_type == 'old':
        from scipy.interpolate import interp1d
        try:
pomm = friction.summtable.read_coordinates([ind],field='pomm')[0]
posb = friction.summtable.read_coordinates([ind],field='posb')[0]
negm = friction.summtable.read_coordinates([ind],field='negm')[0]
negb = friction.summtable.read_coordinates([ind],field='negb')[0]
except AttributeError:
pomm = friction.summtable.readCoordinates([ind],field='pomm')[0]
posb = friction.summtable.readCoordinates([ind],field='posb')[0]
negm = friction.summtable.readCoordinates([ind],field='negm')[0]
negb = friction.summtable.readCoordinates([ind],field='negb')[0]
```python
intshear = self.cyc['Internal Shear LVDT'].values
intshear1 = intshear[np.isfinite(intshear)]

dispx = np.array([np.min(intshear1),
                  -0.0001, 0.0001,
                  np.max(intshear1)])

loady = np.ravel(np.array([negm*dispx[0]+negb,
                          negm*dispx[1]+negb,
                          posm*dispx[2]+posb,
                          posm*dispx[3]+posb]))

loadcorrf = interp1d(disp, loady, kind='linear', bounds_error=True)

elif loadcorr_type == 'bilinear':
    try:
        Gmax = friction.summtable.read_coordinates([ind], field='Gmax')[0]
        gamr = friction.summtable.read_coordinates([ind], field='gamr')[0]
        G2 = friction.summtable.read_coordinates([ind], field='G2')[0]
    except AttributeError:
        Gmax = friction.summtable.read_coordinates([ind], field='Gmax')[0]
        gamr = friction.summtable.read_coordinates([ind], field='gamr')[0]
        G2 = friction.summtable.read_coordinates([ind], field='G2')[0]

loadcorrf = bilinear(Gmax, G2, gamr)

elif loadcorr_type == 'hyperbolic':
    try:
        Gmax = friction.summtable.read_coordinates([ind], field='Gmax')[0]
        gamr = friction.summtable.read_coordinates([ind], field='gamr')[0]
        a = friction.summtable.read_coordinates([ind], field='hypa')[0]
        b = friction.summtable.read_coordinates([ind], field='hypb')[0]
    except AttributeError:
        Gmax = friction.summtable.read_coordinates([ind], field='Gmax')[0]
        gamr = friction.summtable.read_coordinates([ind], field='gamr')[0]
        a = friction.summtable.read_coordinates([ind], field='hypa')[0]
        b = friction.summtable.read_coordinates([ind], field='hypb')[0]

taumax = gamr * Gmax
loadcorrf = hyperbolic(Gmax, taumax, a=a, b=b)

friction.close()
return loadcorrf

def wu_etal_liq_crit(self, **kwargs):
    
    Uses the liquefaction criteria from Wu et al. 2004.
    Initial liquefaction is defined as the occurrence of 6% Single
    Amplitude or 6% Double Amplitude shear strain.

Wu, J., Kammerer, A. M., Riemer, M. F., Seed, R. B., and
criteria." 13th World Conference on Earthquake Engineering,
Vancouver, BC.
```
```
    continue
    else:
      maxs[i] = np.max(strain[0:ind[i]])
      mins[i] = np.min(strain[0:ind[i]])
    else:
      maxs[i] = np.max(strain[ind[i]:ind[i] + 1])
      mins[i] = np.min(strain[ind[i]:ind[i] + 1])
    if (maxs[i] or np.abs(mins[i])) >= 0.06:
      indout = ind[i]
      return self.cyc['Cycles'].values[indout], indout
    else:
      maxs[i] = np.max(stress[ind[i]:ind[i] + 1])
      mins[i] = np.min(stress[ind[i]:ind[i] + 1])
    Gpos = stress[ind[i] + np.argmax(stress[ind[i]:ind[i] + 1])] / strain[ind[i] + np.argmax(stress[ind[i]:ind[i] + 1])]
    Gneg = stress[ind[i] + np.argmin(stress[ind[i]:ind[i] + 1])] / strain[ind[i] + np.argmin(stress[ind[i]:ind[i] + 1])]
    if i == 0:
      maxs[i] = np.max(stress[0:ind[i]])
      mins[i] = np.min(stress[0:ind[i]])
      maxind[i] = np.argmax(stress[0:ind[i]])
      minind[i] = np.argmin(stress[0:ind[i]])
    else:
      maxs[i] = np.max(stress[ind[i]:ind[i] + 1])
      mins[i] = np.min(stress[ind[i]:ind[i] + 1])
      maxind[i] = ind[i] + np.argmax(stress[ind[i]:ind[i] + 1])
      minind[i] = ind[i] + np.argmin(stress[ind[i]:ind[i] + 1])
  G = (np.abs(stress[maxind]) + np.abs(stress[minind])) / 2.
  avgstress = (stress[maxind] + stress[minind]) / 2.
  avgstrain = (strain[maxind] + strain[minind]) / 2.
  Gpos = stress[maxind] / strain[maxind]
  Gneg = stress[minind] / strain[minind]
```
plt.figure('G')
plt.plot(strain, stress)
plt.plot(strain[maxind], stress[maxind], 'ro')
plt.plot(strain[minind], stress[minind], 'ro')
plt.plot(strain[np.where(np.abs(Gpos)<np.max(Gpos)/100)[0]], stress[np.where(np.abs(Gpos)<np.max(Gpos)/100)], 'g+')
plt.figure('Other')
plt.plot(stress)
plt.plot(maxind[np.where(np.abs(Gneg)<np.max(np.abs(Gneg)/100))], stress[np.where(np.abs(Gneg)<np.max(np.abs(Gneg)/100))], 'ro')
plt.plot(maxind[np.where(np.abs(Gpos)<np.max(Gpos)/100)], stress[np.where(np.abs(Gpos)<np.max(Gpos)/100)], 'ro')
plt.show()
pdb.set_trace()

def fileout(self, **kwargs):
    
    Writes the specified time history to file.
    
    motiontype = kwargs.get('motiontype', 'displacement')
sensor = kwargs.get('sensor', 'external')
from GCTSInput import FileMaker
if motiontype == 'displacement':
    if sensor in ['internal', 'int', 'i']:
        FileMaker(self.cyc['Internal Shear LVDT'].values,
                  self.cyc['Time'].values, self.name,
                  sensor=sensor, motiontype=motiontype)
    elif sensor in ['external', 'ext', 'e']:
        FileMaker(self.cyc['Shear Displacement'].values,
                  self.cyc['Time'].values, self.name,
                  sensor=sensor, motiontype=motiontype)
    else:
        print('I cannot understand "{}" sensor'.format(motiontype))
else:
    print('I cannot understand "{}" motiontype'.format(motiontype))
pdb.set_trace()

def saverpickle(testobj, **kwargs):
    fid1=open('%s.dp1'%(testobj.name),'w')
p.dump(testobj, fid1)
fid1.close()

class WaterTest(object):
    
    This class parses the GCTS test file for water only (or friction) tests.
    It returns data to be used to correct the data from regular CV-CSS tests.
    
def __init__(self, infile, **kwargs):
    self.csvimport(infile)
    if kwargs.get('surcharge', False):
        self.calcs_sur(**kwargs)
    else:
        self.calcs1(**kwargs)
def csvimport(self, infile):
datafile = csv.reader(open(infile,'rU'))
rowcount = -1
rows = []
self.units = []
for row in datafile:
    rowcount += 1
    if 'Starting Date: ' in row:
        testdate = row[1]
    if 'Starting Time: ' in row:
        testtime = row[1]
    if len(row) > 17:
        if row[0] == 'Time':
            rows.append(rowcount)
            header = rowcount
            self.headerlabel = row
        if len(self.units) == 0:
            self.units = row
    if len(rows) == 1:
        nrows = rows[-1] - rows[0] - 5
        break
    if row[0] == 'sec':
        if len(self.units) == 0:
            self.units = row
df = pd.read_csv(infile,names=self.headerlabel, skiprows=header+3)#,
    df = df.convert_objects(convert_numeric=True)
    select = df.apply(lambda r : any([isinstance(e, basestring) for e in r ]),axis=1)
    df = df[~select]
    df = df.dropna()
    self.df = df
    self.filename = infile
    self.name = os.path.splitext(self.filename)[0]
    self.date_of_test = datetimeconvert(testdate,testtime)

def calcs1(self,**kwargs):
    'Performs the calculations for the water test.'
    save = kwargs.get('save',True)
    savetype = kwargs.get('savetype','png')
    show = kwargs.get('show',False)
    movie = kwargs.get('movie', True)
    print(self.name)
    self.df['Disp'] = (self.df['Internal Shear LVDT'] -
    self.df['Internal Shear LVDT'][0])
    self.df['Load'] = (self.df['Internal Shear Load'])
    Load = self.df['Load'].values
    Disp = self.df['Disp'].values
    Time = self.df['Time'].values
    #Find indices of zero crossing
    ind = np.where((Disp[:-1] < 0) & (Disp[1:] >= 0))
```
Vel = np.zeros(Disp.shape, dtype=float)
Vel[1:] = np.diff(Disp) / np.diff(Time)

Lmax = np.zeros(ind[0].shape, dtype=float)
Lmin = np.zeros(ind[0].shape, dtype=float)
Dmax = np.zeros(ind[0].shape, dtype=float)
Dmin = np.zeros(ind[0].shape, dtype=float)
Maxind = np.zeros(ind[0].shape, dtype=int)
Minind = np.zeros(ind[0].shape, dtype=int)

Dx = np.max(Disp) - np.min(Disp)
Dy = np.max(Load) - np.min(Load)

maxtype = kwargs.get('maxtype', 'sinefit')
for i in xrange(len(ind[0])):
    if maxtype == 'notsinefit':
        from scipy.optimize import curve_fit
        def mysine(x, A, w, c):
            return A * np.sin(w * x) + c
        if i == 0:
            X = Time[0:ind[0][i]]
            Y = Disp[0:ind[0][i]]
        else:
            X = Time[ind[0][i-1]:ind[0][i]]
            Y = Disp[ind[0][i-1]:ind[0][i]]
        if len(X) < 2:
            Dmax[i] = 0.
            Dmin[i] = 0.
            Lmax[i] = 0.
            Lmin[i] = 0.
        else:
            A = np.max(Y)
            w = 2. * np.pi / (X[-1] - X[0])
            c = Time[ind[0][i-1]]
            popt, pov = curve_fit(mysine, X, Y, p0=[A, w, c])
            Maxind[i] = ind[0][i-1] + np.argmin(np.abs(Y - popt[0]))
            Minind[i] = ind[0][i-1] + np.argmin(np.abs(Y + popt[0]))
            Dmax[i] = Disp[Maxind[i]]
            Dmin[i] = Disp[Minind[i]]
            Lmax[i] = Load[Maxind[i]]
            Lmin[i] = Load[Minind[i]]
    else:
        if i == 0:
            maxind = np.argmax(Disp[0:ind[0][i]])
            minind = np.argmin(Disp[0:ind[0][i]])
            Maxind[i] = maxind
            Minind[i] = minind
        else:
            maxind = np.argmax(Disp[ind[0][i-1]:ind[0][i]])
            minind = np.argmin(Disp[ind[0][i-1]:ind[0][i]])
            Maxind[i] = maxind + ind[0][i-1]
            Minind[i] = minind + ind[0][i-1]
        Dmax[i] = Disp[Maxind[i]]
        Dmin[i] = Disp[Minind[i]]
        Lmax[i] = Load[Maxind[i]]
        Lmin[i] = Load[Minind[i]]

poscoeff = np.polyfit(Dmax, Lmax, 1)
negcoeff = np.polyfit(Dmin, Lmin, 1)
```
print('Pos Coeffs: {}'.format(poscoeff))
print('Neg Coeffs: {}'.format(negcoeff))
self.poscoeff = poscoeff
self.negcoeff = negcoeff
plt.plot(Time,Disp)
plt.plot(Time[Maxind],Dmax,'o')
plt.plot(Time[Minind],Dmin,'o')
plt.figure('{}'.format(self.name))
plt.plot(Dmax,Lmax,'o')
plt.plot(Dmin,Lmin,'o')
xpos = np.array([0,Dmax[-1]])
ypos = poscoeff[1] + poscoeff[0]*xpos
xneg = np.array([0,Dmin[-1]])
yneg = negcoeff[1] + negcoeff[0]*xneg
plt.plot(xpos,ypos)
plt.plot(xneg,yneg)
plt.xlabel('Displacement (mm)')
plt.ylabel('Load (kN)')
titletext = ('Positive: m = {}, b = {}, Negative: m = {}, b = {}'.format(round(poscoeff[0],4),
                                                                 round(poscoeff[1],4),
                                                                 round(negcoeff[0],4),
                                                                 round(negcoeff[1],4)))
plt.title(titletext)
if save:
    plt.savefig(self.name + '-1.' + savetype)
if show:
    plt.show()
try:
    Gmax = np.polyfit(Disp[:200],Load[:200],1)[0]
except TypeError:
    pdb.set_trace()
    pdb.set_trace()
m = np.mean([poscoeff[0], negcoeff[0]])
Gmax = 0.04 # May need to change this
gamr = 0.5 * (Dy - m * Dx) / (Gmax - m)
offsety = np.mean([poscoeff[1], negcoeff[1]])
offsety = (np.max(Load) + np.min(Load)) / 2.
tau = (np.max(Load) - np.min(Load)) / 2.
a = 0.2
b = 0.16
if a == 0:
    b = 0.
else:
    b = -np.log((Gmax ** 2 + m * (Gmax + 1)) / m * a )
    b = -np.log((Gmax - 2 * m) / (a * m))
self.hypa = a
self.hypb = b
hyp = hyperbolic(Gmax, taumax, a=a, b=b,
                  voffset=offsety)
tauhyp = hyp(Disp)
bil = bilinear(Gmax, m, gamr, voffset=offsety)
self.Gmax = Gmax
self.G2 = m
self.gamr = gamr
self.voffset = offsety
# from smooth import smooth
Disp = smooth(Disp, window_len=15)
taubil = bil(Disp)
plt.figure('2')
plt.plot(Disp, Load, 'ro')
plt.plot(Disp, taubil, 'b')
plt.plot(Disp, tauhyp, 'g')
plt.xlabel('Displacement (mm)')
plt.ylabel('Load (kN)')
plt.title('Gmax = {:.4f}, G2 = {:.4f}, $\gamma_r$ = {:.3f}, V.Off={:.4f}'.format(Gmax, m, gamr, offsety))
if save:
    plt.savefig(self.name + '-2.' + savetype)
plt.show()
pdb.set_trace()

if movie:
    moviemaker([Time,Disp,[Load,taubil, tauhyp]], xlabel='Displacement (mm)', ylabel='Load (kN)', num_y=3, moviename=self.name[:-4])
plt.close('all')

def calcs_sur(self,**kwargs):
    '''
    Does the calcs for an air and surcharge friction test.
    '''
    save = kwargs.get('save',True)
savetype = kwargs.get('savetype','png')
show = kwargs.get('show',False)

    Time = self.df['Time'].values
    dt = np.diff(Time)
    ind = np.where(dt!=0)
dt = dt[ind]
    Load = self.df['Internal Shear Load'].values[ind]
    Disp = self.df['Shear Displacement'].values[ind]
    self.PDE = 0.5 * np.sum((Load[1:] + Load[:-1]) * (Disp[1:] - Disp[:-1]))
    Time = Time[ind]

    surcharge = kwargs.get('load')
    if surcharge == None:
        surcharge = float(raw_input('Give me the surcharge load (in kg)!!'))
    self.surcharge = surcharge

    Acc = np.zeros(Disp.shape,dtype=float)
    ind4 = np.where((Disp[:-1]<=0) & (Disp[1:]>0))
    freq = 1. / np.average(np.diff(Time[ind4]))
w = 2 * np.pi * freq
Acc = -Disp*0.001 * w ** 2

inertial_load = Acc * surcharge / 1000 # units of kN
Load_corr = Load - inertial_load
self.PDE_corr = 0.5 * np.sum((Load_corr[1:] + Load_corr[:-1]) * 
                          (Disp[1:] - Disp[:-1]))

DissEn = np.zeros(Time.shape,dtype=float)
DissEn[1:] = 0.5 * ((Load_corr[1:] + Load_corr[:-1]) * 
                     (Disp[1:] - Disp[:-1]))

plt.figure('DE')
plt.plot(Time,DissEn,label='{} kN'.format(surcharge))
plt.legend(loc='upper left')

#Find indices of zero crossing
ind = np.where((Disp[:-1] < 0) & (Disp[1:] >= 0))
Lmax = np.zeros(ind[0].shape,dtype=float)
Lmin = np.zeros(ind[0].shape,dtype=float)
Dmax = np.zeros(ind[0].shape,dtype=float)
Dmin = np.zeros(ind[0].shape,dtype=float)
Maxind = np.zeros(ind[0].shape,dtype=int)
Minind = np.zeros(ind[0].shape,dtype=int)
for i in xrange(len(ind[0])):
    if i == 0:
        if ind[0][i] == 0:
            Maxind[i] = 0
            Minind[i] = 0
            continue
    else:
        maxind = np.argmax(Disp[0:ind[0][i]])
        minind = np.argmin(Disp[0:ind[0][i]])
        Maxind[i] = maxind
        Minind[i] = minind
    else:
        maxind = np.argmax(Disp[ind[0][i-1]:ind[0][i]])
        minind = np.argmin(Disp[ind[0][i-1]:ind[0][i]])
        Maxind[i] = maxind + ind[0][i-1]
        Minind[i] = minind + ind[0][i-1]

Dmax[i] = Disp[Maxind[i]]
Dmin[i] = Disp[Minind[i]]
Lmax[i] = Load_corr[Maxind[i]]
Lmin[i] = Load_corr[Minind[i]]

poscoeff = np.polyfit(Dmax,Lmax,1)
negcoeff = np.polyfit(Dmin,Lmin,1)

plt.figure('{}',format(self.name))
plt.plot(Dmax,Lmax,'o')
plt.plot(Dmin,Lmin,'o')
xpos = np.array([0,Dmax[-1]])
ypos = poscoeff[1] + poscoeff[0]*xpos
xneg = np.array([0,Dmin[-1]])
yneg = negcoeff[1] + negcoeff[0]*xneg
plt.plot(xpos,ypos)
plt.plot(xneg,yneg)
plt.xlabel('Displacement (mm)')
plt.ylabel('Load (kN)')
titletext = ('Positive: m = {}, b = {}; Negative: m = {}, b = {}').format(
    round(poscoeff[0],4),
    round(poscoeff[1],4),
    round(negcoeff[0],4),
    round(negcoeff[1],4)))
plt.title(titletext)
if save:
    plt.savefig(self.name + '.' + savetype)
if show:
    plt.show()
plt.close('{}'.format(self.name))

def runwater(*args, **kwargs):
    
    This is a convenience function that pushes test files through
    the WaterTest and the results into HDF5saver.
    
    if os.name == 'posix':
        defaultDir=(u'/media/Storage/Documents/Python' +
        '/GCTS/ConstantVolume/Friction')
    else:
        defaultDir=''
    infilelist=[]

    if len(args) > 0:
        argsin = list(args)
    else:
        argsin=sys.argv[1:]

    filters = 'CSV (*.csv)' # for qtfiledialog
    # filters = 'CSV|*.csv' # for wxfiledialog
    if argsin==[]:
        filelist=fd.fileopen(message='Choose a gcts water output...',
        filters=filters,
        defaultDir=defaultDir)
    else:
        for file in filelist:
            infilelist.append(file)
        del filelist
    elif len(argsin)>0:
        if argsin[0] in ['all','--all','-a','a']:
            infilelist=glob.glob('*.csv')
        else:
            for file in argsin:
                infilelist.append(file)
        del argsin
    if kwargs.get('surcharge',False):
        h5table = HDF5saver(testtype='surcharge')
        surcharges = []
        for i,infile in enumerate(infilelist):
            print(infile)
            surcharges.append(}
float(raw_input('Give me the surcharge load (in kg): ')))
for i, infile in enumerate(infilelist):
    result = WaterTest(infile, load=surcharges[i], **kwargs)
    hstable.input(result)
else:
    hstable = HDF5saver(testtype='water', filename='WaterSummary.h5')
    for infile in infilelist:
        result = WaterTest(infile, **kwargs)
        hstable.input(result)
    hstable.close()
def runsoil(*args, **kwargs):
    
    This is a convenience function that pushes test files through
    the SoilTest and the results into HDF5saver.

    strain = kwargs.get('strain', False)
PaperFigs = kwargs.get('PaperFigs')
if os.name == 'posix':
    if strain:
        defaultDir=(u'/media/Storage/Documents/Python' +
                    '/GCTS/ConstantVolume/StrainControlled')
    else:
        defaultDir=(u'/media/Storage/Documents/Python' +
                    '/GCTS/ConstantVolume/Sine')
else:
    defaultDir=''
    h5 = kwargs.get('h5file', 'default')
extrasigs = kwargs.get('extrasigs', False)
    cycletype = kwargs.get('cycletype', 'strainSA')
    cycletype = kwargs.get('cycletype', 'ru')
    strainfailval = kwargs.get('strainfailval', '0375')
    rufailval = kwargs.get('rufailval', '98')
    loadcorr = kwargs.get('loadcorr', False)
    loadcorr_type = kwargs.get('loadcorr_type', 'bilinear')
    infilelist=[]
    if len(args) > 0:
        argsin = args
    else:
        argsin=sys.argv[1:]
        filters = ['CSV (*.csv)'] # for qFileDialog
        # filters = ['CSV.*.csv'] # for wxFiledialog
    if argsin==[]:
        filelist=fd.fileopen(message='Choose a gcts output...',
                            filters=filters,
                            defaultDir=defaultDir)
        for file in filelist:
            infilelist.append(file)
        del filelist
    elif len(argsin)>0:
        if argsin[0] in ['all', '--all', '-a', 'a']:
            if strain:
                infilelist=glob.glob('./StrainControlled/*.csv')
            else:
                infilelist=glob.glob('./Sine/*.csv')
        else:
            pass
    else:
        pass
for file in argsin:
    infilelist.append(file)
del argsin
if h5 == 'choose':
    h5file = fd.fileopen(message='Choose a Summary Table...',
                        filters='h5 (*.h5),
                        defaultDir=defaultDir[:-5])
    hstable = HDF5saver(filename=h5file[0], testtype='sand')
eelif h5 == 'default':
    if strain:
        hstable = HDF5saver(filename='StrainSummaryResults.h5',
                             testtype='sand', strain=True)
    else:
        hstable = HDF5saver(testtype='sand')
eelse:
    if strain:
        hstable = HDF5saver(filename=h5,
                             testtype='sand', strain=True)
    else:
        hstable = HDF5saver(filename=h5, testtype='sand')

for infile in infilelist:
    if strain:
        testobj = SoilTest(infile=infile,
                           loadcorr=loadcorr,
                           loadcorr_type=loadcorr_type,
                           extrafigs=extrafigs,
                           cycletype=cycletype,
                           rufailval=rufailval,
                           strain=strain#, **kwargs)
    else:
        testobj = SoilTest(infile=infile,
                           loadcorr=loadcorr,
                           loadcorr_type=loadcorr_type,
                           extrafigs=extrafigs,
                           cycletype=cycletype,
                           rufailval=rufailval,
                           PaperFigs=PaperFigs,
                           strainfailval=strainfailval,
                           #**kwargs
                           )  #'strain01')
    if testobj.Error or PaperFigs:
        #pdb.set_trace()
        pass
    else:
        hstable.input(testobj)
    del testobj
    if PaperFigs:
        pass
    else:
        if kwargs.get('h5plot', True):
            hstable.plot()
            hstable.close()
def runEQ(*args,**kwargs):
    '''
Runs eq test files into SoilTest and saves the results via HDF5saver

```python
#cycletype = kwargs.get('cycletype', 'strainSA')
cycletype = kwargs.get('cycletype', 'ru')
strainfailval = kwargs.get('strainfailval', '02')
rufailval = kwargs.get('rufailval', '98')
loadcorr = kwargs.get('loadcorr', False)
loadcorr_type = kwargs.get('loadcorr_type', 'bilinear')
h5plot = kwargs.get('h5plot', True)
if os.name == 'posix':
    defaultDir=(u'/media/Storage/Documents/Python' +
    '/GCTS/ConstantVolume/EQ')
else:
    defaultDir=''
h5 = kwargs.get('h5file','default')
infilelist=[]
if len(args) > 0:
    argsin = args
else:
    argsin=sys.argv[1:]
    if argsin==[]:
        filelist=fd.fileopen(message='Choose a gcts output of an EQ test...',
        filters='*.csv', # for the wxfiledialog
        defaultDir=defaultDir)
        for file in filelist:
            infilelist.append(file)
        del filelist
    elif len(argsin)>0:
        if argsin[0] in ['all','--all','-a','a']:
            infilelist=glob.glob('./EQ/*.csv')
        else:
            for file in argsin:
                infilelist.append(file)
        del argsin
    if h5 == 'choose':
        h5file=fd.fileopen(message='Choose a Summary Table...',
        filters='*.h5', # for the wxfiledialog
        defaultDir=defaultDir)
        h5table = HDF5saver(filename=h5file[0], testtype='EQ')
    elif h5 == 'default':
        h5table = HDF5saver(testtype='EQ')
    else:
        h5table = HDF5saver(filename=h5, testtype='EQ')
for infile in infilelist:
    testobj = SoilTest(infile=infile, loadcorr=loadcorr,
    loadcorr_type=loadcorr_type,
    testtype='EQ',
    cycletype=cycletype,
    strainfailval=strainfailval,
    rufailval=rufailval
    #**kwargs
    )
    if testobj.Error:
```

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pass
else:
    h5table.input(testobj)
del testobj
if h5plot:
    h5table.plot()
h5table.close()

def runsummary(**kwargs):
    '''
    Opens results files and plots everything
    '''
    filters = 'HDF5 (*.h5)' # for qtdialog
    # filters = 'HDF5 |*.h5' # for wxdialog
    if os.name == 'posix':
        defaultDir=(u'/media/Storage/Documents/Python'+'/GCTS/ConstantVolume')
    else:
        defaultDir=''n
    if os.path.exists(kwargs.get('h5table', 'SummaryResults.h5')):
        h5table = HDF5saver(filename=kwargs.get('h5table', './SummaryResults.h5'))
    else:
        h5file=fd.fileopen(message='Choose a Summary Table...', filters=filters,
                           defaultDir=defaultDir)
        h5table = HDF5saver(filename=h5file[0],**kwargs)
        h5table.plot(**kwargs)
        h5table.close()

def delete(**kwargs):
    '''
    Will delete test results from a .h5 file.
    '''
    filters = 'HDF5 (*.h5)' # for qtdialog
    # filters = 'HDF5 |*.h5' # for wxdialog
    if os.name == 'posix':
        defaultDir=(u'/media/Storage/Documents/Python'+'/GCTS/ConstantVolume')
    else:
        defaultDir=''n
    if os.path.exists(kwargs.get('h5table','SummaryResults.h5')):
        h5table = HDF5saver(filename=kwargs.get('h5table', './SummaryResults.h5'))
    else:
        h5file=fd.fileopen(message='Choose a Summary Table...', filters=filters,
                           defaultDir=defaultDir)
        h5table = HDF5saver(filename=h5file[0],**kwargs)
        h5table.delete(**kwargs)
        h5table.close()

def selector():
    '''
    What would you like to do today?
    '''
x = None

while x not in [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]:
    print('Run Options:
  1. Select a GCTS soil output
    
  2. Select a GCTS soil output and choose .h5 file
    
  3. Select GCTS EQ motions
    
  4. Select a GCTS water output
    
  5. Select a GCTS Surcharge Friction Test
    
  6. Plot all data
    
  7. Import all data and go to a prompt
    
  8. Choose a data table and go to a prompt
    
  9. Select a strain-controlled test
    
  10. Delete some test results
    
  11. Plot \'PaperFigs\'\n    
  12. Quit'

selection = raw_input('Please make a selection: ').split()
try:
    x = int(selection[0])
except IndexError:
    x = None
if x == 1:
    runsoil(h5file='default')
elif x == 2:
    runsoil(h5file='choose')
elif x == 3:
    runEQ()
elif x == 4:
    runwater()
elif x == 5:
    runwater(surcharge=True)
elif x == 6:
    runsummary()
elif x == 7:
    dataprompt()
elif x == 8:
    dataprompt2()
elif x == 9:
    runsoil(strain=True, cycletype='ru')
elif x == 10:
    delete()
elif x == 11:
    runsoil('./Sine/2014-11-21-3-dss.csv', h5file='default',
            PaperFigs=True, h5plot=False, cycletype='strainSA',
            strainfailval='03', loadcorr=False)
elif x == 12:
    break
else:
    print('I didn\'t understand you.')
J.9 Data Reduction of Seismic Compression Lab Data

The file gcts_sc.py takes the output files from CSS seismic compression tests on the GCTS equipment and reduces the data.
def rn2(x,a,b):
    return x ** (a + 1. / (b * x))

def curvPL(x, a, b):
    return x ** (a + b * x)

def curv_power(x, a, b, c):
    return x ** (a + b * x + c + x ** 2)

def curv_power2(x, a, b):
    return x ** (1 + a + b * x)

class asymptotecons(object):
    def __init__(self, **kwargs):
        self.b = kwargs.get('b')

def asymptote(x, a, c):
    y = a / x ** c + self.b
    return y

def power_asymp (x, a, c):
    y = x ** (a / x ** c + self.b)
    return y

def power_asymp (x, a, b, c):
    y = x ** (a / x ** c + b)
    return y

def asymptote(x, a, b, c):
    return a / x ** c + b

def asymptote3(x, b, c):
    return 0.1 / x ** c + b

def asymptote4(x, b):
    return 0.1 / x ** b + b

def asymptote5(x, a, b):
    return a / x ** b + b

def asymptote2(x, a, b):
    return a / (x ** b * (x - 1)) + b

def ellipse(x, a, b):
    return np.sqrt(b**2 - b**2 * (x - a)**2 / a**2)

def exp_cutoff(x,a,b):
    return x ** a * np.exp(b * x)

def power(x,a,b):
    return a * x ** b

class SumTable(pt.IsDescription):
    '''
    Format of output PyTable
    '''

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>104</td>
<td>File = pt.StringCol(itemsize=16,pos=1)</td>
</tr>
<tr>
<td>105</td>
<td>e_0 = pt.Float32Col(pos=2)</td>
</tr>
<tr>
<td>106</td>
<td>e_1 = pt.Float32Col(pos=3)</td>
</tr>
<tr>
<td>107</td>
<td>Dr = pt.Float32Col(pos=4)</td>
</tr>
<tr>
<td>108</td>
<td>gam = pt.Float32Col(pos=5)</td>
</tr>
<tr>
<td>109</td>
<td>Nlim = pt.Float32Col(pos=6)</td>
</tr>
<tr>
<td>110</td>
<td>r0 = pt.Float32Col(pos=7)</td>
</tr>
<tr>
<td>111</td>
<td>s0 = pt.Float32Col(pos=8)</td>
</tr>
<tr>
<td>112</td>
<td>t0 = pt.Float32Col(pos=9)</td>
</tr>
<tr>
<td>113</td>
<td>r1 = pt.Float32Col(pos=10)</td>
</tr>
<tr>
<td>114</td>
<td>s1 = pt.Float32Col(pos=11)</td>
</tr>
<tr>
<td>115</td>
<td>t1 = pt.Float32Col(pos=12)</td>
</tr>
<tr>
<td>116</td>
<td>Gs = pt.Float32Col(pos=13)</td>
</tr>
<tr>
<td>117</td>
<td>mass = pt.Float32Col(pos=14)</td>
</tr>
<tr>
<td>118</td>
<td>Hcyc1 = pt.Float32Col(pos=15)</td>
</tr>
<tr>
<td>119</td>
<td>di = pt.Float32Col(pos=16)</td>
</tr>
<tr>
<td>120</td>
<td>emin = pt.Float32Col(pos=17)</td>
</tr>
<tr>
<td>121</td>
<td>emax = pt.Float32Col(pos=18)</td>
</tr>
<tr>
<td>122</td>
<td>sigv_nom = pt.Float32Col(pos=19)</td>
</tr>
<tr>
<td>123</td>
<td>Dr_nom = pt.Float32Col(pos=20)</td>
</tr>
<tr>
<td>124</td>
<td>mass_ass = pt.Float32Col(pos=21)</td>
</tr>
<tr>
<td>125</td>
<td>Modified = pt.StringCol(itemsize=32,pos=22)</td>
</tr>
<tr>
<td>126</td>
<td>Date_of_Test = pt.Int64Col(pos=23)</td>
</tr>
<tr>
<td>127</td>
<td>Filepath = pt.StringCol(itemsize=128,pos=24)</td>
</tr>
<tr>
<td>128</td>
<td>rpow = pt.Float32Col(pos=25)</td>
</tr>
<tr>
<td>129</td>
<td>apow = pt.Float32Col(pos=26)</td>
</tr>
<tr>
<td>130</td>
<td>rmean = pt.Float32Col(pos=27)</td>
</tr>
<tr>
<td>131</td>
<td>aa = pt.Float32Col(pos=28)</td>
</tr>
<tr>
<td>132</td>
<td>ac = pt.Float32Col(pos=29)</td>
</tr>
<tr>
<td>133</td>
<td>DW_1 = pt.Float32Col(pos=30)</td>
</tr>
<tr>
<td>134</td>
<td>C1 = pt.Float32Col(pos=31)</td>
</tr>
<tr>
<td>135</td>
<td>C2 = pt.Float32Col(pos=32)</td>
</tr>
<tr>
<td>136</td>
<td>rn2_a = pt.Float32Col(pos=33)</td>
</tr>
<tr>
<td>137</td>
<td>rn2_b = pt.Float32Col(pos=34)</td>
</tr>
<tr>
<td>138</td>
<td>mu = pt.Float32Col(pos=35)</td>
</tr>
<tr>
<td>139</td>
<td>sig = pt.Float32Col(pos=36)</td>
</tr>
<tr>
<td>140</td>
<td>ncycles = pt.Float32Col(shape=(10,1),pos=37)</td>
</tr>
</tbody>
</table>

```python
class EQSumTable(pt.IsDescription):
    Format of output PyTable
    File = pt.StringCol(itemsize=128,pos=1)
    Modified = pt.StringCol(itemsize=32,pos=2)
    sigv = pt.Float32Col(pos=3)
    Ar = pt.Float32Col(pos=4)
    MaxSStrain = pt.Float32Col(pos=5)
    MaxNStrain = pt.Float32Col(pos=6)
    Duration = pt.Float32Col(pos=7)
    Dr = pt.Float32Col(pos=8)
    PPresid = pt.Float32Col(pos=9)
    PPerr = pt.Float32Col(pos=10)
    ZCresid = pt.Float32Col(pos=11)
    ZC = pt.Float32Col(pos=12)
    RFresid = pt.Float32Col(pos=13)
```
RFpererr = pt.Float32Col(pos=14)
bPresid = pt.Float32Col(pos=15)
bPPpererr = pt.Float32Col(pos=16)
bZCresid = pt.Float32Col(pos=17)
bZCpererr = pt.Float32Col(pos=18)
bRPresid = pt.Float32Col(pos=19)
bRFpererr = pt.Float32Col(pos=20)
1PPresid = pt.Float32Col(pos=21)
1PPpererr = pt.Float32Col(pos=22)
1ZCresid = pt.Float32Col(pos=23)
1ZCpererr = pt.Float32Col(pos=24)
1RFresid = pt.Float32Col(pos=25)
1RFpererr = pt.Float32Col(pos=26)
MotionType = pt.StringCol(itemsize=32,pos=27)
DissEn = pt.Float32Col(pos=28)
Damage = pt.Float32Col(pos=29)
Date_of_Test = pt.Int64Col(pos=30)
Filepath = pt.StringCol(itemsize=128,pos=31)
steptype = pt.StringCol(itemsize=2,pos=32)

def calcRmsAccel(motion, dt, **kwargs):
    '''
    Calculates the rms acceleration.
    
    Keyword Arguments:
    duration  5to95 [default] Uses the duration from 5-95% of
    the area under the motion squared
    total     Uses the entire time of the input motion
    '''
    motion = np.ravel(motion)
durationtype = kwargs.get('duration','5to95')
NPTS = len(motion)
time = np.linspace(0,(NPTS-1) * dt,NPTS)
asqr = np.cumsum(motion ** 2) * dt

    if durationtype == '5to95':
        int1 = interp1d( asqr, time, 
                        kind='linear')
        T = int1(0.95 * asqr[-1]) - int1(0.05 * asqr[-1])
    else:
        T = time[-1]
    return np.sqrt(asqr[-1] / T)

def datetimeconvert(datestr,timestr):
    try:
        date = dt.datetime.strptime(datestr+timestr,
                     '%m/%d/%y%H:%M:%S')
    except ValueError:
        date = dt.datetime.strptime(datestr+timestr,
                     '%m/%d/%Y%H:%M:%S')
    return int(date.strftime('%y%m%d%H%M%S'))
```python
def unit_lookup(header1, header2, Label):
    '''
    Returns the unit of a given variable (Label).
    header1 is an array of labels: Shear Load, Shear Displacement, etc
    header2 is an array of units corresponding to the labels: kN, mm, etc
    Label is label for which a unit is desired.
    '''
    for i, label in enumerate(header1):
        if Label == label:
            return header2[i]
        break

class RichNewInc(object):
    '''
    Calculates the value of volumetric strain using Richart-Newmark Hypo.
    Returns not the increment, but the next value of volumetric strain.
    It is assumed that each shear strain is one half cycle.
    '''
    def __init__(self, Cycles, Amp, **kwargs):
        self.name = kwargs.get('name')
        self.Dr = kwargs.get('Dr')
        self.sigv = kwargs.get('sigv', 100.)
        self.rtype = kwargs.get('rtype', 'asymptotic')
        self.Amp = Amp
        self.threshold = kwargs.get('threshold', 0.0002)
        self.rcalctype = kwargs.get('rcalctype', 'every')
        self.Cyc = Cycles
        self.Ncalc = kwargs.get('Ncalc', None)
        if self.Ncalc == None:
            self.Ncalc = Ncycles()
        self.N = np.exp(self.Ncalc(0.01, np.log(self.Amp), self.sigv/101.325, self.Dr))
        self.D = np.zeros(Amp.shape, dtype=float)
        self.i = -1
        self.R = np.cumsum(self.Ratio)
        #self.calcr(ToState=True)

def calcr(self, **kwargs):
    '''
    calculates r where D = R^r.
    '''
    Amp = kwargs.get('Amp', self.Amp)
    Dr = kwargs.get('Dr', self.Dr)
    sigv = kwargs.get('sigv', self.sigv)
    R = kwargs.get('R', self.R)
    ToState = kwargs.get('ToState', False)
    if self.rtype == 'quadratic':
        Rlim = np.min((R, 1.2*np.ones(R.shape)), axis=0)
        r0 = (0.3606 - 0.00257 * Dr + 61.1 * Amp - 0.0004098 * sigv)
        if np.isscalar(Amp):
            if r0 < 0.045:
                r0 = 0.045
            elif r0 > 1.:
r0 = 1.
else:
r0[r0<0.045] = 0.045 # Limited here!!
r = (r0 - r0**2 * Rlim + r0 ** 4 * Rlim ** 2)
if ToState:
    self.r0 = r0
elif self.rtype == 'mean':
r = (1.811 - 0.0003387 * sigv - 0.002351 * Dr +
    0.2253 * np.log(Amp))
r = np.max((0.2*np.ones(Amp.shape),r),axis=0)
elif self.rtype == 'asymptotic':
a = 0.1 #* np.ones(Amp.shape, dtype=float)
b = (0.2380 - 0.00202 * Dr + 35.234 * Amp -
    0.0603 * sigv / 101.325 + 7.09347 * Amp *
    sigv /101.325)
if b > 1.:
b = 1.
    #print('b = 1')
if b < 0 :
    #print('b = 0')
    b = 0.
    #pdb.set_trace()
c = b
r = a / R ** c + b
if ToState:
    self.a, self.b, self.c = a*np.ones(self.N.shape), b, c
# Limit r
#r = np.min((np.ones(r.shape, dtype=float),r),axis=0)
if ToState:
    self.r = r
else:
    return r

def __call__(self, **kwargs):
    '''
    This is an iterator-type function.
    Calculates next value of SC for next time step
    '''
    returns = kwargs.get('returns', True)
    self.i += 1
    j = self.i
    if self.Amp[j] < self.threshold:
    else:
        if j == 0:
            r = self.calcr(R=self.R[j], Amp=self.Amp[j])# self.r[j]
        else:
            r = self.calcr(R=self.R[j], Amp=self.Amp[j])# self.r[j]
        if self.rcalctype == 'every':
            R = self.R[j]
            r2 = self.calcr(R=R, Amp=self.Amp[j])
            count = 0
            R2 = self.D[j-1] ** ( 1/ r2) + self.Ratio[j]
            #while np.abs(R2 - R)/R > 0.001:
```python
#count += 1
#R = R2
#r2 = self.calcr(R=R, Amp=self.Amp[j])
#R2 = self.D[j-1]**(1/r2) + self.Ratio[j]

while (np.abs(r - r2) / r) > 0.01:
    count += 1
    R = self.D[j-1]**(1/(r2)) + self.Ratio[j]
    r = r2
    r2 = self.calcr(R=R, Amp=self.Amp[j])
    if count > 100:
        if self.Amp[j] < 5e-5:
            break
        else:
            pdb.set_trace()
    #print('Took avg r')
    #r = (r + r2) / 2.
    r = r2

if returns:
    return self.D[self.i]

def run(self):
    '''
    This just runs thru all the calls
    '''
    for val in self.Amp:
        self.__call__(returns=False)

def totalVolStrain(self):
    '''
    This returns the final value of volumetric strain only.
    '''
    self.run()
    if self.D[-1] == np.inf:
        pdb.set_trace()
    return self.D[-1] * 0.01

def calcNeq(self, **kwargs):
    threshold = kwargs.get('threshold', self.threshold)
    gameff = kwargs.get('gameff', np.max(np.abs(self.Amp)) * 0.65)
    self.gamNeq = gameff
    if gameff < threshold:
        return np.inf
    else:
        N = np.exp(self.Ncalc(0.01, np.log(gameff), self.sigv/101.325, self.Dr))
        finalD = self.D[-1]
        if finalD == 0:
            self.run()
        finalD = self.D[-1]

        # Iterative section: Guess an R
        R = finalD ** (1/0.3)
        r = self.calcr(R=R, Amp=gameff)
        R2 = finalD ** (1 / r)
        count = 0
```

while np.abs(R-R2)/R2 > 0.01:
    count += 1
    R = R2
    r = self.calcr(R=R, Amp=gameff)
    R2 = finalD ** (1 / r)
    if count > 100:
        if np.abs(R-R2)/R2 < 0.1:
            break
        if np.abs(R-R2) < 0.1:
            break
    return -2000
self.Neq = R * N
return self.Neq

class LineAcc(object):
    
    Calculates the value of volumetric strain assuming a linear accumulation
    of damage (Palmgren-Miner).
    Returns not the increment, but the next value of damage.
    To obtain the shear strain, multiply by the value of ev.
    
    def __init__(self, Cycles, Amp, **kwargs):
        self.name = kwargs.get('name')
        #self.Ntype = kwargs.get('Ntype',0.01)
        self.Dr = kwargs.get('Dr')
        self.sigv = kwargs.get('sigv', 100.)
        self.threshold = kwargs.get('threshold', 0.0002)
        self.Amp = np.max([Amp, np.ones(Amp.shape)*0.000], axis=0)
        self.Cyc = Cycles
        self.Ncalc = kwargs.get('Ncalc')
        self.ev = kwargs.get('ev',0.01)
        self._R = Cycles / self.N
        self.D = np.cumsum(self._R)
        self.i = -1

    def __call__(self, **kwargs):
        
        This is an iterator function.
        
        returns = kwargs.get('returns', True)
        self.i += 1
        if returns:
            return self.D[self.i]

    def calcNeq(self, **kwargs):
        
        Calculates Equiv Number of Cycles
        
        evtotal = kwargs.get('evtotal', self.D[-1])
        gameff = kwargs.get('gameff', 0.65 * np.max(np.abs(self.Amp)))
        evN = kwargs.get('ev', self.ev)
        if gameff < self.threshold:
self.Neq = np.inf
return np.inf
else:
    N = np.exp(self.Ncalc(evN, np.log(gameff), self.sigv/101.325, self.Dr))

self.Neq = evtotal * N / evN
return self.Neq
def ByrneNeq(EvTarget, gam, Dr, **kwargs):
    
    Calculates the number of equivalent cycles using Byrne’s model.
    
    threshold = kwargs.get('threshold', 0.0002)
    original = kwargs.get('original', True)
    sigv = kwargs.get('sigv', 100.)
    cyclelimit = kwargs.get('cyclelimit', 3000)
    Ev = 0.
    cyclecount = 0.
    while Ev < EvTarget:
        cyclecount += 0.5
        Ev = ByrneIncrem(Ev, gam, Dr=Dr, cycles=0.5, sigv=sigv, threshold=threshold, original=original)
        if cyclecount > cyclelimit:
            break

    return cyclecount
def ByrneIncAll(gam, Dr, **kwargs):
    
    Does the same as ByrneIncrem, but all at once.
    
    cyc = kwargs.get('cycles', 0.5 * np.ones(gam.shape))
    threshold = kwargs.get('threshold', 0.0002)
    original = kwargs.get('original', True)
    sigv = kwargs.get('sigv', 100.)
    Ev = np.zeros(gam.shape)
    for i, amp in enumerate(gam):
        Ev[i] = ByrneIncrem(Ev[i-1], amp, Dr=Dr, cycles=cyc[i], sigv=sigv, threshold=threshold, original=original)

    return Ev
def ByrneIncrem(Evprev, gam, **kwargs):
    
    Calculates the value of volumetric strain using Byrne’s method (1991).
Returns not the increment, but the next value of volumetric strain.

It is assumed that each shear strain is one half cycle.

Make sure your Ev previous and gam are the same units.

```python
Dr = kwargs.get('Dr')
sigv = kwargs.get('sigv', 100.)
cyc = kwargs.get('cycles', 0.5)
threshold = kwargs.get('threshold', 0.0002)
```

```python
# if cyc != 0.5:
#     pdb.set_trace()
if kwargs.get('original', True):
    c1 = 7600 * Dr ** -2.5
    c2 = 0.4 / c1
else:
    c1 = 0.456 - 67.17 * gam + 0.005046 * Dr + 0.001413 * sigv
    c2 = -0.6306 + 101.521 * gam + 0.0207865 * Dr + 0.7257 * c1
if gam < threshold:
    Evinc = 0
else:
    gam = gam - threshold
    # This is what Byrne does; see eq. 17
    # The above gives better results and is what Byrne did,
    # but it is inconsistent with the way I have calibrated the model.
    passes = int(cyc / 0.5)
    i = 0
    Evp = Evprev
    while i < passes:
        i += 1
        Evinc = 0.5 * gam * c1 * np.exp(-c2 * Evp / gam)
        Evp = Evinc + Evp
        Evinc = Evp - Evprev
    return Evinc + Evprev
```

```python
class HDF5saver(object):
    '''
    This object will save the data to a pytable HDF5 file.
    '''
    def __init__(self,**kwargs):
        testtype = kwargs.get('testtype','sine')
        testtype = kwars.get('testtype','sine')
        filename = kwars.get('filename','SummaryResults.h5')
        # Check to see if the output table exist, if not, create it.
        self.outfile = pt.openFile(filename,mode='a',
                                   title='Cyclic Compression Lab Testing Results')
        # Check if the internal summary table exists
        if self.outfile.__contains__('/Summary'):
            self.summtabale = self.outfile.root.Summary
        else:
            self.summtabale = self.outfile.createTable('/', 'Summary',
                                                      SumTable)
        else:
            filename = kwars.get('filename','EQSummary.h5')
            # Check to see if the output table exist, if not, create it.
            self.outfile = pt.openFile(filename,mode='w', # notice how I am deleting the
                                        previous table.
            title='EQ Motion Testing Results')
```

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# Check if the internal summary table exists
if self.outfile.__contains__('/EQSummary'):
    self.summtable = self.outfile.root.EQSummary
else:
    self.summtable = self.outfile.createTable('/',
                                          'EQSummary',
                                          EQSumTable)

self.testtype = testtype

def input(self, ResultObj, **kwargs):
    
    # Check to see if an entry already exists
    name = ResultObj.infile
    name = str(os.path.basename(name))
    if self.testtype == 'sine':
        name = str(path.basename(name))
        if self.outfile.__contains__('/EQSummary'):
            self.delete(name)
        entry = self.summtable.row
        entry['File'] = name
        entry['e_0'] = ResultObj.e_0
        entry['e_1'] = ResultObj.e_1
        entry['Dr'] = ResultObj.Dr
        entry['gam'] = ResultObj.gam
        entry['Nlim'] = ResultObj.Nlim
        if ResultObj.Nlim < 4:
            entry['r0'] = np.nan
            entry['r1'] = np.nan
            entry['t0'] = np.nan
            entry['t1'] = np.nan
            entry['rpow'] = np.nan
            entry['apow'] = np.nan
            entry['rmean'] = np.nan
            entry['aa'] = np.nan
            entry['ab'] = np.nan
            entry['ac'] = np.nan
            if ResultObj.lognorm:
                entry['mu'] = np.nan
                entry['sig'] = np.nan
                entry['rn2_a'] = np.nan
                entry['rn2_b'] = np.nan
            else:
                entry['r0'] = ResultObj.r0
                entry['s0'] = ResultObj.s0
                entry['t0'] = ResultObj.t0
                entry['r1'] = ResultObj.r1
                entry['s1'] = ResultObj.s1
                entry['t1'] = ResultObj.t1
                entry['rpow'] = ResultObj.rpow
                entry['apow'] = ResultObj.apow
                entry['rmean'] = ResultObj.rmean
                entry['aa'] = ResultObj.aa
                entry['ab'] = ResultObj.ab
                entry['ac'] = ResultObj.ac

    else:
        entry['r0'] = ResultObj.r0
        entry['s0'] = ResultObj.s0
        entry['t0'] = ResultObj.t0
        entry['r1'] = ResultObj.r1
        entry['s1'] = ResultObj.s1
        entry['t1'] = ResultObj.t1
        entry['rpow'] = ResultObj.rpow
        entry['apow'] = ResultObj.apow
        entry['rmean'] = ResultObj.rmean
        entry['aa'] = ResultObj.aa
        entry['ab'] = ResultObj.ab
        entry['ac'] = ResultObj.ac
if ResultObj.lognorm:
    entry['mu'] = ResultObj.mu
    entry['sig'] = ResultObj.sig
    entry['rn2_a'] = ResultObj.rn2_a
    entry['rn2_b'] = ResultObj.rn2_b
    entry['Gs'] = ResultObj.Gs
    entry['mass'] = ResultObj.mass
    entry['Hcyc1'] = ResultObj.Hcyc1
    entry['di'] = ResultObj.di
    entry['emin'] = ResultObj.emin
    entry['emax'] = ResultObj.emax
    entry['sigv_nom'] = ResultObj.sigv_nom
    entry['Dr_nom'] = ResultObj.Dr_nom
    entry['mass_ass'] = ResultObj.mass_ass
    entry['Modified'] = strftime("%Y-%m-%d %H:%M:%S")
    entry['Date_of_Test'] = ResultObj.date_of_test
    entry['Filepath'] = infile
    entry['DW_1'] = np.mean(ResultObj.cyc['DE'].values[-50:] / ResultObj.cyc['Cycles'].values[-50:])
else:
    entry = self.summtable.row
    entry['File'] = name
    entry['sigv'] = ResultObj.sigv
    entry['Ar'] = ResultObj.Ar
    entry['MaxSStrain'] = ResultObj.MaxSStrain
    entry['MaxNStrain'] = ResultObj.MaxNStrain
    entry['Duration'] = ResultObj.Duration
    entry['Dr'] = ResultObj.Dr
    entry['PPresid'] = ResultObj.resid[0]
    entry['PPpererr'] = ResultObj.perError[0]
    entry['ZCresid'] = ResultObj.resid[1]
    entry['ZCpererr'] = ResultObj.perError[1]
    entry['RFresid'] = ResultObj.resid[2]
    entry['RFpererr'] = ResultObj.perError[2]
if ResultObj.byrne:
    entry['bPPresid'] = ResultObj.bresid[0]
    entry['bPPpererr'] = ResultObj.bperError[0]
    entry['bZCresid'] = ResultObj.bresid[1]
    entry['bZCpererr'] = ResultObj.bperError[1]
    entry['bRFresid'] = ResultObj.bresid[2]
    entry['bRFpererr'] = ResultObj.bperError[2]
if ResultObj.linear:
    entry['lPPresid'] = ResultObj.lresid[0]
    entry['lPPpererr'] = ResultObj.lperError[0]
    entry['lZCresid'] = ResultObj.lresid[1]
    entry['lZCpererr'] = ResultObj.lperError[1]
    entry['lRFresid'] = ResultObj.lresid[2]
    entry['lRFpererr'] = ResultObj.lperError[2]
    entry['MotionType'] = ResultObj.MotType
entry['DissEn'] = ResultObj.cyc['DE'].values[-1]
entry['Damage'] = ResultObj.cyc['Dam'].values[-1]
entry['Date_of_Test'] = ResultObj.date_of_test
entry['Filepath'] = infile
entry['steptype'] = ResultObj.steptype

entry.append()
self.summtable.flush()

def read(self):
    '''
    Reads in the result of the Summary Table.
    '''
    results = self.summtable.read()
    return results

def delete(self,*arg,**kwargs):
    '''
    Deletes an entry from an H5 Table.
    '''
    filters = 'csv (*.csv)' # for qtfiledialog
    # filters = 'csv |*.csv' # for wxfiledialog
    returns = kwargs.get('returns',False)
    infilelist = []
    if len(arg) == 0:
        filelist=fd.fileopen(
            message='Select the files you want to remove from the table:',
            filters=filters,
            defaultDir=(u'/media/Storage/Documents/Python' +
            '/GCTS/ConstantVolume'))
        print('Files to remove from {}:'.format(self.filename))

        for file1 in filelist:
            infilelist.append(file1)
            print(file1 + '
')
        del filelist
        print('
')

        selection = raw_input('Are you sure you want to remove these ' +
            'files from "{}"? [y]/n: '.format(self.filename))

        if selection.lower() == 'n':
            return
        elif selection.lower() == 'y':
            pass
        elif selection == '':
            pass
        else:
            return
    else:
        for val in arg:
            infilelist.append(val)

    rowdata = []
    for name in infilelist:
        name = str(os.path.basename(name)).split('.') #
        try:
            row1 = self.summtable.getWhereList('File == name')
except NameError:
    row1 = self.summtable.get_where_list('File == name')
except AttributeError:
    pdb.set_trace()
if len(row1) == 0:
    pass
else:
    for i, val in enumerate(row1):
        if kwargs.get('returns') == True:
            rowdata.append(self.summtable.read(val, val+1))
        try:
            self.summtable.remove_row(val)
        except NameError:
            self.summtable.removeRows(val-i)
        except IndexError, NotImplementedError:
            pdb.set_trace()
if returns == True:
    return rowdata

def plot(self, **kwargs):
    interval = kwargs.get('interval', 24.)
    from mpl_toolkits.mplot3d import Axes3D
    gam = self.summtable.read(field='gam')
    Dr = self.summtable.read(field='Dr')
    Nlim = self.summtable.read(field='Nlim')
    sigv_nom = self.summtable.read(field='sigv_nom')
    C1 = self.summtable.read(field='C1')
    C2 = self.summtable.read(field='C2')
    C2C1 = C2 * C1
    rn2_a = self.summtable.read(field='rn2_a')
    rn2_b = self.summtable.read(field='rn2_b')
    Date = self.summtable.read(field='Modified')
    fig = plt.figure(1)
    # ax = fig.add_subplot(111, projection='3d')
    ax = fig.gca(projection='3d')
    ax.scatter(gam, Dr, zs=C1, marker='o', s=75, c=sigv_nom, cmap='spectral',
               alpha=1, edgecolors='none',)
    # ax.scatter(CSR[ind2], Dr[ind2], zs=np.log10(N[ind2]), facecolor='r')
    ax.set_zlabel(r'$C_1$')
    ax.set_ylabel('Dr (%)')
    ax.set_xlabel('$\gamma$')
    c1 = 0.456 - 67.17 * X + 0.005046 * Y + 0.001413 * 100
    X, Y = np.linspace(28, 120, num=10)
    x = X, Y = np.meshgrid(X, Y)
    c1 = 0.456 - 67.17 * X + 0.005046 * Y + 0.001413 * 100
    ax.plot_surface(X, Y, c1, rstride=1, cstride=1, cmap='coolwarm',
                    linewidth=0, antialiased=False)
fig = plt.figure(2)
ax = fig.add_subplot(111, projection='3d')
ax.scatter(gam, Dr, zs=C2, marker='o', s=75, c=sigv_nom, cmap='spectral',
           alpha=1, edgecolors='none',
           # ax.scatter(CSR[ind2], Dr[ind2], zs=np.log10(N[ind2]), facecolor='r')
ax.set_zlabel(r'$C_2$')
ax.set_ylabel('Dr (%)')
ax.set_xlabel('$\gamma$')
c2 = -0.6306 + 101.521 * X + 0.0207865 * Y + 0.7257 * c1
self.MotType = re.search('Dr{}\\(.+?)\\'.format(self.Dr_nom), infile).group(1)

    except AttributeError:
        print('AttributeError!!!!')

    self.limEvstrain = kwargs.get('limEvstrain',0.01)
    self.byrne = kwars.get('byrne',True)
    self.lognorm = kwars.get('lognorm', True)
    self.linear = kwars.get('linear', True)
    self.emin = kwars.get('emin',0.68)
    self.emax = kwars.get('emax',0.9)
    self.verbose = kwars.get('verbose',True)

    if 'infile' == None:
        infile = raw_input('Nothing to do. Specify an input file:')
        self.csvimport(infile)
    else:
        self.csvimport(infile)
        self.infile = infile
        self.Drcorr()
        self.calcs()
        self.DamagePred()
        # self.dissen(verbose=True)
        # self.plotter()

    def csvimport(self, infile):
        '''
        This function pulls in the data from the GCTS output file.
        The GCTS file should not have the data separated into stages.
        '''
        self.data=[]
        self.label=[]
        self.name=[]
        self.Gs=[]
        self.mass=[]
        self.cyc_header=[]
        self.pist_area=[]
        testtime = None
        footer = []
        datasection=0
dimsec=0
datafile = csv.reader(open(infile,'rU'))
rowcount = -1
header = None
Volume = None
for row in datafile:
    rowcount ++ 1
    if datasection == 0:
        if self.Gs:
            pass
        elif 'Specific Gravity: ' in row:
            self.Gs=float(row[1])
self.Gs = 2.66  # Because sometimes I forget to change the value in the GCTS software

if self.name:
    pass
elif 'Specimen: ' in row:
    self.name = row[1]

if self.mass:
    pass
elif 'Dry Mass of Specimen: ' in row:
    self.mass = float(row[1]); self.mass_unit = row[2]
    if self.mass == 0:
        self.mass = float(input('Input the dry mass (g) for specimen %s:' % self.name))
elif 'Moist Mass of Specimen: ' in row:
    self.mass = float(row[1]); self.mass_unit = row[2]
    if self.mass == 0:
        self.mass = float(input('Input the dry mass (g) for specimen %s:' % self.name))

if 'Type: ' and 'Universal' in row:
    dimsec = 1
if 'Starting Date: ' in row:
    testdate = row[1]
if 'Starting Time: ' in row:
    testtime = row[1]

if dimsec == 1:
    if 'Height: ' in row:
        self.hi = float(row[3]) * 25.4
        if row[4] == '(mm)'
            pass
        else:
            self.hi = self.hi * 25.4
            self.hi_unit = 'mm'  # Convert to mm
    if 'Diameter: ' in row:
        self.di = float(row[3]) * 25.4
        if row[4] == '(mm)'
            pass
        else:
            self.di = self.di * 25.4
            self.di_unit = 'mm'  # Convert to mm
    self.area = (self.di / 2) ** 2 * np.pi  # in mm^2

if 'Volume: ' in row:
    Volume = row[3]
dimsec = 0

if len(row) >= 17:
    if header == None:
        if Volume != None:
            datasection = 1
        if row[0] == 'Time':
            header = rowcount
            self.headerlabel = row

        if row[0] == 'sec':
            self.units = row

        if datasection == 1:
            if row[0][-14:] == 'Static Loading':
                footer = rowcount
if footer == []:
    df = pd.read_csv(infile, names=self.headerlabel, skiprows=header+3)
else:
    df = pd.read_csv(infile, names=self.headerlabel, skiprows=header+3, nrows=footer - header - 4)
    df = df.convert_objects(convert_numeric=True)
select = df.apply(lambda r: any((isinstance(e, basestring) for e in r)), axis=1)
df = df[~select]
df = df.dropna()

# Fix the time values
ind = np.where(time[1:] < time[:-1])
for i, val in enumerate(ind[0]):
    if val == ind[0][-1]:
        time[val+1:] += time[val]
    else:
        time[val+1:ind[0][i+1]+1] += time[val]
df['Time'] = time

# Create a new dataframe that contains only the cyclic portion
try:
    x = df['Shear Load'] * 2.
except KeyError:
    df['Shear Load'] = df['Internal Shear Load']
try:
    self.cyc = df[columns].reset_index(drop=True)
except KeyError:
    raise KeyError
self.date_of_test = datetimeconvert(testdate, testtime)

def calcs(self, **kwargs):
    ...
    EQTest
    This does the heavy lifting.
    ...
    # Calculate the volumes
    self.Vcyc_T1 = self.Hcyc1 * self.area  # in mm^2
    if self.Gs == 2.65:
        pass
    else:
        Gs = self.Gs
        self.Gs = 2.65
        print('Changed Gs from {} to 2.65'.format(Gs))
    try:
        self.Vcyc_s = self.mass / (self.Gs * 0.001)  # in mm^3 where density of water is 0.001 g/mm^3
    except TypeError:
        self.Vcyc_s = self.mass_ass / (self.Gs * 0.001)  # in mm^3 where density of water is 0.001 g/mm^3
self.mass = self.mass_ass

print('Assuming a mass of {}g'.format(self.mass_ass))

nLVDT = (self.cyc['Internal Normal LVDT'].values - self.cyc['Internal Normal LVDT'].values[0])

self.cyc['Volume'] = self.Vcyc_T1 - nLVDT * self.area
self.cyc['Vol voids'] = self.cyc['Volume'] - self.Vcyc_s

# Calc e
self.cyc['e'] = self.cyc['Vol voids'] / self.Vcyc_s
self.e_0 = self.cyc['e'].values[0]
self.e_1 = 0.99 * self.cyc['Vol voids'].values[0] / self.Vcyc_s - 0.01

self.Dr = (self.emax-self.e_0)/(self.emax-self.emin)*100

#Calc changes in volume, damage, cycle ratio
self.cyc['DeltaV'] = (self.Vcyc_T1 - self.cyc['Volume']) / self.Vcyc_T1
self.cyc['Dam'] = self.cyc['DeltaV'] / self.limEvstrain
self.dt = np.mean(np.diff(self.cyc['Time'].values))
self.Ar = self.calcAr(self.SStrain,self.dt)

self.sigv = (np.mean(self.cyc['Normal Load'].values / self.area) * 10**6) # to convert from mm^2 to m^2 to get kPa

self.MaxSStrain = np.max(self.SStrain)
ind5 = np.where(np.abs(self.SStrain) > 0.0005) # set this as needed for duration
self.Duration = (self.cyc['Time'].values[ind5][-1] - self.cyc['Time'].values[ind5][0])

if self.MotType == 'Step loadin':  # threshold = kwargs.get('threshold', 0.0002)
    threshold = kwargs.get('threshold', 0.000)
    Load = cc.Load(self.SStrain, dt=self.dt)
    Amps = [Load.PP_Amp, Load.ZC_Amp, Load.RF_Amp]
    Ncalc = Ncycles()
    Cycs = [Load.PP_Cyc, Load.ZC_Cyc, Load.RF_Cyc]
    Times = [Load.PP_time, Load.ZC_time, Load.RF_time]
    colors = ['rs', 'gs', 'ms']
    colors2 = ['r^', 'g^', 'm^']
    colors3 = ['r+', 'g+', 'm+']
    colors4 = ['rx', 'gx', 'mx']
    stresses = self.cyc['Shear Load'].values / (self.area * 10 ** -6)
    strains = self.cyc['Internal Shear LVDT'].values / self.Hcyc1
    DE1 = np.zeros(stresses.shape, dtype=float)
    DE1[1:] = np.cumsum((stresses[1:] + stresses[:-1]) * (strains[1:] - strains[:-1])) * 0.5
    self.cyc['DE'] = DE1

    if self.MotType == 'Step loadin':  # threshold = kwargs.get('threshold', 0.0002)
        threshold = kwargs.get('threshold', 0.000)
        Load = cc.Load(self.SStrain, dt=self.dt)
        Amps = [Load.PP_Amp, Load.ZC_Amp, Load.RF_Amp]
        Ncalc = Ncycles()
        Cycs = [Load.PP_Cyc, Load.ZC_Cyc, Load.RF_Cyc]
        Times = [Load.PP_time, Load.ZC_time, Load.RF_time]
        colors = ['rs', 'gs', 'ms']
        colors2 = ['r^', 'g^', 'm^']
        colors3 = ['r+', 'g+', 'm+']
        colors4 = ['rx', 'gx', 'mx']
    if self.MotType == 'Step loadin':  # threshold = kwargs.get('threshold', 0.0002)
        threshold = kwargs.get('threshold', 0.000)
        Load = cc.Load(self.SStrain, dt=self.dt)
        Amps = [Load.PP_Amp, Load.ZC_Amp, Load.RF_Amp]
        Ncalc = Ncycles()
        Cycs = [Load.PP_Cyc, Load.ZC_Cyc, Load.RF_Cyc]
        Times = [Load.PP_time, Load.ZC_time, Load.RF_time]
        colors = ['rs', 'gs', 'ms']
        colors2 = ['r^', 'g^', 'm^']
        colors3 = ['r+', 'g+', 'm+']
        colors4 = ['rx', 'gx', 'mx']
    if self.MotType == 'Step loadin':  # threshold = kwargs.get('threshold', 0.0002)
        threshold = kwargs.get('threshold', 0.000)
        Load = cc.Load(self.SStrain, dt=self.dt)
        Amps = [Load.PP_Amp, Load.ZC_Amp, Load.RF_Amp]
        Ncalc = Ncycles()
        Cycs = [Load.PP_Cyc, Load.ZC_Cyc, Load.RF_Cyc]
        Times = [Load.PP_time, Load.ZC_time, Load.RF_time]
        colors = ['rs', 'gs', 'ms']
        colors2 = ['r^', 'g^', 'm^']
        colors3 = ['r+', 'g+', 'm+']
        colors4 = ['rx', 'gx', 'mx']
labels = ['P2P', 'OX', 'RF']
Damage = []
if self.byrne:
bDamage = []
if self.lognorm:
lnDamage = []
if self.linear:
1Damage = []
plt.plot(self.cyc['Time'].values, self.cyc['DeltaV'].values, '-b', label='Data')
for i, amp in enumerate(Amps):
cyc = Cyxs[i]
time = Times[i]
RNFunc = RichNewInc(cyc, amp=Dr=self.Dr, sigv=self.sigv_nom,
                      threshold=threshold, rtype='asymptotic', Ncalc=Ncalc,
                      rcalcftype='every')
D = np.zeros(cyc.shape, dtype=float)
if self.lognorm:
LogNormFunc = LogNormInc(cyc, amp=Dr=self.Dr,
                          sigv=self.sigv_nom, threshold=threshold)
Dln = np.zeros(cyc.shape, dtype=float)
if self.byrne:
Dbyr = np.zeros(cyc.shape, dtype=float)
if self.linear:
Linear = LineAcc(cyc, amp=Dr=self.Dr, sigv=self.sigv_nom,
                  threshold=threshold, Ncalc=Ncalc,
                  ev=self.limEvstrain)
Dlin = Linear.D
for j in xrange(len(amp)):
D[j] = RNFunc()
if self.byrne:
Dbyr[j] = ByrneIncrem(Dbyr[j-1], amp[j],
cycles=cyc[i],
Dr=self.Dr,
sigv=self.sigv_nom,
threshold=threshold)
if self.lognorm:
Dln[j] = LogNormFunc()
plt.plot(time, D*0.01, colors[i], label='{}'.format(labels[i]+'-R-N'))
Damage.append(D)
if self.byrne:
bDamage.append(Dbyr)
plt.plot(time, Dbyr, colors2[i],
label='{}'.format(labels[i]+'-Byrne'))
if self.lognorm:
lnDamage.append(Dln)
plt.plot(time, Dln*0.01, colors4[i],
label='{}'.format(labels[i]+'-ln'))
if self.linear:
1Damage.append(Dlin)
plt.plot(time, Dlin*0.01, colors3[i],
label='{}'.format(labels[i]+'-P-M'))
plt.legend(bbox_to_anchor=(1.05, -0.05), loc='lower right', borderaxespad=0.)
plt.xlabel('Time (sec)')
plt.ylabel(r'$\varepsilon _v$')
[xmin, xmax, ymin, ymax] = plt.axis()
plt.axis([xmin, xmax, ymin, np.min([1.7*self.cyc['DeltaV'].values[-1], ymax])])
plt.savefig(self.infile[:-4] +'-1'+'.'+'png')
plt.figure('2')
plt.plot(self.cyc['Time'].values, self.SStrain, 'k-', lw=1.5)
plt.xlabel('Time (sec)')
plt.ylabel('Shear Strain')
plt.gcf().subplots_adjust(wspace=0, bottom=0.2, left=0.2)
plt.savefig(self.infile[:-4] +'-2'+'.'+'png')
plt.savefig(self.infile[:-4] +'-2'+'.'+'pdf')

if PaperFigures:
    lw = 2
    plt.figure('Dam-PF')
    plt.plot(self.cyc['Time'].values[::10],
             self.cyc.DeltaV.values[::10],
             'o', color='gray',
             ms=4, label='Data', alpha=0.9)
    plt.plot(Load.ZC_time, Damage[1] * self.limEvstrain, '-k', lw=lw,
             label='R-N')
    plt.plot(Load.ZC_time, bDamage[1] , '--k', lw=lw,
             dashes=(10,5),
             label='Byrne')
    plt.plot(Load.ZC_time, lDamage[1] * self.limEvstrain, '-.k', lw=lw,
             dashes=(10,5,2,5),
             label='P-M')
    plt.legend(loc='lower right', numpoints=1) # try scatterpoints=1 if ax.legend
    plt.xlabel('Time (sec)')
    plt.ylabel(r'Volumetric Strain, $\varepsilon _v$')
    [xmin, xmax,ymin,ymax] = plt.axis()
    plt.axis([0, 1.2 * Load.ZC_time[-1],0,
              np.min([1.7*self.cyc['DeltaV'].values[-1],ymax])])
    plt.tight_layout()
    plt.savefig(self.infile[:-4] +'-PF.png')
    plt.savefig(self.infile[:-4] +'-PF.pdf')
plt.close('all')

# residual = observed - predicted
self.resid = [(self.MaxNStrain - Damage[i][-1] * self.limEvstrain)
              for i in [0,1,2]]
self.perError = [self.resid[i] / self.MaxNStrain * 100.
                 for i in [0,1,2]]
if self.byrne:
    self.bresid = [self.MaxNStrain - bDamage[i][-1] for i in [0,1,2]]
                      for i in [0,1,2]]
if self.linear:
    self.lresid = [(self.MaxNStrain - lDamage[i][-1] * self.limEvstrain)
                   for i in [0,1,2]]
                      for i in [0,1,2]]

def Drcorr(self):
    '''
    Corrects the relative density and void ratio since Qingsheng didn’t keep track of volumetric strains while the confining load was being
applied.

```python
df1 = pd.read_csv('/media/Storage/Documents/Python/SeismicComp/DrCorr.csv')
df2 = df1[(df1['sigv_nom']==self.sigv_nom) & (df1['Dr_nom']==self.Dr_nom)]
self.mass_ass = df2['mass'].values[0]
self.Vstr_avg = df2['Vstr_avg'].values[0]
self.Hcyc1 = self.hi - df2['deltaH'].values[0] # Assuming it was 24 mm high to begin.
self.e_new = df2['e_new'].values[0]
self.Dr_new = df2['Dr_new'].values[0]
self.standev = df2['standev'].values[0]
self.standevomean = df2['standevomean'].values[0]
```

def calcAr(self, motion, dt, **kwargs):
    
    Calculates the following:
    \[ \frac{I_a}{(\max(\text{abs}(\text{motion}))^{**2} \times \text{time})} \]
    
    if 1 in motion.shape or len(motion.shape) == 1:
        NumMotions = 1
    else:
        NumMotions = np.min(motion.shape)
    Ar = np.zeros([NumMotions,], dtype=float)
    if NumMotions == 1:
        Ar = (calcRmsAccel(motion, dt, **kwargs) / np.max(np.abs(motion))) # Assume data is in rows
    else:
        for i in xrange(NumMotions):
            Ar[i] = (calcRmsAccel(motion[i,:], dt, **kwargs) / np.max(np.abs(motion[i,:]))) # Assume data is in rows
        return Ar
```

class SineTest(object):
    
    This object controls all the calcs and i/o for each test.
    
    Keyword Definition
    file name/path of the GCTS data file for the test.
    
    def __init__(self,**kwargs):
        infile = kwargs.get('infile')
        try:
            self.sigv_nom = int(re.search('soids/(.+?)kPa',infile).group(1))
            self.Dr_nom = int(re.search('kPa/Dr(.+?)/',infile).group(1))
        except AttributeError:
            print('AttributeError!!!!!!')
        self.byrne = kwargs.get('byrne',True)
        self.emin = kwargs.get('emin',0.68)
        self.emax = kwargs.get('emax',0.9)
        self.ncycles = np.ones((10,)) * -1
        self.lognorm = kwargs.get('lognorm', True)
        self.linear = kwargs.get('linear', True)
        self.verbose = kwargs.get('verbose',True)
        self.limEvstrain = kwargs.get('limEvstrain',0.01)
self.Error = False

if 'infile' == None:
    infile = raw_input('Nothing to do. Specify an input file:')
    self.csvimport(infile)
else:
    self.csvimport(infile)
    self.infile = infile
    self.Drcorr()
    val = self.calcs()
    #self.scratch()
    # self.dissen(verbose=True)
    if val == 0:
        return
    if self.byrne:
        self.ByrneCalcs()
    if self.lognorm:
        self.LogNormCalcs()
    self.plotter()
    self.calcNcycles

def csvimport(self, infile):
    
    This function pulls in the data from the GCTS output file.
    The GCTS file should not have the data separated into stages.

    :param self:
    :param infile:
    
    self.data=[]
    self.label=[]
    self.name=[]
    self.Gs=[]
    self.mass=[]
    self.cyc_header=[]
    self.pist_area=[]
    footer = []
    datasection=0
    dimsec=0
    datafile = csv.reader(open(infile,'rU'))
    rowcount = -1
    for row in datafile:
        rowcount += 1
        if datasection==0:
            if self.Gs:
                pass
            elif 'Specific Gravity: ' in row:
                self.Gs=float(row[1])
                self.Gs=2.66 #Because sometimes I forget to change the value in the GCTS software
                if self.name:
                    pass
                elif 'Specimen: ' in row:
                    self.name=row[1]
        if dimsec==0:
            pass
            elif 'Dry Mass of Specimen: ' in row:
                self.mass=float(row[1]); self.mass_unit=row[2]
if self.mass==0:
    self.mass=float(raw_input('Input the dry mass (g) for specimen %s:' %self.name))

elif 'Moist Mass of Specimen: ' in row:
    self.mass=float(row[1]); self.mass_unit=row[2]
    if self.mass==0:
        self.mass=float(raw_input('Input the dry mass (g) for specimen %s:' %self.name))

if 'Type:' and 'Universal' in row:
    dimsec=1

if 'Starting Date: ' in row:
    testdate = row[1]

if 'Starting Time: ' in row:
    testtime = row[1]

if dimsec==1:
    if 'Height: ' in row:
        self.hi=float(row[3])*25.4;
        if row[4] == '(mm)'
            pass
        else:
            self.hi=self.hi*25.4
            self.hi_unit= 'mm' #Convert to mm
    if 'Diameter: ' in row:
        self.di=float(row[3])*25.4;
        if row[4] == '(mm)'
            pass
        else:
            self.hi=self.hi*25.4
            self.hi_unit= 'mm' #Convert to mm
    self.area = (self.di / 2) ** 2 * np.pi # in mm^2
    dimsec=0

if len(row) >= 17:
    datasection = 1
    if row[0] == 'Time':
        header = rowcount
        self.headerlabel = row
        if row[0] == 'sec':
            self.units = row
        if datasection == 1:
            if row[0][:7] == 'Stage 2':
                footer = rowcount
                break
            if footer == []:
                df = pd.read_csv(infile,names=self.headerlabel,skiprows=header+3)
            else:
                df = pd.read_csv(infile,names=self.headerlabel,skiprows=header+3,
                                nrows = footer - header - 4)
        # Create a new dataframe that contains only the cyclic portion
        columns = ['Time', 'Cycles','Shear Load','Shear Displacement',
                   'Normal Load','Normal Displacement','
                   'Internal Shear Load','Internal Shear LVDT',
                   'Internal Normal LVDT']
        try:
x = df['Shear Load'] * 2.
except KeyError:
    df['Shear Load'] = df['Internal Shear Load']
try:
    self.cyc = df[columns].reset_index(drop=True)
except KeyError:
    raise KeyError
self.date_of_test = datetimeconvert(testdate,testtime)

def calcs(self, **kwargs):
    """
    SineTest
    This does the heavy lifting.
    """
    # Calculate the volumes
    self.Vcyc_T1 = self.Hcyc1 * self.area  # in mm^2
    if self.Gs == 2.65:
        pass
    else:
        Gs = self.Gs
        self.Gs = 2.65
        print('Changed Gs from {} to 2.65'.format(Gs))
    try:
        self.Vcyc_s = self.mass / (self.Gs * 0.001)  # in mm^3 where density of water is 0.001 g/mm^3
    except TypeError:
        self.Vcyc_s = self.mass_ass / (self.Gs * 0.001)  # in mm^3 where density of water is 0.001 g/mm^3
        self.mass = self.mass_ass
    self.cyc['Volume'] = self.Vcyc_T1 - (self.cyc['Internal Normal LVDT'] * self.area)
    self.cyc['Vol_voids'] = self.cyc['Volume'] - self.Vcyc_s
    # Calc e
    self.cyc['e'] = self.cyc['Vol_voids'] / self.Vcyc_s
    self.e_0 = self.cyc['e'].values[0]
    self.e_1 = 0.99 * self.cyc['Vol_voids'].values[0] / self.Vcyc_s - 0.01
    self.Dr = (self.emax-self.e_0)/(self.emax-self.emin)*100
    self.cyc['Dr'] = ((self.emax-self.cyc['e'].values)/
                      (self.emax-self.emin)*100)

    # Calc changes in volume, damage, cycle ratio
    stresses = self.cyc['Internal Shear Load'].values / (self.area * 10 ** -6)
    self.cyc['Stress'] = stresses
    strains = self.cyc['Internal Shear LVDT'].values / self.Hcyc1
    self.cyc['Strain'] = strains
    DE1 = np.zeros(stresses.shape, dtype=float)
    DE1[1:] = np.cumsum((stresses[1:] + stresses[:-1]) *
                        (strains[1:] - strains[:-1])) * 0.5
    self.cyc['DE'] = DE1
    self.cyc['DeltaV'] = (self.Vcyc_T1 - self.cyc['Volume']) / self.Vcyc_T1
    self.cyc['Dam'] = self.cyc['DeltaV'] / self.limEvstrain
    df = self.cyc[self.cyc['Dam']>1]
    try:
        self.Nlim = df['Cycles'].values[0]
    if self.Nlim < 4:
print('Too few cycles to run some analyses')
self.calcStrain()
self.Error = True
return 0
except IndexError:
    print('Did not reach {}% Vol strain'.format(self.limEvstrain*100))
    self.Nlim = -1
    return 0
self.cyc['ratio'] = self.cyc['Cycles'] / float(self.Nlim)
self.cyc['r'] = (np.log(self.cyc['Dam'].values) / np.log(self.cyc['ratio'].values))
strain = self.cyc['Internal Shear LVDT'].values
ind = np.where(((strain[:-1] < 0) & (strain[1:] >= 0)) | ((strain[:-1] > 0) & (strain[1:] <= 0))) & np.abs(strain[:-1]<0.03)
self.cyc2 = self.cyc.ix[ind[0]]
r = self.cyc2['r'].values
D = self.cyc2['Dam'].values
R = self.cyc2['ratio'].values
stress = self.cyc2['Shear Load'].values
self.cyc4 = self.cyc2[(self.cyc2['ratio']<0.5]
r2 = self.cyc4['r'].values
D2 = self.cyc4['Dam'].values
R2 = self.cyc4['ratio'].values
ind5 = np.where(D < 0.8)
ind5 = np.where(D < 0.8)
self.rmean = np.mean(r[ind5])
b = r[0]
# Get the regression coefficients for various functional forms
popt2,pov2= curve_fit(rn2, R, r, **dict(maxfev=10000))
self.aa, self.ac = popt2[0]
plt.plot(R,r,'ok', ms=3, alpha=0.5)
plt.title('Asymptotic $r$')
plt.plot(R,asymptote4(R,*popt2), '-k', lw=2,
label=r'$r = {{ {:.3f} / R^{{ {:.3f} }} + {:.3f} }}$'.format(self.aa, self.ac, self.ab))
except:
pdb.set_trace()
self.aa = -1
self.ab = -1
plt.plot(R,asymptote4(R,*popt2), '-k', lw=2,
label=r'$r = {{ {:.3f} / R^{{ {:.3f} }} + {:.3f} }}$'.format(self.aa, self.ac, self.ab))
except:
pdb.set_trace()
self.aa = -1
self.ab = -1
plt.plot(R,asymptote4(R,*popt2), '-k', lw=2,
label=r'$r = {{ {:.3f} / R^{{ {:.3f} }} + {:.3f} }}$'
self.aa, self.ac, self.ab))
cyc3 = self.cyc2[self.cyc2['Dam']<=1.25]
popt2,pcov2 = curve_fit(curv_power, cyc3['ratio'].values,
cyc3['Dam'].values, p0=[0.3, 0.0001,0])
popt3, pcov3 = curve_fit(power, cyc3['ratio'].values * 100, cyc3['Dam'].values * 100, p0=[1.3, 0.000001, 0])

popt, pcov = curve_fit(curv_power, self.cyc2['ratio'].values, self.cyc2['Dam'].values, p0=[0.3, 0.0001, 0])

self.r0 = popt2[0]
self.s0 = popt2[1]
self.t0 = popt2[2]
sel.r1 = popt[0]
sel.s1 = popt[1]
sel.t1 = popt[2]
sel.rpow = popt3[1]
sel.apow = popt3[0]

# Calculate the strain
self.calcStrain()
if self.verbose:
    print('Test: %s, Dr=%.2f, Strain: %.2f per., Cycles to %.3f Vol strain: %.1f Cycles to %.3f Vol strain: %.1f
self.r0,self.s0,self.t0))
return 1

def calcStrain(self, **kwargs):
    
    Calculates the average shear strain over the majority of the cyclic portion.
    
    cycrange = kwargs.get('cycrange', 75)
    # Get the zero crossings
    strain = self.cyc['Internal Shear LVDT'].values / self.Hcyc
    ind = np.where((strain[:-1] < 0) & (strain[1:] >= 0))[0]
    cycles = int(len(ind) * cycrange / 100)  # Currently runs throughout the entire file.
    May want to limit this to 1% strain
    # Calc the max and min in each cycle
    maxs = np.zeros(cycles, dtype=float)
    mins = np.zeros(cycles, dtype=float)
    for i in xrange(cycles+1):
        if i == 0:
            continue
        maxs[i-1] = np.max(strain[ind[i-1]:ind[i]])
        mins[i-1] = np.min(strain[ind[i-1]:ind[i]])
    self.gam = np.mean(maxs - mins) / 2

    def DiscreteCycles(self, **kwargs):
        
        Modifies the cycle count so that partial cycles are given, and saved as 'CyclesD' in the dataframe.
        
        returns = kwargs.get('returns', False)
cycles = self.cyc['Cycles'].values
    time = self.cyc['Time'].values
    ind = np.where((cycles[:-1] != cycles[1:]))
    cyclesD = np.zeros(cycles.shape, dtype=float)
    for i, val in enumerate(ind[0]):
        if i == 0:
in1 = 0
in2 = val + 1
prevcyc = 0.
else:
in1 = ind[0][i-1] + 1
in2 = val + 1
prevcyc = cycles[in1] - 1.
time2 = time[in1:in2] - time[in1]
cyclesD[in1:in2] = prevcyc + time2 / time2[-1]
in1 = ind[0][i-1] + 1
in2 = len(time)
prevcyc = cycles[in1] - 1.
time2 = time[in1:in2] - time[in1]
cyclesD[in1:in2] = prevcyc + time2 / time2[-1]
if returns:
    return cyclesD

def scratch(self, **kwargs):
    ...
    A place to try new things without making a mess elsewhere.
    ...
#    pdb.set_trace()
cycles = self.cyc2['Cycles'].values
cycles2 = self.DiscreteCycles(returns=True)

    pdb.set_trace()
D = self.cyc2['Dam'].values
R = self.cyc2['ratio'].values
plt.figure('scratch')
plt.plot(R, D)

    print(popt)
plt.plot(R, curvPL(R, *popt), label='CurvPL fit')
plt.plot(R, logcdf(R, *popt2), label='logcdf')
plt.legend()
plt.show()

Dn = D / D15
plt.plot(cycles[:ind15], Dn[:ind15], '-o')
print(cycles[:ind15])
print(Dn[:ind15])

    def LogNormCalcs(self, **kwargs):
        '''
        Calculates the parameters mu and sig for the log-normal-cdf-fit of the D-R curve.
        '''

    LogNormCalcs(self, **kwargs):
R1 = self.cyc2['ratio'].values
R = R1[R1<1.6]
D = self.cyc2['Dam'].values[R1<1.6]
plt.figure('LogNormCDF Method')
plt.plot(R, logcdf(R, *popt), 'o')
plt.plot(R, logcdf(R, *popt), '-')
plt.xlabel(r'$R = n / N$')
plt.ylabel(r'$D$')
plt.title(r'Log Norm Fit: $\mu =$ {:.3f}, $\sigma =$ {:.3f}'.format(popt[0]))
self.sig = popt[0]
self.mu = 0.
def ByrneCalcs(self, **kwargs):
    r'''Calculates parameters C1 and C2 for the Byrne model.
    (Byrne, Peter. 1991. "A cyclic shear-volume coupling and pore pressure
    model for sand." Proceedings: Second International Conference on Recent
    Advances in Geotechnical Earthquake Engineering and Soil Dynamics,
    r'''
    def byrneexp(x,c1,c2):
        r'''returns $\Delta \epsilon_v / \gamma$'''
        return c1 * np.exp(-c2 * x)
sstrain = self.cyc['SStrain'].values
ind = np.where((sstrain[:-1] < 0) & (sstrain[1:] >= 0))[0]
DV = self.cyc['DeltaV'].values
vstrain = np.zeros(ind.shape, dtype=float)
for i,index in enumerate(ind):
    try:
        if (i == 0):
            if index == 0:
                vstrain[i] = 0
            else:
                vstrain[i] = np.max(DV[:index])
        else:
            vstrain[i] = np.max(DV[ind[i-1]:index])
    except ValueError:
        pdb.set_trace()
dvstrain = np.zeros(vstrain.shape, dtype=float)
dvstrain[1:] = np.diff(vstrain)
evogam = vstrain / self.gam
devogam = dvstrain / self.gam
# Now, to the parameters:
C1 = dvstrain[1] / self.gam
popt, pcov = curve_fit(byrneexp, evogam[1:], devogam[1:], p0=[C1, 0.4 / C1])
plt.figure('Byrne\'s Method')
plt.plot(evogam, devogam, 'ko', ms=6, label='Data')
plt.plot(evogam,byrneexp(evogam, *popt), 'k',lw=2, label='Best Fit:
  $C1=${:.2f},
  $C2=${:.2f}'.format(*popt))
plt.legend(loc='best')
```python
plt.xlabel(r'\$\epsilon_v / \gamma\$')
plt.ylabel(r'\$\Delta \epsilon_v / \gamma\$')
sel.f1, sel.f2 = popt[0], popt[1]

# def dissen(self,**kwargs):
#     ...'''
#     verbose = kwangs.get('verbose',True)
#     stresses = self.cyc['stress_int'].values # may want to change to internal
#     strains = self.cyc['strain_int'].values
#     maxind = self.cycind
#     disEn = np.cumsum((stresses[1:maxind] + stresses[:maxind-1]) *
#                        (strains[1:maxind] - strains[:maxind-1])) * 0.5
#     disEn2 = np.zeros([len(self.cyc.index),],dtype=float)
#     disEn2[1:maxind] = disEn
#     self.DE = disEn[-1]
#     disEn2[maxind:] = self.DE
#     sel.cyc['DE'] = disEn2
#     # Calculate the liquefaction-corrected dissipated energy
#     # Calculate the PEC (Green's Dissertation, eq. 4-15)
#     Ru = self.cyc['Ru'].values
#     ind = np.where(Ru > 0.65)
#     self.PEC = self.cyc['DE'].values[ind][0] / 0.4225
#     if verbose:
#         print('Total DE: %.4f, Corrected DE: %.4f' % (self.DE, self.DE_corr))
# def plotter(self, **kwargs):
#     ...'''

Keyword Definition
save True [default] or False
savetype png or pdf, etc
show Should the figures be shown? True or False

save = kwangs.get('save',True)
savetype = kwangs.get('savetype','png')
show = kwangs.get('show',False)
fontsize = kwangs.get('fontsize',15)
lw = 5
```
if kwargs.get('latex', True):
    fs = kwargs.get('fs', 18)
    import matplotlib
    matplotlib.rcParams.update({'font.size': fs,
        'font.family': 'STIXGeneral', 'mathtext.fontset': 'stix'})
        fontsize=18
else:
    import matplotlib
    matplotlib.rcParams.update({'font.size': 12,
        'font.family': 'sans', 'text.usetex': False})

# Time plot
plt.figure('Results of %s'%self.name)
plt.subplot(121) # This stopped working in the gcts-cv-css code
if not PaperFigures:
    plt.title(r'$D_r$=%.1f\%, $\gamma_{cyc}$=%.2f\%, $N_{%.1f}$=%.1f'(
        self.Dr,self.gam*100,self.limEvstrain*100,self.Nlim))
    plt.plot(self.cyc['SStrain'].values,
        self.cyc['Shear Load'].values / (self.area * 10 ** -6),
        '-k', lw=0.8, alpha=0.7)
    plt.ylabel('Shear Stress (kPa)', fontsize=fontsize)
    plt.xlabel('Shear Strain', fontsize=fontsize)
    plt.setp(plt.subplot(121).get_xticklabels(), rotation=90)

    plt.subplot(122)
    try:
        plt.plot(self.cyc['SStrain'].values,
            self.cyc['DeltaV'].values, 
            '-k', lw=0.8, alpha=0.7)
    except:
        pdb.set_trace()
    self.cyc.plot(x='Shear Strain',
        y='DeltV')
    plt.xlabel(r'Shear Strain', fontsize=fontsize)
    plt.ylabel(r'Volumetric Strain', fontsize=fontsize)
    if PaperFigures:
        [xmin, xmax, ymin, ymax] = plt.axis()
        plt.axis([xmin, xmax, ymax, ymin])
    plt.setp(plt.subplot(122).get_xticklabels(), rotation=90)
    plt.tight_layout()

plt.figure('2')
if self.Nlim < 4:
    lw = 1.6
    plt.plot(self.cyc['ratio'].values, self.cyc['Dam'].values, 'o',
        label='Data')
else:
    lw = 1.6
    plt.plot(self.cyc2['ratio'].values[:3],
        self.cyc2['Dam'].values[:3], 'ok',
        label='Data', ms=7, alpha=0.4)
    if self.limEvstrain < 0.01:
else:
    plt.plot(self.cyc2['ratio'].values,
             curv_power(self.cyc2['ratio'].values, self.r0, self.s0,
                        self.t0), '-k', lw=lw,
             label=r'$R^{\{ \cdot2f\} + (\cdot3f)R + (\cdot3f)R^2 }$'.format(self.r0,
                                self.s0, self.t0))
    plt.plot(self.cyc2['ratio'].values,
             self.cyc2['ratio'].values ** self.rmean, 'k-.',lw=lw,
             label=r'$R^{\cdot3f}$'.format(self.rmean))
    if self.aa != -1:
        plt.plot(self.cyc2['ratio'].values,
                 asymptote(self.cyc2['ratio'].values, self.aa,
                            self.ab,
                            self.ac), 'k:', lw=lw,
                 label=r'$R^{\{ \cdot3f \} / R^{\{ \cdot3f \}} + \cdot3f }$'.format(self.aa,
                                                                 self.ac, self.ab))
    if self.lognorm:
        plt.plot(self.cyc2['ratio'].values,
                 logcdf(self.cyc2['ratio'].values, self.sig),
                 'k--', lw=lw,
                 label=r'$1 + erf((\log(R)-\cdot1f)/\cdot1f)$'.format(self.mu, self.sig))
    plt.ylabel(r'Damage = $rac{\varepsilon_v}{%.1f \%}$'%(self.limEvstrain*100),
               fontsize=fontsize)
    plt.xlabel(r'$R=\frac{n}{N}$', fontsize=fontsize)
    plt.axis([0,1.1,0,1.1])
    plt.legend(loc='lower right', numpoints=1)
    plt.tight_layout()
    if show:
        plt.show()
    if save:
        import matplotlib
        figures=[manager.canvas.figure for manager in
                 matplotlib._pylab_helpers.Gcf.get_all_fig_managers()]
        for i, figure in enumerate(figures):
            figure.savefig(self.infile[:-4] +'-'+str(i+1)+'.'+savetype)
            if PaperFigures:
                figure.savefig(self.infile[:-4] +'-'+str(i+1)+'.'+'pdf')</code>
self.standev = df2['standev'].values[0]
self.standevomean = df2['standevomean'].values[0]

def calcNcycles(self):
    '''
    Calculates the number of cycles to various volumetric strains.
    From 0.001 to 0.01.
    '''
    strains = 0.001 * np.arange(1,11)
    VolStrain = self.cyc2['DeltaV'].values
    Cycles = self.cyc2['Cycles'].values
    for i, ev in enumerate(strains):
        try:
            self.ncycles[i] = Cycles[np.where(VolStrain >= ev)[0][0]]
        except IndexError:
            self.ncycles[i] = -1

def runsine(*args,**kwargs):
    '''
    Takes the output files from the GCTS and runs them through SineTest
    '''
    h5 = kwargs.get('h5file','default')
    infilelist=[]
    if len(args) > 0:
        argsin = args
    else:
        argsin=sys.argv[1:]
        # argsin.append('/media/Storage/Documents/Python/SeismicComp/Sinusoids/50kPa/Dr30/1.csv')
    numtests = len(argsin)
    if argsin==[]:
        filters = 'CSV (*.csv)' # for qtfiledialog
        filelist=fd.fileopen(message='Choose a gcts output...',
                            filters=filters,
                            defaultDir=(u'/media/Storage/Documents/Python/SeismicComp/Sinusoids/'))
        for file in filelist:
            if file == '/media/Storage/Documents/Python/SeismicComp/DrCorr.csv':
                continue
            infilelist.append(file)
        del filelist
    elif len(argsin)>0:
        if argsin[0] in ['all','--all','-a','a']:
            infilelist=glob.glob('*.csv')
        else:
            for file in argsin:
                if file == '/media/Storage/Documents/Python/SeismicComp/DrCorr.csv':
                    continue
                infilelist.append(file)
            del argsin
        numtests = len(infilelist)
        if h5 == 'choose':
h5file = fd.fileopen(message='Choose a Summary Table...',
                    filters='h5|*.h5',
                    defaultDir=(u'/media/Storage/Documents/Python' +
                                '/GCTS/ConstantVolume'))

h5table = HDF5saver(filename=h5file[0])
else:
h5table = HDF5saver()

for infile in infilelist:
    print(infile)
    try:
        testobj = SineTest(infile=infile)
    except KeyError:
        continue
    if testobj.Nlim < 0:
        continue
    if testobj.Error:
        continue
    h5table.input(testobj)

    del testobj
    print(numtests)

h5table.close()

def runEQ(*args,**kwargs):
    h5 = kwargs.get('h5file','default')
    infilelist=[]
    if len(args) > 0:
        argsin = args
    else:
        argsin=sys.argv[1:]
    # argsin.append('/media/Storage/Documents/Python/SeismicComp/EQmotions/100kPa/Dr30/Step
    # loadin/97.csv')
    if os.name == 'posix':
        rootdir = '/media/Storage/Documents/Python/SeismicComp/EQmotions/
    else:
        rootdir = 'D:\Documents\Python\SeismicComp\EQmotions'
    for root, dirnames, filenames in os.walk(rootdir):
        for filename in fnmatch.filter(filenames, '*.csv'):
            argsin.append(os.path.join(root, filename))

    if argsin==[]:
        filelist = []
        for file in filelist:
            if file == '/media/Storage/Documents/Python/SeismicComp/DrCorr.csv'
                continue
        infilelist.append(file)
    del filelist
    if len(argsin)>0:
        if argsin[0] in ['all','--all','-a','a']:
            infilelist=glob.glob('*.csv')
        else:
            for file in argsin:
                if file == '/media/Storage/Documents/Python/SeismicComp/DrCorr.csv':
                    continue
            infilelist.append(file)
    del argsin
    if h5 == 'choose':
h5file=fd.fileopen(message='Choose a Summary Table...',
  filters='h5|*.h5',
  defaultDir=(u'/media/Storage/Documents/Python' +
  '/GCTS/ConstantVolume'))
else:
h5table = HDF5saver(filename=h5file[0])
for infile in infilelist:
  print(infile)
  try:
    testobj = EQTest(infile=infile)
  except KeyError:
    continue
  h5table.input(testobj)
del testobj
h5table.close()
def PMcalibrator(**kwargs):
  '''
  This function fit curves for N to a range of volumetric strains.
  '''
  import statsmodels.api as sm
  import pandas as pd
  formula = kwargs.get('formula', 'np.log(N) ~ np.log(gam) + sigv_norm + Dr')
  noterms = formula.count('+') + 2
  infile = kwargs.get('infile', 'SummaryResults.h5')
  outfile = kwargs.get('outfile', 'PMCalResults.h5')
  strains = 0.001 * np.arange(1,11)
  class PMtable(pt.IsDescription):
    VolStrain = pt.Float32Col(pos=1)
    formula = pt.StringCol(itemsize=128, pos=2)
    Coeffs = pt.Float32Col(shape=(noterms,), pos=3)
    R2adj = pt.Float32Col(pos=4)
    f = pt.open_file(infile, 'r')
    table = f.root.Summary
    cyc = table.read(field='ncycles')
    ncycles = cyc.reshape(-1,10)
    data0 = np.vstack((
      table.read(field='Nlim'),
      table.read(field='gam'),
      table.read(field='sigv_nom')/101.325,
      table.read(field='Dr'))).T
    data = pd.DataFrame(data0, columns=[
      'Nlim','gam','sigv_norm','Dr'])
    # Clean up:
    f.close()
    del table, data0
    f = pt.open_file(outfile, 'w', title='PM Calibration Parameters')
    outtable = f.create_table('/', 'PMresults', PMtable)
    for i, strain in enumerate(strains):
      print('


 Strain={}

'.format(strain))
      data['N'] = ncycles[:,i]
      model = sm.formula.ols(formula=formula, data=data)
      results = model.fit()}
print(results.summary())
row = outtable.row
row['VolStrain'] = strain
row['formula'] = formula
row['Coeffs'] = results.params
row['R2adj'] = results.rsquared_adj
row.append()
outtable.flush()
f.close()
class Ncycles(object):
    '''Calculates the number of cycles to any given volumetric strain between
    0.001 and 0.01.
    '''
def __init__(self, **kwargs):
    calfile = kwargs.get('calfile',
                        '/media/Storage/Documents/Python/SeismicComp/PMCalResults.h5')
    try:
        self.f = pt.open_file(calfile, 'r')
    except AttributeError:
        self.f = pt.openFile(calfile, 'r')
    self.table = self.f.root.PMresults
    self.strains = self.table.read(field='VolStrain')
    self.formula = self.table.read(field='formula')
    Coeffs = self.table.read(field='Coeffs')
    self.Coeffs = Coeffs.reshape(-1, len(Coeffs[0]))
    self.table.close()
    self.f.close()

def formula(self):
    print(self.formula)

def __call__(self, Target_ev, *args, **kwargs):
    if len(args) == 0:
        args = self.oldargs
    else:
        self.oldargs = args

    # interpolate between periods if necessary
    if np.round(Target_ev, 4) not in self.strains:
        lowind = np.where(Target_ev > self.strains)[0][-1]
        T_low = self.strains[lowind]
        T_hi = self.strains[lowind + 1]
        N_low = self.__call__(T_low, *args)
        N_hi = self.__call__(T_hi, *args)
        x = np.array([T_low, T_hi])
        Y_N = np.array([N_low, N_hi])
        try:
            f_N = interp1d(x, Y_N, axis=0)
            try:
                del N
            except:
                pass
            N = f_N(Target_ev)
        except interp1d.error:
            pass
    else:
        return self.formula(*args, **kwargs)
return N
except ValueError:
    pdb.set_trace()
else:
    i = np.abs(self.strains - Target_ev).argsort()[0] # Identify the strain index
    mults = [1.]
    mults.extend(args)
    if np.all([np.isscalar(val) for val in mults]):
        return np.sum(self.Coeffs[i] * np.array(mults))
else:
    num = np.max([1 if np.isscalar(val) else len(val) for val in mults])
    return np.sum(self.Coeffs[i][:, np.newaxis] * np.array([val * np.ones((num,), dtype=float) if np.isscalar(val) else val for val in mults]), axis=0)

def selector():
    '''
    This is where you might want to start
    '''
    x = None

    while x not in [1,2,3,4,5,6,7]:
        print('Run Options:\n 1. Select a GCTS soil output\n 2. Select a GCTS soil output and choose .h5 file\n 3. Select a GCTS water output\n 4. Plot all data\n 5. Import all data and go to a prompt\n 6. Delete some test results (not implemented)\n 7. Plot selected test results (not implemented)\n 8. Quit'
        selection = raw_input('Please make a selection: ').split()
        try:
            x = int(selection[0])
        except IndexError:
            x = None

        if x == 1:
            runsoil(h5file='default')
        elif x == 2:
            runsoil(h5file='choose')
        elif x == 3:
            runwater()
        elif x == 4:
            runsummary()
        elif x == 5:
            dataprompt()
        elif x == 7:
            break
        else:
            print('I didn\'t understand you.')
```python
class LogNormInc(object):
    '''
    Calculates the value of volumetric strain using the LogNormal fun.form.
    Returns not the increment, but the next value of volumetric strain.
    It is assumed that each shear strain is one half cycle.
    '''
    def __init__(self, Cycles, Amp, **kwargs):
        from scipy.special import erf, erfinv
        self.erf = erf
        self.erfinv = erfinv
        self.name = kwargs.get('name')
        self.Dr = kwargs.get('Dr')
        self.sigv = kwargs.get('sigv', 100.)
        self.mu = kwargs.get('mu', 0.0)
        self.threshold = kwargs.get('threshold', 0.0002)
        self.Amp = Amp
        self.Cyc = Cycles
        self.N = np.exp(-2.97272 * np.log(self.Amp) + 0.002292 * self.sigv + 0.02435 * self.Dr - 13.874)
        self._R = Cycles / self.N
        self._R = self._R / self._R
        self.sig = np.exp(-0.578 * np.log(self.Amp) + 0.0012 * self.sigv + 0.0064 * self.Dr - 2.3598)
        self.D = np.zeros(Amp.shape, dtype=float)
        self.R = np.cumsum(self._R)
        self.i = -1
        
        def __call__(self, **kwargs):
            '''
            This is an iterator function.
            '''
            erf = self.erf
            erfinv = self.erfinv
            returns = kwargs.get('returns', True)
            self.i += 1
            if self.Amp[self.i] < self.threshold:
            else:
                if self.i == 0:
                else:
                        erf((np.log(self.R[self.i-1]) - self.mu) / self.sig[self.i]))
            if returns:
                return self.D[self.i]
        
        def run(self):
            '''
            This just runs thru all the calls
            '''
            for val in self.Amp:
```

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```python
self.__call__(returns=False)

def PMtest():
    Ncalc = Ncycles()
    print(Ncalc.formula[0])
    Dr = 45.
    sigv_norm = 1.
    gam = 0.004
    MyNcycles = np.zeros(Ncalc.strains.shape)
    for i, ev in enumerate(Ncalc.strains):
        MyNcycles[i] = np.exp(Ncalc(ev, np.log(gam), sigv_norm, Dr))
        print(MyNcycles)
    for stra in [0.0015, 0.0095]:
        print('Strain: {}, N={}'.format(stra, np.exp(Ncalc(stra))))
    pdb.set_trace()

def PMresulttable(**kwargs):
    '''
    Prints out a table summarizing the results of the PMcalibrator.
    '''
    import pandas as pd
    calfile = kwargs.get('calfile', 'PMCalResults.h5')
    f = pd.open_file(calfile, 'r')
    table = f.root.PMresults
    strains = table.read(field='VolStrain')
    formula = table.read(field='formula')
    Coeffs0 = table.read(field='Coeffs')
    Coeffs = Coeffs0.reshape(-1, len(Coeffs0[0]))
    Rsqadj = table.read(field='R2adj')
    table.close()
    f.close()

    heads = ['$\varepsilon_v$ (%)', '$\phi_1$', '$\phi_2$', '$\phi_3$', '$\phi_4$', '$R^2_{adj.}$']
    align = [('^', '^'), ('^', '^'), ('^', '^'), ('^', '^'), ('^', '^'), ('^', '^')]
    fields = range(6)
    data = []
    for i, stra in enumerate(strains):
        data.append((np.round(stra*100.,1),
                      round(Coeffs[i,0],2),
                      round(Coeffs[i,1],3),
                      round(Coeffs[i,2],3),
                      round(Coeffs[i,3],4),
                      round(Rsqadj[i],2)))
    pan.table(sys.stdout, data, fields, heads, align)
```

J.10 Implementation of ASTM ‘Cycle Counting’ Methods

The file `CycleCounting.py` returns cycle and amplitude pairs from an irregular motion.

```python
import pdb
import numpy as np

class Load(object):
    '''
    Accepts a 1D array of values.
    Returned Amplitudes are single amplitudes.
    '''

def __init__(self, load, **kwargs):
    self.mean = kwargs.get('mean', 0.) # <<======================= Do I want to auto-set as zero?
    if self.mean == 'mean':
        self.mean = np.mean(load)
    self.dt = kwargs.get('dt', 1.)
    self.time = np.linspace(0,(len(load)-1) * self.dt, len(load))
    self.load = load
    self.PRthrshld = kwargs.get('PRthrshld', 0.)

    if kwargs.get('AriasRatio', False):
        self.Ar = self.calcAriasRatio(load, self.dt)

    runall = kwargs.get('runall', True)
    if runall == True:
        self.calcZeroCrossing(returns=False)
        self.calcPeak2Peak(returns=False)
        self.calcRainflow(returns=False)
        self.calcPR(thrshld=self.PRthrshld)

def countCycles(self, *args, **kwargs):
    if (len(args) == 0) or ('all' in args):
        args = ['ZC', 'PP', 'RF']

    if 'ZC' in args:
        self.calcZeroCrossing(**kwargs)
    if 'PP' in args:
        self.calcPeak2Peak(**kwargs)
    if 'RF' in args:
        self.calcRainflow(**kwargs)

def calcAriasRatio(self, motion, dt):
    ...
Calculates the following:
\[ \frac{I_a}{(\max(\text{abs}(\text{motion})))^2 \cdot \text{time}} \]

```python
if len(motion.shape) == 2:
    return (np.trapz(motion ** 2, dx=dt, axis=1) / np.max(np.abs(motion), axis=1) ** 2 / (dt * max(motion.shape)))
else:
    return (np.trapz(motion ** 2, dx=dt) / np.max(np.abs(motion)) ** 2 / (dt * len(motion)))
```

```python
def calcZeroCrossing(self, **kwargs):
    
    Calculates the number of cycles using the zero crossings to separate cycles. This is the same as the mean crossing peak counting in section 5.2.2 of ASTM 1049 - 85 (2011).

    # This AmpType is here for ease of performing my seismic compression calculations. To correspond with the cycle count of my sinusoidal motions, I needed to divide the cycles by two. But this is not the ASTM spec advises.
    AmpType = kwargs.get('AmpType', 'SC')
    if AmpType == 'SC':
        divisor = 2.
    else:
        divisor = 1.
    returns = kwargs.get('returns', True)
    zero = self.mean
    load = self.load
    time = self.time
    ind = np.where(((load[:-1] >= zero) & (load[1:] < zero)) | ((load[:-1] < zero) & (load[1:] >= zero)))
    Amp = np.zeros(len(ind[0]), dtype=float)
    Cycles = np.ones(len(ind[0]), dtype=float) / divisor
    time2 = np.zeros(len(ind[0]))
    for i, ind2 in enumerate(ind[0]):
        if i == 0:
            if ind2 == 0:
                Amp[i] = 0.
                time2[i] = time[ind2]
                continue
            else:
                Amp[i] = np.max(np.abs(load[:ind[0][i]]))
                time2[i] = time[np.argmax(np.abs(load[:ind[0][i]]))]
        else:
            Amp[i] = np.max(np.abs(load[ind[0][i-1]:ind[0][i]]))
            time2[i] = time[ind[0][i-1] + np.argmax(np.abs(load[ind[0][i-1]:ind[0][i]]))]
    self.ZC_Amp = Amp
    self.ZC_Cyc = Cycles
    self.ZC_time = time2
```
if returns == True:
    return Amp, Cycles

def calcPeak2Peak(self, **kwargs):
    
    Calculates the number of cycles using peak to peak.
    This is the Simple-Range Counting Method from Section 5.3 of ASTM
    1049 - 85 (2011) where both positive and negative ranges are counted.
    Optional Keyword arguments:
    returns = True [default] or False
    thrshld = 0 [default]. Threshold load under which no cycles are
    counted.
    
    returns = kwargs.get('returns', True)
    thrshld = kwargs.get('thrshld', 0.)
    AmpType = kwargs.get('AmpType', 'SC')
    if AmpType == 'SC':
        divisor = 2.
    else:
        divisor = 1.
    load = self.load
    time = self.time
    dLoad = np.diff(load)
    ind = np.where(np.sign(dLoad[-1]) != np.sign(dLoad[1:]))
    ind2 = ind[0] + 1
    peaks = load[ind2]
    Amp = np.abs(peaks[1:] - peaks[:-1]) / divisor
    Cycles = np.ones(Amp.shape, dtype=float) * 0.5
    time2 = time[ind2[:-1]]
    ind4 = np.where(Amp != 0)
    Amp = Amp[ind4]
    Cycles = Cycles[ind4]
    Amp = Amp[:-1] + np.sign(Amp[-1])
    self.PP_Amp = Amp
    self.PP_Cyc = Cycles
    self.PP_time = time
    if returns == True:
        return self.PP_Amp, self.PP_Cyc

def calcRainflow(self, **kwargs):
    
    The Rainflow counting method as described in Section 5.4.4 of ASTM
    
    returns = kwargs.get('returns', True)
    Amp = np.abs(Amp) >= thrshld
    self.PP_Amp = Amp
    self.PP_Cyc = Cycles
    self.PP_time = time
    if returns == True:
        return self.PP_Amp, self.PP_Cyc

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# motions, I needed to divide the Amplitudes by two. But this is not
# the ASTM spec advises.
AmpType = kwargs.get('AmpType', 'SC')
if AmpType == 'SC':
    divisor = 2.
else:
    divisor = 1.
zero = self.mean
load = self.load
time = self.time
dLoad = np.diff(load)
ind = np.where(((dLoad[:-1] >= zero) & (dLoad[1:] < zero)) |
               ((dLoad[:-1] < zero) & (dLoad[1:] >= zero)))
ind2 = ind[0] + 1
peaks = load[ind2]
t = time[ind2]
Amp = []
Cyc = []
del ind
S = 0
ind = [0,1,2]
indorder = []

while ind[-1] < len(peaks):
    # Step 2 and 1
    if len(ind) < 3:
        ind.append(ind[-1]+1)
        try:
            Y = np.abs(peaks[ind[-3]] - peaks[ind[-2]])
            X = np.abs(peaks[ind[-2]] - peaks[ind[-1]])
        except IndexError:
            break
    if X < Y: # Step 3a
        ind.append(ind[-1] + 1)
        continue
    else: # Step 3b
        if S == ind[-3]: # Step 5
            Amp.append(Y)
            Cyc.append(0.5)
            indorder.append(ind[-2])
            S = ind[-2]
            ind.remove(ind[-3])
            continue
        else: # Step 4
            Amp.append(Y)
            Cyc.append(1.)
            ind.remove(ind[-2])
            ind.remove(ind[-3])
            indorder.append(ind[-2])
            continue

#Step 6
for val in ind:
    if val == ind[0]:
        ...
val0 = val
continue
elif val == ind[-1]:
    break
else:
    Amp.append(np.abs(peaks[val] - peaks[val0]))
    Cyc.append(0.5)
    val0 = val
    indorder.append(val)
time2 = t[indorder]
time2, Amp, Cyc = zip(*sorted(zip(time2, Amp, Cyc)))
self.RF_Amp = np.array(Amp) / divisor
self.RF_Cyc = np.array(Cyc)
self.RF_time = np.array(time2)
if returns == True:
    return self.RF_Amp, self.RF_Cyc

def plotter(self, figname=None, **kwargs):
    '''
    A plotting function for convenience of testing.
    '''
    import matplotlib.pyplot as plt
    if figname == None:
        plt.figure()
    else:
        plt.figure(figname)
    plt.plot(self.time, self.load, 'b', label='Input Loading')
    plt.plot(self.PP_time, self.PP_Amp, 'rx', label='PP')
    plt.plot(self.RF_time, self.RF_Amp, 'c^', label='RF')
    plt.plot(self.ZC_time, self.ZC_Amp, 'g+', label='ZC')
    plt.legend(loc='best')
    plt.xlabel('Time')
    plt.ylabel('Amp')
    plt.show()

def calcPR(self, **kwargs):
    '''
    Calculates the ratio of the peak of the motion to the average peak size.
    Ignores any peaks below the threshold
    '''
    thrshld = kwargs.get('thrshld', 0.)
    returns = kwargs.get('returns', False)
    self.PR = {}

    def mycalculator(Amps, Cycles, thrshld):
        ind = np.where(np.abs(Amps) >= thrshld)[0]
        if len(ind) == 0.:
            return 0
        else:
            return (np.max(np.abs(Amps)) /
np.average(Amps[ind], weights=Cycles[ind])

myAmps = ['ZC_Amp', 'PP_Amp', 'RF_Amp']
myCycs = ['ZC_Cyc', 'PP_Cyc', 'RF_Cyc']

for cyc, amp in zip(myCycs, myAmps):
    try:
        thisamp = self.__dict__[amp]
        thiscyc = self.__dict__[cyc]
    except ValueError:
        continue
    self.PR[amp[:2]] = mycalculator(thisamp, thiscyc, thrshld)
    if returns == True:
        return self.PR

if __name__ == '__main__':
    import EquivLin as el
    # motion, NFFT, FA, f, w, NPTS, dt = el.getInMotion('NGA_no_41_ORR021.AT2')
    # motion = np.array([1, -2, 1, -3, -1, 3, -4, 4, 2])
    # time = np.linspace(0, 15, 200)
    # motion = np.sin(time * 5)
    dt = 0.5
    MyLoad = Load(motion, dt=dt)
    ZCAmp, ZCycles = MyLoad.calcZeroCrossing()
    PPAmp, PPCycles = MyLoad.calcPeak2Peak()
    RFamp, RFCyc = MyLoad.calcRainflow()
    MyLoad.plotter()