

Chapter 9. Summary and Conclusions

9.1 Restatement of Research Objective

The states-of-practice for performing earthquake liquefaction analyses and remedial ground densification designs have evolved relatively independent of each other. This is in spite of the fact that liquefaction is typically induced in saturated sands as part of the remedial ground densification process. The goal of this research is to assess the feasibility of using the vast amount of data collected over the years on earthquake induced liquefaction for remedial ground densification design via energy-based concepts.

9.2 Overview of Research

The energy dissipated by frictional mechanisms during the relative movement of sand grains is hypothesized to be directly related to the ability of a soil to resist liquefaction (i.e., *Capacity*). Assuming a linearized hysteretic model, a “simplified” expression was derived for computing the energy dissipated in the soil during an earthquake (i.e., *Demand*). Using this expression, the cumulative energy dissipated per unit volume of soil and normalized by the initial mean effective confining stress (i.e., normalized energy demand: *NED*) was calculated for 126 earthquake case histories for which the occurrence or non-occurrence of liquefaction is known. By plotting the computed *NED* values as a function of their corresponding SPT penetration resistance, a correlation between the normalized energy capacity of the soil (*NEC*) and SPT penetration resistance was established by the boundary giving a reasonable separation of the liquefaction / no liquefaction data points. *NEC* is the cumulative energy dissipated per unit volume of soil up to initial liquefaction, normalized by the initial mean effective confining stress, and the *NEC* correlation with SPT penetration resistance is referred to as the *Capacity* curve.

The assessment of the feasibility of using the *Capacity* curve in remedial ground densification design was two fold. First, because earthquake motions and the motions induced in the soil by remedial ground densification techniques differ in amplitude, duration, and frequency content, the dependence of *NEC* on such things needed to be determined (i.e., if *NEC* varied as a function of the amplitude, duration, and frequency

content of the induced motions, then the *NEC Capacity* curve derived from earthquake case histories may not apply to remedial ground densification techniques). Towards this end, the calibration parameters for energy-based pore pressure generation models were examined for their dependence on the amplitude of the applied loading. The premise being that if the relationship between dissipated energy and pore pressure generation is independent of the amplitude of loading, then the energy required to generate excess pore pressures equal to the initial effective confining stress should also be independent of the load amplitude. However, no conclusive statement could be made from results of this review. Next, first order numerical models were developed for computing the spatial distribution of the energy dissipated in the soil during treatment using the vibratory probe method, deep dynamic compaction, and explosive compaction. In conjunction with the earthquake *Capacity* curves, the models were used to predict the spatial extent of induced liquefaction during soil treatment and compared with the predicted spatial extent of improvement using empirical expressions and guidelines. Although the proposed numerical models require further validation, the predicted extent of liquefaction and improvement are in very good agreement, thus giving credence to the feasibility of using the *Capacity* curve for remedial ground densification design.

Although further work is required to develop energy-based remedial densification design procedures, the potential benefits of such procedures are as follows. By using the *Capacity* curve, the minimum dissipated energy required for successful treatment of the soil can be determined. Because there are physical limits on the magnitude of the energy that can be imparted by a given technique, such an approach may lead to improved feasibility assessments and initial designs of the densification programs.

9.3 Summary of Major Findings

- From the critical review of existing energy-based liquefaction evaluation procedures presented in Chapter 2, it was determined that none of the existing procedures are at the required stage of development for use in remedial densification design. This does not necessarily preclude the use of these

procedures for performing earthquake liquefaction evaluations, but such use is cautioned.

- The author proposed a new energy-based excess pore pressure generation model in Chapter 4. The model accurately predicted the excess pore pressures generated in a numerous cyclic laboratory tests on various silt-sand mixtures. The proposed model has a single calibration parameter for which preliminary correlations with relative density of medium- and fine-grained sands were presented.
- A new energy-based liquefaction evaluation procedure is presented in Chapter 5. Similar to the stress-based procedure, the proposed energy-based procedure uses a *Capacity* curve, which was derived from analyzing earthquake case histories. The purpose for developing the energy-based procedure was for use in remedial densification design, which will be discussed subsequently. However, for earthquake analyses, this proposed energy-based liquefaction evaluation procedure offers several advantages over the commonly used stress-based procedure, especially when used in conjunction with total stress site response analyses (e.g., SHAKE).

SHAKE is often used in conjunction with the stress-based procedure to compute refined estimates of the amplitude of the shear stresses induced in the soil column. Although such site response analyses give a refined estimate of the *amplitude* of the induced shear stress, magnitude scaling factors (*MSF*) are still relied on to account for the *duration* effects of the earthquake motion (i.e., *Demand* is a function of both the amplitude and duration of the applied loading). On the contrary, by quantifying *Demand* in terms of dissipated energy, as is done in the proposed energy-based liquefaction evaluation procedure, integration of the shear stress-strain time histories computed from SHAKE analyses inherently accounts for the amplitude, duration, and frequency content of the design motion.

- As part of the proposed energy-based liquefaction evaluation procedure, a new procedure was developed for computing number of equivalent cycles (N_{eqv}) for earthquake motions. Using this procedure, a correlation was developed relating N_{eqv} to earthquake magnitude and site-to-source distance, as opposed to earlier correlations, which express N_{eqv} only as a function earthquake magnitude. Aside from the main focus of this thesis, the proposed N_{eqv} correlation was used to derive magnitude scaling factors (MSF) for the stress-based liquefaction evaluation procedure. The newly derived MSF are functions of both earthquake magnitude and site-to-source distance. In comparing the currently used MSF and the proposed MSF , the former may under predict the *Demand* imposed on the soil at low magnitudes (i.e., $M < 6$) and over predict the *Demand* for large magnitude earthquakes in the near field.
- A procedure for determining the a_{max} at the surface of a soil profile is presented in Chapter 6. The proposed procedure is based on an observed relationship between the characteristics of rock outcrop motions and a_{max} at the surface of uniform profiles. To validate the proposed procedure, it was used to predict a_{max} values for soft soil sites subjected to the Loma Prieta earthquake at short and long epicentral distances. For the limited comparison conducted as part of this study, the predicted results were in good agreement with field observations.
- First order numerical models were proposed for computing the spatial distribution of energy dissipation in the soil during treatment using the vibratory probe method, deep dynamic compaction, and explosive compaction. In conjunction with the energy-based *Capacity* curve presented in Chapter 5, the models were used to prediction the spatial extent of induced liquefaction during treatment. The predicted extent of liquefaction was in very good agreement with the predicted extent of improvement using empirical expressions and guidelines, thus giving credence to the feasibility of using the *Capacity* curve for remedial ground densification design.

9.4 Recommendations for Future Work

The use of earthquake data in remedial ground densification design was shown to be feasible using the energy-based concepts presented in this thesis. However, considerable more work is required to develop energy-based design procedures that can be easily used by practitioners for designing remedial ground densification programs. Particularly, correlations need to be developed relating the amount of energy dissipated per unit volume of soil to a quantifiable measure of improvement (e.g., increase in penetration resistance or magnitude of induced settlement). This would be analogous to the empirical expressions proposed by Fernandez and Corcoran (2001) which relate the total mechanical energy imparted to soil by surface compactors to post-treated dry density.