Chapter 7

Summary, Conclusions, and Suggestions for Future Research

7.1 Summary and Conclusions

The primary focus of this research was to evaluate the effects of vibration on the penetration resistance and the pore water pressure measured during CPT testing in saturated clean sands. The study consisted of an evaluation of the literature related to cone penetration resistance and pore pressure development in sands, index and strength testing in the laboratory, calibration chamber testing, and the evaluation of the in-situ behavior of cohesionless soils during static and vibratory cone penetration testing. The information obtained from each of these phases of the project contributed to an empirical correlation of the penetration resistance with the relative density of the soil, an evaluation of the effects of vibration frequency on the measured penetration resistance value, and a proposed method for evaluating the input energy and energy efficiency of the vibratory unit used in the testing.

The first chapter includes a general statement of the problem addressed through the research and the scope of work related to the experimental testing program. An outline of the dissertation is also presented in this chapter.

Chapter 2 includes 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 penetration of a cone penetrometer. It appears that the penetration resistance is highly dependent on the initial lateral effective stress, relative density of the soil, soil fabric, compressibility, OCR, stiffness, and age of the soil deposit. The type of boundary condition and D_{cc}/d_{cp} ratio present in the calibration chamber can influence the penetration resistance and pore pressure measurement at certain density and stress conditions.

Little information was found in the literature regarding the generation of excess pore water pressures during cone penetration in saturated clean sands. Pore water pressures measured at a finite distance away from a vibrating probe revealed excess water pressures that approached the vertical effective stress in the soil (Baez 1995). An analysis of the soil response during vibratory pile driving suggests that the shear strain at the soil/pile interface increases and the shear strain away from the pile decreases as the frequency of vibration is increased. This indicates that the pore water pressure induced in the soil stratum away from the pile is dependent on both the frequency of vibration and the strain at the soil/pile interface.

A summary of the index and strength testing properties of Light Castle Sand was presented in Chapter 3. A complete discussion of the equipment used in the experimental testing program is also included in the chapter. Cyclic triaxial test results reveal that the NDE at the point of failure in the test specimen is a function of the CSR applied to the soil. An analysis of the dynamic force generated by the rotary turbine and counter rotating mass vibrators reveals a minimal energy loss during propagation of the vibration through the rod system. The total energy imparted into the soil per cycle of vibration was defined as the integral of the product of the dynamic force and displacement over the full cycle of motion associated with the vibration.

A description of the Virginia Tech calibration chamber, the associated pluviation and saturation systems, and the sample preparation and testing procedures was presented in Chapter 4. The sample was placed inside the calibration chamber through an air pluviation technique. Perforated plates inside the pluviator control the density of the sample. Target densities of 25% and 55% were used in the testing. A saturation system was added to the calibration chamber as part of the project, which allows for the saturation of the samples after pluviation. Cone penetration tests were performed in the chamber in dry and saturated samples with and without vibration applied to the penetrometer.

An analysis of the penetration resistance and pore water pressure data collected during the calibration chamber investigation was presented in Chapter 5. The data reduction procedure and stress normalization procedures were also included. The effects of saturation, cone type, and the influence of the lateral and vertical boundaries on penetration resistance and pore water pressure were discussed. A statistical analysis of the penetration test data, comparisons of the measured penetration resistance values to those estimated from cavity expansion theory, and the representative penetration resistance and pore pressure curves were also presented in the chapter.

When possible, penetration tests were performed in each of the samples at both the center and off-center testing locations. For a given testing condition, the static penetration resistance value at the vertical center of a loose sample is approximately equal for each test, regardless of the testing order, location, type of test previously performed. Similar results were noted for vibratory tests and static and vibratory tests in medium dense samples at the low stress level using the 10-cm^2 cone.

The static penetration resistance measured in dry samples was approximately equal to that measured in saturated samples for static tests performed at similar stress and density conditions. However, the vibratory penetration resistance measured at the sample center in dry samples was much greater than the values recorded for saturated samples, suggesting the presence of water significantly affected the response of the soil to vibratory loading.

A comparative analysis of the data in loose samples revealed a fairly constant influence of the lateral boundary on the penetration resistance and pore pressure values at the center and off-center testing locations. This behavior was noted for both boundary conditions, both modes of vibration, both cones, and all stress states. Penetration tests performed in medium dense samples at the low stress level with the 10-cm^2 cone produced similar results, while tests performed at the elevated stress levels resulted in penetration resistance and pore pressure values that were highly dependent on the proximity of the cone to the lateral boundary. The ANOVA statistical analysis agreed with these qualitatively and quantitatively based conclusions.

A comparison of the pore pressure values measured at the different element locations revealed that the magnitude and response of the pore pressure generated during penetration was not dependent on the pore pressure transducer location. Dummy cone tests performed in loose samples at the low stress levels revealed an induced water pressure away from statically penetrating cone that was approximately equal to that measured on the cone itself. Vibratory tests performed under similar conditions revealed an induced water pressure away from the penetrating cone that was approximately 88% of the confining stress in the soil. It is therefore suggested that the pore water pressure measured on the advancing cone is not representative of the pore water pressures present in the zone of influence of the penetrometer.

The penetration resistance measured during the calibration chamber testing in the loose samples agrees with the estimations from empirical techniques and cavity expansion theory. The penetration resistance measured in the medium dense samples agrees with the approximations obtained through cavity expansion theory for the intermediate and high stress level and falls below the approximation at the low stress level. The low value of the measured penetration resistance at the low stress level may be attributed to the absence of a constant vertical stress boundary in the chamber. The penetration resistance value measured in the medium dense samples is also significantly less than that estimated from the empirical techniques. This may be attributed to grain size distribution, angularity, and compressibility differences between of Light Castle sand and the sand used to form the empirical relationships.

An evaluation of the effects of vibration on the penetration resistance measurement was presented in Chapter 6. The chapter includes a direct comparison of the static and vibratory penetration test data for different stress and density conditions, a proposed method for estimating the relative density of the soil using the static and vibratory penetration resistance values, and an analysis of the influence of the frequency of vibration on the penetration resistance value. A proposed method for evaluating the energy efficiency of the vibratory unit is also presented in the chapter.

A comparison of the static and vibratory penetration resistance values reveals that vibration can significantly influence the penetration resistance value. The vibration seems to dramatically influence the penetration resistance at the low stress level because the zone of influence of the vibration overlaps the shearing zone of influence of the cone penetrometer. As shown through cavity expansion theory and the dummy cone tests, the pore water pressure is significantly increased in the volume of soil associated with the zone of influence of the cone penetrometer, resulting in a reduction in effective stress and subsequent penetration resistance decrease.

The influence of the vibration on the penetration resistance value decreases as the density and the mean effective stress in the soil increases. It was shown through cavity expansion theory that the zone of influence of the cone penetrometer increased as the effective stress and relative density of the soil increased. It is suggested that the vibration does not substantially decrease the penetration resistance at the elevated stress levels because the pore water pressure was not significantly elevated throughout the entire zone of influence of the cone penetometer.

Trendlines were generated for both relative densities that relate RR to the vertical effective stress in the soil. Calibration chamber tests performed at stresses outside of the target stress levels seem to agree well with that estimated through the proposed relationships. A family of curves was generated through a regression analysis that relates RR to vertical effective stress for different density soils. Several tests performed on soil samples outside of the target density values also seem to agree well with the proposed values estimated through the family of curves.

An approximation of the first fundamental frequency of the soil deposit averaged 32 Hz for the two density soils. The largest reduction in penetration resistance occurred when the input vibration was near this value, suggesting that resonance conditions existed between the input motion and the soil.

A NIE based approach was developed to evaluate the energy imparted into the soil by the rotary turbine vibrator. The approach is similar to those developed for evaluating the energy imparted into the soil during SPT testing. The NIE per cycle of vibration determined for the unit was normalized by the volume of soil within the zone of influence of the vibrator. This volume of soil was approximated at the low stress level by using the water pressure information measured away from the vibrating penetrometer during the dummy cone tests and was estimated at the elevated stress levels using cavity expansion theory and numerical relationships presented in the literature. Test results indicate that NIE introduced into the soil mass prior to the reduction in penetration resistance agrees well with the NDE at the point of failure in the soil structure, especially at the low stress levels where a high excess pore water pressure and low effective stress levels were observed.

7.2 Suggestions for Future Research

The present research program has shown that vibration can influence the penetration resistance and pore water pressure measurements under certain density and stress conditions. The following recommendations are made in order to better define the relationship between the dynamic load and the measured CPT parameters:

- Install a dynamic load cell at the tip location in the cone penetrometer to provide a means for directly measuring the cyclic force imparted into the soil during the vibration.

- Perform field tests in clean sand deposits where the geotechnical parameters are well established to evaluate the relative density/effective stress/RR correlations developed through this research. Accelerometers should be mounted in the cone rod system to evaluate the propagation properties of the rods as they are exposed to different stress conditions and impedance properties.

- Perform field tests at sites where liquefaction was and was not observed to develop an empirical CSR versus RR correlation that considers the in-situ behavior of the soil during vibratory loading. This correlation may remove some of the questions regarding the use of surface features to define subsurface liquefaction and may provide a direct measure of evaluated zones in a soil column that are susceptible to large strength loss during dynamic loading.

- Mount accelerometers and pore pressure transducers in calibration chamber samples prior to stress application and vibratory penetration of the cone. This instrumentation will provide the information that will allow for direct measurement of the zone of influence of the vibration used in the NIE calculations.

- Develop a vibrator that can generate a large enough input energy to liquefy the soil deposit at the higher stress levels. The penetration resistance value measured in this liquefied soil may provide an estimation of the undrained steady-state strength of the soil.

- Generate relationships of the force and frequency combination needed to liquefy the soil for different density and stress conditions. This information can be related to liquefaction based analysis or soil improvement techniques involving vibroflotation, vibrocompaction, and stone columns.