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## Chapter 1

### Introduction

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#### 1.1 Statement of the Problem

Site characterization for geotechnical purposes is generally defined as "the identification and description of the subsurface strata within the areas of influence of a project" (Mitchell 1978). It is generally considered one of the most important tasks in geotechnical engineering, and is performed on most projects to provide information needed for geotechnical design. Given the need for high quality, site-specific information, a significant amount of research has been performed over the years related to the use of in-situ testing techniques for site characterization purposes. Although the bulk of these investigations were focused on site characterization for static loading problems (i.e. bearing capacity and settlement), a significant amount of research has surfaced within the last 35 years related to the use of in-situ testing techniques to evaluate the behavior of soils during earthquake loading.

Most in-situ approaches used to evaluate the behavior of soils during seismic shaking involve correlating a testing parameter obtained from the in-situ test to the resistance of the soil deposit to strength loss during cyclic loading. The testing parameter measured during the in-situ test indirectly takes into account the density and stiffness of the soil, the OCR, the age, and other geotechnical/geological factors related to the soil structure and its behavior during dynamic loading (Mitchell and Brandon 1997). The resistance of the soil to the loading is considered as the capacity of the soil to resist strength loss during loading and is generally determined through empirical correlations or field observations.

One such in-situ technique used to estimate the soil response to dynamic loading is the cone penetration test (CPT), which involves the penetration of a cone penetrometer into the ground at a constant rate of displacement. The most recent CPT empirical correlation adopted by the 1997 NCEER committee is presented as Figure 1.1 for saturated clean sands exposed to a  $M_w = 7.5$  earthquake. The figure includes a direct comparison of the penetration resistance measured during the test to the cyclic stress

imparted into the soil during an earthquake. The figure can be broken down into four main components:

- The penetration resistance ( $q_{cIN}$ ) value located on the abscissa. This value was measured during the penetration test and was corrected for fines content and depth based on empirical relationships presented in Youd and Idriss (1997).
- The cyclic stress ratio (CSR) value on the ordinate. It is generally determined using the *simplified procedure* established by Seed and Idriss (1971), which takes into account the ground accelerations generated by an earthquake, the stress conditions present in the soil, and the flexibility of the soil mass. The ground accelerations used in the calculation are generally obtained from either earthquake records at the site of interest or through records obtained from sites of similar geologic composition. The CSR value can also be estimated through the cyclic testing of undisturbed soil samples in the laboratory, but such samples are difficult and expensive to obtain. Empirical correction factors are also needed to relate the lab generated values to field approximations, with the magnitude of the factor dependent on the type of testing apparatuses.
- Records of field performance at sites where liquefaction was and was not observed after an earthquake. Surface evidence of liquefaction was manifested in the form of ground subsidence, sand boils, and/or lateral spreading.
- The cyclic resistance ratio (CRR) curve. This curve empirically generated curve divides the conditions where liquefaction and non-liquefaction was observed for earthquakes of different CSR values. Points along this CRR curve are considered as the capacity of the soil to resist strength loss during loading for a given  $q_{cIN}$  measurement and CSR.

The use of Figure 1.1 to characterize the potential for soil strength loss during dynamic loading involves comparing the CRR estimated from the corrected penetration resistance measurement to the cyclic stresses imparted into the soil during the earthquake (CSR). The general procedure for estimating the strength loss potential of the soil at the site involves measuring the penetration resistance value at the site, correcting the value to

account for depth and fines content, and then projecting the corrected value upwards until it intersects the CRR curve in Figure 1.1. This point of intersection defines the maximum CSR that the soil can resist without causing high pore water pressure, strength loss, and possible large strains (i.e. liquefaction) during the seismic loading. If the CSR value computed from the *simplified procedure* or laboratory tests is greater than this CRR value approximated from the curve, the soil may undergo significant amounts of strength loss during seismic shaking. If the computed CSR value is less than this CRR value, the soil is considered resistant to liquefaction.

The above mentioned soil evaluation procedure involves the correlation of the penetration resistance, which is an indirect measurement of the soil density, to surficial evidence of soil response to seismic loading through the CRR. (Figure 1.1). The approach assumes that liquefaction occurred only at the sites where subsidence, sand boils, and lateral spreading were observed and did not take into account the soil deformation over the entire depth of the soil stratum. Similarly, the CSR values computed for each of the sites were not always based on acceleration measurements at the site itself, which lends to the possibility that the estimated CSR values were not always indicative of the actual loading conditions in the soil column during the earthquake. Thirdly, the correlation was developed for clean sands exposed to a  $M_w = 7.5$  earthquake. A separate in-situ investigation is therefore needed to provide information regarding the grain size distribution of the soil so that a proper correction to the clean sand equivalent value is made. Similarly, earthquakes of magnitudes other than  $M_w = 7.5$  are also corrected using empirical factors. As noted by Youd and Idriss (1997), both the soil gradation and earthquake magnitude correction factors are not well established and should be used with caution.

To account for the indirect nature of the approach and the questions regarding the empirical correction factors, an in-situ approach was developed as part of this research to directly measure the response of a soil mass to dynamic loading. The approach involves the measurement of the penetration resistance during vibratory penetration of a cone penetrometer and then relating these penetration resistance values to the potential of the soil deposit to exhibit large strains during seismic loading. The approach is based on the direct in-situ measurement of the soil response to a given input energy, and takes into account the soil density and the effective stress condition in the soil.

## **1.2 Scope of Work**

The primary focus of this research was to evaluate the effects of vibration on the penetration resistance measurement obtained during CPT testing in saturated clean sands. The study consisted a literature review, index and strength testing in the laboratory, cone penetration testing in a large calibration chamber, and analyses of the strength testing and cone penetration test data. The initial phase of the research project involved a comprehensive literature review related to cone penetrometer testing and the behavior of saturated cohesionless soils during dynamic loading. The second phase of the project involve the modification of the Virginia Tech calibration chamber to allow for the testing of saturated sand samples. The third project phase included index testing and monotonic and cyclic triaxial testing on the sand used in the calibration chamber investigation, while the fourth phase involved static and vibratory penetration tests in saturated sand samples at different density and stress conditions. Vibrators of different force, frequency, and direction of vibration vibrators were used in the testing. The final phase of the project involved a quantitative and qualitative analysis of the penetration resistance and pore pressure measurements. The results of the investigations led to an overall evaluation of the effects of vibration on the penetration resistance, the development of empirical correlations of the penetration resistance with the relative density of the soil, and an evaluation of the effects of vibration frequency on the measured penetration resistance value. A method for evaluating the input energy and energy efficiency of the vibratory unit used in the testing is also proposed.

## **1.3 Outline of Dissertation**

A summary of the information presented in the literature related to cone penetration testing, the behavior cohesionless soils during cyclic loading, and the pore pressure developed in sands during static and vibratory loading is presented in Chapter 2. The chapter also includes a discussion of background information related to the definition of liquefaction based on steady-state principles.

The ICU and cyclic triaxial test results are presented in Chapter 3. The procedure used to compute the energy capacity of the soil during dynamic loading is also presented at this time. The equipment used in the experimental testing program and representative vibration measurements are also discussed in the chapter.

The Virginia Tech calibration chamber and the pluviation and saturation systems used in the cone penetration testing program are presented in Chapter 4. The penetration resistance and pore pressure measurements obtained from the testing in this calibration chamber are included in Chapter 5. Chapter 5 also includes a qualitative, quantitative, and statistical analysis of the effects of the testing location, cone type, boundary condition, and mode of penetration on the penetration resistance and pore pressure values measured during the testing.

An evaluation of the effects of vibration on the penetration resistance measurement is presented in Chapter 6. The chapter includes a qualitative comparison of the static and vibratory penetration test data. Proposed methods for estimating the relative density of the soil and evaluating the energy efficiency of the vibratory unit are also presented in the chapter. The effect of vibration frequency on the penetration resistance value is also discussed.

A summary of the results and conclusions of the work performed as part of the study is presented in Chapter 7. Recommendations for future research are also presented in the chapter.

The calibration curves associated with the different pieces of the testing equipment are presented in Appendix A. Appendix B contains the sample preparation and CPT testing procedure developed as part of the study. The results of the statistical analysis of the penetration resistance data is provided in Appendix C.