
Chapter 5

Calibration Chamber Test Results

5.1 Introduction

The purpose of this chapter is to review and summarize the data obtained from the calibration chamber tests and to determine representative penetration resistance and pore water pressure curves for each of the test conditions. The chapter begins by briefly redefining the equipment used and conditions present during the testing, and provides a general overview of the testing procedure. The chapter contains the data reduction procedure used to generate representative penetration resistance and pore pressure curves for all of the test conditions, and includes discussions of the effects of the degree of saturation, test location, and cone type on the penetration resistance and pore pressure measurements. An evaluation of the effects of the pore pressure transducer location on the measured pore water pressures as well as an evaluation of the relationship between the measured penetration resistance value and the testing sequence is also included in the chapter. The results of a series of dummy cone tests performed in loose samples are also presented. The chapter contains a statistical analysis of the representative penetration test data for each test condition and a comparison of the static penetration test data measured during the tests to values estimated from empirical and analytical techniques. The chapter is concluded with the presentation of a series of curves and regression parameters that represent the penetration resistance and pore pressure ratios encountered during the testing. It is these representative curves that are used in the analysis of the effects of vibration on the penetration resistance presented in Chapter 6.

5.2 Equipment and Test Conditions

Light Castle sand was used in all of the calibration chamber and laboratory testing as part of this study, and can be identified as a uniform clean sand (*SP*) composed of subrounded to subangular quartz grains. A grain size distribution curve for Light Castle sand was presented in Figure 3.1 of Chapter 3. A 15-cm² Fugro piezocone and a 10-cm² Georgia Tech piezocone were used in the testing. Pore pressures were measured at the midface (U_1) and shoulder (U_2) locations on the 15-cm² penetrometer and at the shoulder (U_2) location on the 10-cm² cone (Figure 3.21). Both cones were suggested by

their respective manufacturers to be robust in nature and capable of withstanding the vibration induced through the vibratory portion of the testing.

Testing in the calibration chamber involved both static and vibratory cone penetrometer tests in loose ($D_r = 20\%$ to 30%) and medium dense ($D_r = 50\%$ to 60%) sand samples. Three different effective stress levels and $K = 0.45$ to 0.6 conditions were used in the testing. The three vertical effective stress levels were set at 7.5 kPa, 55 kPa, and 110 kPa to simulate depths of 0.8 m, 6.4 m, and 12.8 m, respectively, based on the density of the soil in the loose condition. Tests were performed in both dry conditions and saturated states with different levels of backpressure. Measurements of the tip resistance, sleeve friction, and pore water pressure were recorded with depth during each penetration test. Included as Tables 5.1 through 5.5 are the number of tests performed at each test condition for the different cone penetrometers and vibrators. A total of 118 penetration tests were performed in the calibration chamber as part of the study.

The calibration chamber testing was initially performed using the Fugro 15-cm^2 cone penetrometer until electrical problems developed in the instrument. The 10-cm^2 cone was then obtained from Georgia Tech so that the testing could continue, which corresponded to the beginning of the testing in the medium dense samples at the low stress level. No static tests at the intermediate and high stress levels or vibratory penetration tests at any stress level were performed in the medium dense samples with the 15-cm^2 cone penetrometer prior to the development of the electrical problems. Consequently, test data was only obtained for the 15-cm^2 cone in the medium dense samples at the low stress level (see Tables 5.1 through 5.4).

Three different vibratory units were used in the calibration chamber testing to provide dynamic excitation to the cone penetrometer. The first unit, the pneumatic impact vibrator, did not provide enough of a dynamic excitation to modify the penetration resistance and was subsequently limited in use in the testing. Since the penetration resistance and pore pressure values measured using this vibrator did not differ greatly from those obtained from the static penetration tests, the measured test data was included with the static test results in all comparative analyses. The reader is referred to Section 6.2 of Chapter 6 for a further discussion of the test results using the pneumatic impact vibrator. The bulk of the vibratory testing involved the use of the rotary turbine unit, with the test results used in the analyses presented in Sections 5.6 through 5.8. The counter rotating mass vibrator was built towards the end of the testing program, and was

primarily used to evaluate the effect of the vibration frequency on the penetration resistance and pore pressure behavior during penetration. The results of the testing using this are included in Chapter 6.

All three vibratory units used in the testing were mounted on top of a 1.0m section of cone rod that was attached to the top of the cone penetrometer. The vibration from each of the vibratory units was measured at the bottom of the unit through a series of load cells and at the top of the cone by an accelerometer. Discussions of the details of each of the vibratory units and their associated load and frequency outputs are included in Sections 3.4 and 3.7 of Chapter 3, respectively.

5.3 Testing Procedure

A general schematic of the chamber system is presented as Figure 5.1, with a brief outline of the primary components mentioned herein. A more detailed discussion of the calibration chamber components and testing procedures is included in Chapter 4.

The Virginia Tech calibration chamber is 1.5m in diameter, 1.5m tall, and is cylindrical in shape. A sand sample is air pluviated into the chamber inside a 40-mil membrane liner to a predetermined density. The sample is purged with CO₂ and then inundated with water from the bottom to the top through a recently implemented water saturation system. Tests performed at the intermediate and high stress levels involved sealing the sample and applying confining and vertical pressures through independent pressure application systems. A water pressure can be applied to the interior of the test specimen through an independent water pressure system if desired. A hydraulic press is then mounted onto the lid of the chamber to push the penetrometer at a constant rate of displacement into the sample. Penetration tests were performed in the calibration chamber both statically and with vibration applied at the top of the rod. The vibration was started either at the beginning of penetration or at a depth of about 0.45m into the sample. The tip resistance, sleeve friction, and pore water pressure were measured during penetration and recorded using an automated data acquisition system. In the vibratory tests, the force and acceleration generated by the vibrator were also recorded through a second high-speed data acquisition system.

Penetration tests were performed in the calibration chamber with and without stresses applied to the sample. Tests performed without applied stresses simulated a rigid

wall condition with a zero lateral strain boundary (*BC3*). These tests did not involve the placement of the top plate and lid over the sample, which removed the hole diameter restrictions from the top lid when using the 15-cm² cone for the testing. As such, penetration tests were performed at the low stress condition at both the center and off-center locations. Penetration tests performed at the off-center locations resulted in chamber to cone ratios (D_{cc}/d_{cp}) of 10 for the 15-cm² cone and 12 for the 10-cm² cone, while tests performed at the center location corresponded to D_{cc}/d_{cp} ratios of 34 and 41, respectively. The off-center test holes were located at a distance of 0.35m from the center of the sample and were spaced 60° apart from one another in plan view. A schematic showing the location of the both the center and off-center test is presented as Figure 5.2.

Penetration tests were also performed in the calibration chamber with stresses applied to the sample. This testing condition is defined as a flexible wall condition with constant vertical and lateral stress boundaries (*BC1*) and was present at the medium and high stress states where the sample was sealed and confining and vertical stresses were applied to the sample. As shown in Tables 5.1 through 5.3, penetration tests using the 10-cm² penetrometer were performed under these conditions at the sample center (D_{cc}/d_{cp} ratio = 41) and at a radius of $r = 0.35\text{m}$ away from the center (D_{cc}/d_{cp} ratio = 12). Tests conducted under applied stresses using the 15-cm² penetrometer were only performed at the sample center because the diameter of the cone was larger than the diameter of the non-center port openings in the lid of the chamber.

5.4 Data Reduction Procedure

5.4.1 Penetration Test Results

As noted in the previous section, penetration tests were performed in the calibration chamber statically and with a dynamic load applied to the drill rod and cone penetrometer. The rotary turbine and the counter rotating mass vibrators provided a force and frequency combination that resulted in a penetration resistance values that were different from the values obtained during static penetration for certain density and stress conditions. An example of this influence of vibration on the penetration resistance is presented as Figure 5.3, where the test results from loose saturated samples at the low stress state are compared. As shown through this comparison, the vibratory penetration resistance is significantly less than the static at the vertical center of the sample ($z = 0.75\text{m}$),

suggesting that the dynamic load imparted into the soil by the vibrator influenced the penetration resistance.

The cone penetration tests were performed in the calibration chamber for two density states and three different effective stress levels. Given the nature of the testing program and the stress application procedure associated with the chamber, the stress values listed in Section 5.2 should be considered as the *target* stress values. The *actual* stress values recorded during the testing varied slightly from the target stress levels for most of the chamber tests because of the difficulty in generating exact vertical stresses from the air pistons. This resulted in fluctuations of the recorded penetration resistance and pore pressure values for a given target stress condition. A stress normalization procedure was therefore undertaken so that the penetration resistance values could be compared. This normalization procedure was performed for the different density and target stress levels. It was also performed for the pore pressure readings at two densities and three stress levels used in the testing.

5.4.2 Stress Normalization Procedure

Numerous stress normalization approaches have been presented in the literature that attempt to relate the penetration resistance value to the stress level of the soil (e.g. Schmertmann 1978; Robertson 1982; and Olsen 1984, 1994; and Olsen and Mitchell 1995). These normalization techniques range from simple linear normalization to complex stress focus approaches that use a stress exponent based on soil type and strength. Each of these approaches involves the use of an empirically generated exponent to modify the vertical effective stress, which is in turn used as the normalizing parameter:

$$q_{c(N)} = \frac{q_c}{(\sigma_v')^c} \quad (5.1)$$

where $q_{c(N)}$ is the normalized penetration resistance, q_c is the measured penetration resistance, σ_v' is the vertical effective stress in the soil, and c is the stress exponent. The values of c noted in the literature typically range from 0.4 to 1.0 and are highly dependent on the soil type, relative density, and vertical effective stress in the soil. A value of c between 0.5 and 0.7 is commonly used for stress ranges between 100 and 200kPa (Olsen 1997). However, Schmertmann (1978) and Robertson (1982) suggest that any magnitude of c can be used to represent the normalization behavior of a given soil type, provided the value is empirically or theoretically verified. As discussed in Section 5.11, a value of c of 1.0 resulted in a normalized penetration resistance value for each relative density that

was constant for the range of stresses used in the testing. As such, a linear normalization procedure ($c = 1.0$) was used in the study.

Presented as Tables 5.6 through 5.9 are the stress conditions and test results for static and vibratory penetration tests performed at both densities and all stress levels. The penetration resistance (q_c), excess pore water pressure (Δu), and sleeve friction (f_s) values listed in the tables are the actual values measured during the tests at a depth of $z = 0.75\text{m}$ into the sample. The vertical effective stress (σ_v'), horizontal effective stress (σ_h'), and back pressure (u_b) conditions listed in these tables were the stress conditions present at the vertical center of the sample ($z = 0.75\text{m}$) prior to penetration. The normalization procedure used in the analyses involved the computation of the total and effective stress with depth in the sample above and below this center location and then normalizing the reduced testing parameter (tip resistance or pore pressure) by the actual initial vertical stress present in the sample using Equation 5.1. Thus, the testing parameter measured at a defined depth was normalized by the actual initial effective stress calculated for that same depth, resulting in the generation of penetration resistance and pore pressure ratio curves for the sample depth.

5.4.3 Formulation of Representative Trendlines

As shown through Tables 5.1 through 5.4, 118 penetration tests were performed in a total of 57 different samples, resulting in numerous penetration tests at certain test conditions (e.g. there were 5 penetration tests performed at the low stress, low D_{cc}/d_{cp} ratio, loose density condition with the 15-cm² cone). A representative curve was formed for each of these data sets by fitting a best-fit trendline through the following testing conditions:

- a) Tests performed at off-center locations using a particular cone penetrometer (10-cm² or 15-cm²). These test locations are referenced as the low D_{cc}/d_{cp} location in all subsequent discussions.
- b) Tests performed at center location using a particular cone penetrometer (10-cm² or 15-cm²). This test location is referenced as the high D_{cc}/d_{cp} location in all subsequent discussions.
- c) The combined data set that includes tests performed at both the low and high D_{cc}/d_{cp} locations using a particular cone penetrometer (10-cm² or 15-cm²).

- d) The combined data set that includes tests performed at both the low and high D_{cc}/d_{cp} locations using both penetrometers.

The majority of the penetration tests performed as part of the testing program exhibited a shape of the normalized penetration resistance curve similar to that presented in Figure 5.4. Plots of the pore pressure ratio ($\Delta u/\sigma_v'$) with depth in the sample exhibited a similar shape. Both of these curves showed an inconsistent increase in the measured soil property down to depth of about 0.2m into the sample, after which a plateau was generally encountered down to a depth of about 1.35m. A rapid increase in the penetration resistance at depths less than 0.2m is particularly pronounced in tests performed at the elevated stress levels, and is mainly attributed to the influence of the upper rigid boundary present during the testing. The measured values within this zone exhibited a great deal of scatter, especially in the vibratory tests and in tests performed at the low stress levels, and were therefore not considered representative of the actual soil conditions. Thus, the test data at depths less than 0.2m into the sample were excluded from all analyses. Similarly, both the penetration resistance and the pore water pressure values rapidly increased at depths greater than 1.35m into the sample, marking the influence of the rigid lower boundary on the testing parameter. Data obtained during the tests at these depths was also excluded for similar reasons.

The penetration resistance and pore pressure data considered for analysis is the data that has not been strongly influenced by the rigid upper and lower boundaries present in the chamber. The penetration tests at each test condition were compiled into cases (a) through (d) noted above and fit with a quadratic regression curve. Each of these regression curves allows for the generation of plots of normalized penetration resistance or pore pressure versus depth into the calibration chamber that is considered representative of the given test location and condition, and is used in the analyses presented in Sections 5.5 through 5.7.

Several of the normalized penetration resistance trendlines generated through the analysis noted in (a) through (d) above were fit through data sets of more than one penetration test, resulting in a standard deviation above and below the mean penetration resistance value. The standard deviation can be considered as the range of values encountered for a given test conditions, and generally gives some idea of the variation in the test data relative to the mean value. This variation of the test data is primarily due to

the differences in the bulk sample density at a given test condition (e.g. the loose state ranges from $20 < Dr\% < 30$) and soil fabric fluctuations that were generated during the pluviation of the sample. A summary of the standard deviation values for the test conditions with multiple penetration tests is included in Tables 5.10 and 5.11 for both densities, both modes of penetration, and all stress levels. The values included in this table were based on the normalized penetration resistance values measured at the vertical center of the sample. The mean penetration resistance values and the values generated by the representative trendline are also included in these tables. A complete discussion of the data used to form the representative trendline is included in Sections 5.5 through 5.8.

An Analysis of Variance (ANOVA) was performed on the compiled data sets to determine the statistical variability at a given test condition, between the test conditions, and to determine whether or not variations in the measured penetration resistance values were statistically significant. The analysis was performed for the following conditions:

- a) Variability of the test data at a given test condition
- b) Effect of stress on penetration resistance values
- c) Effect of vibration on penetration resistance values
- d) Effect of test location on penetration resistance values
- e) Effect of cone type on penetration resistance values

The penetration resistance values used in the analysis were based on the average of the penetration test data from $z = 0.70\text{m}$ to $z = 0.80\text{m}$. The results of all ANOVA analyses are included in Section 5.10.

5.5 Effects of Saturation on Penetration Resistance

5.5.1 Static Penetration Tests

A comparison of the calibration chamber test results was made in order to evaluate the effects of saturation on the static penetration resistance measurements. As stated in Section 5.2, penetration tests were run in the calibration chamber in both dry and saturated states. B-values between 0.9 and 0.97 were recorded in the saturated specimens prior to the penetration testing. A comparison of the normalized penetration resistance versus depth in the calibration chamber is presented as Figure 5.4 for a series of penetration tests in loose samples at the intermediate stress level. Figures 5.4a includes the results of a series of saturated tests performed in identical samples and the

corresponding best-fit trendline for the test data, while Figure 5.4b includes the results from several dry tests. The normalized penetration resistance was used to compare the test data instead of the raw penetration resistance value because the effective stress varied slightly between tests for tests performed at the elevated stress levels, resulting in different penetration resistance measurements. The rationale for choosing the vertical effective stress as the normalizing parameter is discussed in the previous section. All tests included in Figure 5.4 were performed in the center port of the calibration chamber ($D_{cc}/D_{cp} = 34$) and involved the use of the 15-cm² cone penetrometer.

It is shown through Figure 5.4 that the normalized penetration resistance is fairly constant with depth in the chamber for tests performed in both dry and saturated samples, indicating a uniform density distribution vertically within the sample. It is also evident from this comparison that there is a range of normalized penetration resistance values within each test condition. The standard deviations for both the dry and saturated tests were determined to be 0.89 and 2.92, respectively, which are primarily attributed to differences between tests in the placement density and fabric of the soil during the pluviation process (e.g. the density ranged from 20<Dr%<30 for the loose samples). The magnitude of the standard deviation for the saturated tests is larger than the dry tests, and is most likely attributed to the larger data set compiled for the saturated condition. In the saturated tests, there also may be a minor contribution to the variation through volume change during inundation of the sample. However, given the relatively small change in height measured during the inundation process (typically less than 20 mm), the void ratio change from the inundation is less than 0.002. As such, the effects of the inundation on the final relative density of the soil are expected to be small. Similar results were noted by Caillemer (1975).

The best-fit trendlines for both the dry and saturated tests in loose samples at the intermediate stress level are presented as Figure 5.5a. Included as Figure 5.5b is a quantitative comparison of the difference between the two trendlines with depth into the chamber, as expressed through Equation 5.2:

$$1 - \left(\frac{q_{c(Sat)}}{q_{c(Dry)}} \right) \cdot 100 \quad (5.2)$$

where $q_{c(Sat)}$ is the penetration resistance measured in saturated samples and $q_{c(Dry)}$ is the penetration resistance measured in dry samples. Values generated from Equation 5.2 that approach values of 1.0 suggest that $q_{c(Sat)}$ is much less than $q_{c(Dry)}$, while values near zero suggest the penetration resistance values are approximately equal.

It can be seen from this relationship that the values generated from Equation 5.2 are relatively small near the center of the sample (less than 15%), suggesting the penetration resistance of the dry samples approximates that of the saturated samples for the given stress conditions. This agreement between the test data is primarily due to the drained nature of the static penetration test and the absence of negative pore pressures initially present in the sample, as indicated by the high B-values measured prior to the test. As such, the results of the dry tests were included with the saturated test results for all further analyses. Similar results were noted for tests performed at the high stress levels in the loose sample. A comparative analysis was not performed for the medium dense samples due to the lack of dry penetration tests at this density condition.

5.5.2 Vibratory Penetration Tests

A comparison of the penetration resistance test results was also made to evaluate the effects of the state of saturation on the vibratory penetration resistance measurement. Presented as Figure 5.6 are the results of static and vibratory penetration tests performed in saturated samples at the loose density and intermediate stress level. Also included in this figure are the penetration resistance measurements from a combined penetration test performed in a dry sample at a similar density and stress state. The vibration in this combined penetration test was started at a depth of $z = 0.42\text{m}$ in the sample such that the test consisted of static penetration down to a depth of 0.42m and then vibratory penetration from $z = 0.42\text{m}$ to $z = 1.38\text{m}$. The penetration resistance value for each of the tests was normalized by the vertical effective stress present in the sample prior to testing using Equation 5.1. All tests presented in Figure 5.6 were performed with the 15-cm^2 penetrometer at the center port location.

It can be seen through Figure 5.6 that the static penetration resistance in the dry sample was approaching the saturated static penetration resistance prior to vibration ($z < 0.42\text{m}$), confirming the drained nature of the static penetration test. However, vibratory penetration resistance measured in the dry sample is much greater than that measured in the saturated sample at all depths in the chamber, suggesting that the presence of water in the void space of the soil significantly influenced the behavior of the soil during dynamic

penetration. This influence of the pore water on the vibratory penetration resistance is further quantified through Equation 5.3, which suggests that the vibratory penetration resistance is approximately 40% greater than the static in the center of the sample for the given test condition (Figure 5.7). Given this difference in the dry and saturated soil behavior during vibration, the measurements obtained from the penetration tests in dry samples were separated from the saturated tests for all further analyses. A complete discussion of pore pressure development during penetration and its effects on the penetration resistance is included in Chapter 6.

5.6 Boundary Effects on Penetration Resistance and Pore Pressure Measurements

The bulk of the investigations noted in the literature related to cone penetration testing involve the correlation of a cone measurement (i.e. q_c) to a soil property associated with engineering design (i.e. D_r). Since the dimensions of a calibration chamber are finite relative to field conditions, major concerns are often directed at the effects of the lateral boundaries on the penetration resistance measurements from calibration chamber tests. A general discussion of the influence of the calibration chamber size and boundary condition on the penetration resistance measurement is presented in Section 2.6.2 of Chapter 2.

It was stated in Section 5.3 that the boundary condition in the Virginia Tech calibration chamber is dependent on the presence of an applied lateral stress to the sample. If a lateral stress is applied, the sample moves away from the rigid support jacket and is supported by the applied confining stress, generating a flexible wall boundary condition ($BC1$). If no confining stress is applied, the sample is supported by a steel jacket, which forms a rigid lateral boundary ($BC3$).

As noted in Tables 5.1 through 5.4, penetration tests were performed in the calibration chamber at two different test locations. For the purpose of this study, what is of particular interest is not whether or not boundary effects are present during the testing, but whether or not the magnitude of the boundary effects is significantly different at the two different testing locations. An investigation was therefore undertaken to evaluate the difference in lateral boundary effects at the two testing locations. As noted in Section 5.2 and in Tables 5.1 and 5.2, penetration tests in the loose samples at the elevated stress levels using the 15-cm² cone were limited to the center port (high D_{cc}/d_{cp} ratio) location due to hole diameter restrictions in the calibration chamber top plate. Similarly, the

development of electrical problems with the 15-cm² cone limited testing in the medium dense samples to only static tests at the low stress level. Thus, the influences of the D_{cc}/d_{cp} on the penetration resistance ratios could not be evaluated for the 15-cm² cone for certain density and stress conditions.

Similar to the penetration resistance measurements, an investigation was undertaken to evaluate variational lateral boundary effects on the pore water pressure measurement at the two testing locations. The evaluation was performed for static tests and vibratory tests using the rotary turbine vibrator by comparing the induced pore water pressure normalized by the vertical effective stress ($\Delta u/\sigma_v'$), hence referred to as the pore pressure ratio, at the different test locations for each stress condition, density, and mode of penetration. The pore pressure ratio has been used by other researchers (i.e. Azzouz et al. 1983; Mayne and Bachus 1988) to evaluate dissipation characteristics of soils using piezocone testing, and has been noted by Lunne et al. (1997) as an acceptable approach for induced water pressure considerations. The comparison included herein simply involves the computation of the difference in the pore pressure ratios, subsequently referred to as the pore pressure ratio differential, at the different test locations for a given density and stress condition. The pore pressure ratio was determined for both cone penetrometers, where water pressure was measured during penetration at the midface (U_1) and shoulder (U_2) locations on the 15-cm² cone and at the midface (U_1) and shoulder (U_2) location on the 10-cm² cone. As previously stated, equipment problems limited testing in the medium dense samples with the 15-cm² penetrometer to static tests at the low stress levels. Also, the influences of the D_{cc}/d_{cp} on pore water pressure could not be evaluated in the loose samples for the 15-cm² cone at the elevated stress levels due to chamber restrictions.

5.6.1 Influence of Test Location on Normalized Penetration Resistance Value

5.6.1.1 Qualitative Analysis

The influence of the test location on the normalized penetration resistance was evaluated both qualitatively and quantitatively as part of the study. The qualitative analysis consists of a direct comparison of the normalized penetration resistance measurements through the Truth Plot presented as Figure 5.8. The average penetration test data for both relative densities and each stress level is presented in the diagram for both the 15-cm² and 10-cm² cones. The data used in the analysis is presented in Tables 5.10 and 5.11 and represents the average normalized penetration resistance data for a given test condition. The following conclusions can be inferred from the comparison:

Loose Samples

- a) For a given cone penetrometer, the normalized penetration resistance value measured at the center location is approximately equal to that measured at the off-center location for static and vibratory tests at all stress levels.
- b) The static and vibratory penetration resistance values obtained from the 15-cm² cone are approximately equal to that measured using the 10-cm² cone for tests performed at the low stress level.
- c) The grouping of the static normalized penetration values at all stress levels and the vibratory normalized penetration resistance values at the high stress level indicates that the values are approximately equal.

Medium Dense Samples

- a) The normalized penetration resistance value measured at the center location is approximately equal to that measured at the off-center location only for tests at the low stress level with the 10-cm² cone penetrometer.
- b) The static penetration resistance value measured at the off-center location was significantly greater than that measured at the center location for tests performed with the 15-cm² cone at the low stress levels.
- c) The penetration resistance measured at off-center location was less than that measured at the center location for tests at the elevated stress levels.

The observations noted in the previous discussion indicate that the testing condition and/or cone penetrometer can influence the normalized penetration resistance value under certain testing conditions. A quantitative analysis was therefore performed to attempt to define the magnitude of any influence of the testing condition on the measured testing parameters.

5.6.1.2 Quantitative Analysis of Loose Sands

Presented as Figure 5.9 are comparisons of the best-fit trendlines for penetration tests performed at the two different D_{cc}/d_{cp} ratios in loose samples at low confining

stresses (cases (a) and (b) in Section 5.4). Figure 5.9a includes the results of the penetration testing with the 10-cm² cone penetrometer while Figure 5.9b includes the test results using the 15-cm² penetrometer. Also present in Figures 5.9a and 5.9b are the trendlines fit through the combined data set when both the low and high D_{cc}/d_{cp} ratios are grouped together (case (c) noted in Section 5.4). The results of both the static and vibratory testing are included in these figures. The standard deviation where more than one penetration test was performed is included in Table 5.10.

It can be seen through Figure 5.9 that the best-fit trendline for the low D_{cc}/d_{cp} ratio approximates the trendline for the high D_{cc}/d_{cp} ratio for static penetration tests performed with both penetrometers. The approximation is particularly evident in the vertical center of the sample, where the influences of the upper and lower boundaries are minimized.

A quantitative evaluation of the effect of the lateral boundary on the penetration resistance can be made through the use of the Test Location Factor (*TLF*). The *TLF* is defined as the ratio of the penetration resistance measured at the low D_{cc}/d_{cp} ratio to that measured at the center of the sample, or:

$$TLF(\%) = \left\{ 1 - \left(\frac{q_{c(off\ center)}}{q_{c(center)}} \right) \right\} \cdot 100 \quad (5.3)$$

where $q_{c(off-center)}$ is the penetration resistance measured at the low D_{cc}/d_{cp} ratio and $q_{c(center)}$ is the penetration resistance measured at the high D_{cc}/d_{cp} ratio (center port location). A positive value of the *TLF* suggests that the penetration resistance for the low D_{cc}/d_{cp} ratio is lower than the penetration resistance measured at the center of the sample, while a negative value suggests the opposite is true.

As shown through Figure 5.10a, the *TLF* for static penetration tests at low stress level is a negative value at the vertical center of the sample ($z = 0.75m$), indicating that the penetration resistance at the low D_{cc}/d_{cp} ratio is greater than that measured at the high D_{cc}/d_{cp} ratio. This behavior is noted for both the 10-cm² and the 15-cm² cone penetrometers, and is most likely attributed to the rigid wall lateral boundary present during the tests. However, the *TLF*'s for both the 15-cm² and 10-cm² cone penetrometers are small in magnitude ($TLF < 15\%$), suggesting that the boundary effect on penetration resistance measurement is fairly similar at the two test locations for the defined testing condition. Consequently, a trendline was fit through the collective group of data

generated from all tests at the low and high D_{cc}/d_{cp} ratios for each cone penetrometer (case (c) noted in Section 5.4). This trendline was chosen to represent the penetration resistance measured using the particular penetrometer for the given stress and density condition, and was further used in the analyses included in Section 5.7.

Also included in Figure 5.9 are the trendlines generated from vibratory penetration tests performed at the low stress level and two different D_{cc}/d_{cp} ratios for both the 10-cm² and the 15-cm² cones. The corresponding TLF's for each of the cones is presented as Figure 5.10b. The standard deviation of the test data is presented in Table 5.10 where more than one penetration test was performed.

It can be seen from Figures 5.9 and 5.10 that the effects of the lateral boundary on the vibratory penetration resistance is fairly constant for the two D_{cc}/d_{cp} ratios for the 15-cm² cone, as noted by the TLF that is less than 18% at the vertical center of the sample ($z = 0.75m$). Similar test results were noted for the 10-cm² penetrometer. As such, the trendline fit through the combined data set that included both the low and high D_{cc}/d_{cp} ratios (case (c) noted in Section 5.4) was chosen to represent the penetration resistance of the soil for the given stress and density for the analyses included in Section 5.7. This procedure was performed for each cone penetrometer.

A comparison of the normalized penetration resistance obtained from tests at the low and high D_{cc}/d_{cp} ratios at the elevated stress levels was also performed for the 10-cm² cone (Figures 5.11 through 5.13). The standard deviation for conditions where more than one penetration test was performed is included in Table 5.10. The TLF calculated from static penetration tests at the medium and high stress levels was less than 15% and were positive in value, suggesting that the penetration resistance at center of the sample was slightly greater than at the low D_{cc}/d_{cp} ratio (Figures 5.11 and 5.13). Similar results were observed for the vibratory testing. This positive value of the TLF is attributed to the effects of the flexible wall boundary (*BCI*) present during the testing. At these stress states, a confining stress is applied to the sample and the soil is pushed away from the rigid forming jacket that initially supports the sample, forming a flexible wall boundary. The presence of this lateral boundary resulted in penetration resistance values lower than those obtained with rigid walls. However, given the minor influence of the test location on the measured penetration resistance, the effects of this additional influence of the lateral boundary were ignored and the trendline fit through the combined data set (case (c) noted in Section 5.4) was chosen to represent the penetration resistance using the 10-

cm² cone for the analyses included in Section 5.7. The best-fit curve generated from the test data at the large D_{cc}/d_{cp} location (case (b) noted in Section 5.4) was used for the 15-cm² cone in the comparative analyses presented in Section 5.7.

5.6.1.3 Quantitative Analysis of Medium Dense Sands

Presented as Figure 5.14 are comparisons of the trendlines formed for static penetration tests performed at the low and high D_{cc}/d_{cp} ratios in medium dense samples at low confining stress. Tests performed using both the 15-cm² and 10-cm² cone are included in this figure. The standard deviation where more than one penetration test was performed has been included in Table 5.11. Also present in Figure 5.14 is the trendline formed from the data set generated when the test results from both the low and high D_{cc}/d_{cp} ratios were grouped together. Trendlines were formed from this combined data set for both the 15-cm² and 10-cm² cone penetrometers.

It can be seen through Figure 5.14a that the representative trendline for tests performed at the low D_{cc}/d_{cp} ratio at the low stress using the 10-cm² cone penetrometer is similar in magnitude and shape to that of the high D_{cc}/d_{cp} ratio. As shown in Figure 5.14b, the TLF using this cone was less than 10% at the vertical midpoint of the sample ($z = 0.75m$), suggesting that the influence of the lateral boundary on the penetration resistance measurement is fairly constant for the two D_{cc}/d_{cp} ratios for the given test condition. Thus, the trendline fit through the combined data that included both the low and high D_{cc}/d_{cp} ratios (case (c) noted in Section 5.4) was chosen as the representative penetration resistance curve for the 10-cm² cone at the low stress, medium dense state. This curve was used in the comparative analyses presented in Section 5.7

As indicated by Figure 5.14a, the best-fit trendline for the tests performed with the 15-cm² cone at the low D_{cc}/d_{cp} ratio is considerably higher than that of the high D_{cc}/d_{cp} ratio for all depths in the calibration chamber, suggesting that the rigid lateral boundary significantly affected the penetration resistance in tests towards the sample edge ($r = 0.35m$). A quantification of the degree of the additional lateral boundary effect is shown through Figure 5.14b, where the TLF is computed with depth in the chamber. As shown through this relationship, the penetration resistance at the vertical center of the sample ($z = 0.75m$) for the low D_{cc}/d_{cp} ratio is approximately 90% greater than at the high D_{cc}/d_{cp} ratio, indicating that the effects of the rigid wall lateral boundary is significantly different at the two testing locations. Also, the trendline computed from tests performed at the large D_{cc}/d_{cp} ratio fell fairly close to representative trendline computed for tests

performed with the 10-cm² cone, suggesting that the influence of the lateral boundary on the penetration resistance measured with the 15-cm² penetrometer at the high D_{cc}/d_{cp} ratio is very similar to that encountered with the 10-cm² penetrometer. Consequently, the trendline formed from the tests using this cone at the high D_{cc}/d_{cp} ratio (case (b) noted in Section 5.4) was chosen to represent the penetration resistance of the medium dense sands at the low stress state for the analyses presented in Section 5.7.

Included as Figure 5.15 are comparisons of the best-fit trendlines for the vibratory and static testing using the 10-cm² cone at the low stress state. The standard deviation where more than one penetration test was performed has been included in Table 5.11. It can be seen through Figure 5.15a that the vibratory penetration resistance measured at the vertical center of the sample is approximately the same for the low and high D_{cc}/d_{cp} ratios. Further evidence of this relationship is shown through Figure 5.15b, where the TLF measured for the vibratory tests at the vertical center of the sample is approximately zero, suggesting that there is a negligible difference in the lateral boundary effects on the vibratory penetration resistance at the two testing locations. Since tests were not performed at this density with the 15-cm² penetrometer, the trendline formed from the combined data set from both test locations for the 10-cm² cone (case (c) noted in Section 5.4) was chosen as the final representative penetration resistance curve. The parameters associated with this curve have been included in Table 5.12.

Presented as Figure 5.16 are the normalized penetration resistance curves for static and vibratory tests performed using the 10-cm² penetrometer at both D_{cc}/d_{cp} ratios at the intermediate stress level. The best-fit trendline representing the collective data set has also been included for both modes of penetration. It can be seen through Figure 5.16 that the static penetration resistance measured at the low D_{cc}/d_{cp} ratio is much less than that measured at the high D_{cc}/d_{cp} ratio, revealing a non-constant influence of the lateral boundary on the penetration resistance for the different testing locations. A quantification of this variational lateral boundary influence is shown through the TLF, which is a positive value of about 21% and 28% for the static and vibratory penetration tests at the vertical center of the sample (Figure 5.17). As noted in Section 5.6.1.2, this is most likely due to influences of the flexible wall boundary present during the testing at the elevated stress conditions. Since no evaluation of the influence of the lateral boundary on the penetration resistance was made for the 15-cm² cone, the data collected at the center of the sample (case (b) noted in Section 5.4) was chosen to represent the penetration resistance of the medium dense condition at the intermediate stress levels.

The parameters for both the static and vibratory normalized penetration resistance curves are included in Table 5.12.

Presented in Figure 5.18 are the trendlines formed from penetration tests performed at both D_{cc}/d_{cp} ratios in medium dense samples at the high stress level. Both the static and vibratory test results have been included. It is shown through this figure that the penetration resistance obtained from tests at the low D_{cc}/d_{cp} ratios is significantly less than that measured at the high D_{cc}/d_{cp} ratio, noting a large variation of the influence of the lateral boundary at the different test locations. As shown in Figure 5.19, the additional influence of the lateral boundary is identified by TLF's of approximately 30% for the vibratory tests and 35% for the static tests. Since tests were not performed at this stress level with the 15-cm² cone, the data collected at the center of the sample (case (b) noted in Section 5.4) was chosen to represent the penetration resistance of the medium dense condition at the high stress levels. The parameters associated with each of these normalized penetration resistance curves are included in Table 5.12.

5.6.2 Influence of Test Location on Induced Pore Water Pressure in Loose Sands

Presented as Figures 5.20 and 5.21 are comparisons of the pore pressure ratios measured during static and vibratory penetration tests for the 10-cm² and 15-cm² cones, respectively. Included in these figures are the trendlines formed from the independent data sets of tests performed at the low and high D_{cc}/d_{cp} ratios (conditions (a) and (b) in Section 5.4) and trendline formed when the data from both D_{cc}/d_{cp} ratios were grouped together (condition (c) in Section 5.4).

It can be seen through Figures 5.20a and 5.21 that the pore pressure ratio measured for the high D_{cc}/d_{cp} ratio is less than the pore pressure ratio determined for the low D_{cc}/d_{cp} ratio during static penetration. This behavior was observed for both penetrometers, and was particularly noted in the vertical center of the sample where the influences of the top and bottom boundary conditions are minimized. A further inspection of these figures also suggests that the pore water pressure calculated for the high D_{cc}/d_{cp} ratio is approximately equal to that identified at the low D_{cc}/d_{cp} ratio at the vertical center of the sample during vibratory penetration. As shown in Figures 5.20b and 5.22, the pore pressure ratio differential at the two testing locations is between 0.05 and 0.07 for the static tests and 0.02 and 0.01 for the vibratory tests for both cone penetrometers and element locations. Although small in magnitude, the larger pore pressure ratio

differential for the static tests is most likely attributed to the additional influences of the rigid lateral boundary on the lateral drainage at the small D_{cc}/d_{cp} ratio relative to the large D_{cc}/d_{cp} ratio. In the vibratory tests, the influences of the lateral boundary seems to be the same at the two testing locations, as indicated by the very low differential in the pore pressure ratios for the both cone penetrometers. Given this information, the trendlines formed from the collective data sets of both D_{cc}/d_{cp} ratios (case (c) noted in Section 5.4) were chosen to represent the pore pressure response during static and vibratory penetration at the low stress conditions for the analyses presented in Section 5.7.

Presented as Figure 5.23a are the pore pressure ratios determined from penetration tests in loose samples at the medium stress level using the 10-cm² cone. Included in this figure are the trendlines formed from the independent data sets of the low and high D_{cc}/d_{cp} ratios and the data set formed when the low and high D_{cc}/d_{cp} ratios are grouped together. Both the static and vibratory test results are included in the figure. No evaluation was made for the 15-cm² cone due to testing restrictions of the calibration chamber.

It is observed through Figure 5.23a that the pore pressure ratio measured at the high D_{cc}/d_{cp} ratio is less than the pore pressure ratio measured at the low D_{cc}/d_{cp} ratio during static and vibratory penetration. As noted through Figure 5.23b, the difference in the pore pressure ratios at the two testing locations is only 0.03 for both types of tests, suggesting that the influence of the lateral boundary is approximately the same at both testing locations for both modes of penetration. Thus, the trendlines formed from the collective data sets of both D_{cc}/d_{cp} ratios (case (c) noted in Section 5.4) were chosen to represent the pore pressure response during static and vibratory penetration at the intermediate stress conditions for the analyses presented in Section 5.10. Similar results and conclusions are noted for tests performed at the high stress levels (Figure 5.24).

5.6.3 Influence of Test Location on Induced Pore Water Pressure in Medium Dense Sands

Presented as Figure 5.25a and 5.26a are the pore pressure ratios calculated from the results of penetration testing in the medium dense samples at the low stress levels for the 10-cm² and 15-cm² cones, respectively. Also included as Figures 5.25b and 5.26b are plots of the pore pressure ratio differentials determined for the two testing locations.

An inspection of Figures 5.25 and 5.26 indicates that the induced pore water pressure measured during static penetration at the low D_{cc}/d_{cp} ratio is greater than that measured at the high D_{cc}/d_{cp} at all depths in the chamber. This increase is approximately 0.15 at the U_2 location for static tests performed with the 10-cm² cone and 0.1 at both the U_1 and U_2 location for static tests using the 15-cm² cone. Negligible differences in the pore pressure ratios were determined for the vibratory penetration tests using the 10-cm² cone at the center of the sample (Figure 5.25a). However, large variations in the measured pore water pressures were noted at the top and the bottom of the sample in all test locations, revealing large influences of the vertical boundaries on the test results (Figure 5.25). This behavior was particularly evident in tests performed at the low D_{cc}/d_{cp} ratio. The trendlines formed from the static penetration tests at the high D_{cc}/d_{cp} ratio (case (b) noted in Section 5.4) were therefore chosen to represent the pore pressure response during penetration at the low stress level for the analyses presented in Section 5.7. The regression parameters for this curve have been included in Table 5.13.

Plots of the pore pressure ratio determined for static and vibratory penetration tests performed at the intermediate and high stress levels with the 10-cm² cone are presented as Figures 5.27 and 5.28, respectively. The pore pressure ratio differentials determined for the two testing locations are also included in these figures. It is shown through these comparisons that there is a negligible difference in the induced pore water pressure for the different testing locations at the elevated stress levels. Thus, the trendlines formed from the collective data sets of both D_{cc}/d_{cp} ratios (case (c) noted in Section 5.4) were chosen to represent the pore pressure response during static and vibratory penetration at the elevated stress conditions. The parameters associated with these trendlines are included in Table 5.13.

5.7 Influence of Cone Size on Recorded Measurements

A comparison of the penetration resistance measurements obtained from tests using the 15-cm² and 10-cm² cone penetrometers was made in order to evaluate the effects of the cone type on the penetration resistance of the soil. The penetration resistance values compared in the evaluation were generated from the representative trendlines noted in Sections 5.6.1 and 5.6.2 for the different density and stress conditions. As stated in Section 5.4, the vibratory test data used in the analyses was obtained from penetration using the rotary turbine vibrator. Unless otherwise stated, the final evaluation of the influence of the cone type on the penetration resistance value resulted in the generation of

the representative penetration resistance curves for the different density and stress conditions.

An evaluation of the pore pressure transducer location was made in order to determine if the location of the pore pressure transducer on the cone penetrometer influenced the magnitude of the pore pressure generated during static and vibratory penetration in clean sands. Also included in this section is an evaluation of the effects of the cone type on the magnitude of the pore pressure ratio determined through the testing.

As stated in section 5.2 and noted in the previous sections, pore pressure transducers were located at the shoulder (U_2) location on the 10-cm² cone and at the midface (U_1) and shoulder (U_2) locations on the 15-cm² cone. The ceramic pore pressure elements located over the transducers were continuously inspected for indications of abrasion and smearing and were saturated with a glycerin and water mixture in a vacuum for a minimum of one hour prior to the penetration test. The elements were saturated separate from the cone itself and were assembled onto the cone prior to the testing using the saturation device noted in Figure 3.29 of Chapter 3. Extreme caution was taken when assembling the elements onto the body of the cone to ensure that all air bubbles were removed from the cavity of the transducer housing. A rubber membrane was placed over the elements prior to the testing so that a high degree of saturation was maintained in both the element and the transducer housing. A complete discussion of the element saturation and assembly procedure has been included in Section 3.4.4 of Chapter 3.

The pore pressure ratios used in the following evaluations were obtained from the representative trendlines noted in sections 5.6.2 and 5.6.3 for the different densities, stress conditions, modes of penetration, and cone penetrometers. As stated in section 5.4, the vibratory test results used in the analyses were based on tests performed with the rotary turbine vibrator. Unless otherwise stated, the final evaluation of the influence of the transducer location and cone size on the pore pressure ratio will determine the representative pore pressure ratio curve for the given density and stress condition.

5.7.1 Penetration Resistance in Loose Sands

Presented as Figure 5.29a is a comparison of the representative trendlines identified in Section 5.6.1 above for tests performed in loose samples at the low stress state. The results of both the static and vibratory penetration resistance tests are included in this figure. It is shown through this comparison that the static penetration resistance

measured using the 15-cm² penetrometer is very close that obtained from the 10-cm² penetrometer at any depth in the chamber. A similar behavior was noted for the vibratory tests. Further evidence of the agreement of the test data is identified through a direct comparison of the penetration resistance measurements using Equation 5.4:

$$\text{Cone Factor (CF)} = \left\{ 1 - \left(\frac{q_{c(10\text{cm}^2)}}{q_{c(15\text{cm}^2)}} \right) \right\} \cdot 100 \quad (5.4)$$

where CF is the cone factor, $q_{c(10\text{cm}^2)}$ is the penetration resistance measured using the 10-cm² penetrometer and $q_{c(15\text{cm}^2)}$ is the penetration resistance measured using the 15-cm² penetrometer. Values of the cone factor near zero suggest that the penetration resistance measured using the 10-cm² cone is approximately equal to that obtained using the 15-cm² cone, while values near 100% suggest large differences in the measured penetration resistance values.

It is shown through Figure 5.29b that the cone factor is less than 18% at the center of the sample for both the static and vibratory tests, implying that the effects of the cone type on the penetration resistance measurement was minimal at the low stress condition. This allows the test data from both the 10-cm² cone and 15-cm² cone to be grouped together for the given stress and density condition and implies that a best fit trendline through the entire data set can be considered representative of the penetration resistance for the testing condition (case (d) mentioned in Section 5.4). The parameters obtained from the curve fit through this collective data set have been included in Table 5.12.

Presented as Figure 5.30 are the representative normalized penetration resistance curves generated from tests using both the 10-cm² and 15-cm² cones at the intermediate stress level. The normalized penetration resistance curves from both the static and vibratory testing are included in this figure, with the corresponding Cone Factors included in Figure 5.31. Similar curves and comparisons have been generated for the tests performed at the high stress levels (Figures 5.32 and 5.33). The penetration resistance curves used in the analyses were those mentioned in Section 5.6.1 of this chapter.

Similar to the results calculated for the low stress level, it appears that the Cone Factor for tests at the elevated stress levels is less than 15% at the vertical center of the

sample, implying that the penetration resistance is not dependent on the cone type for the given stress and density conditions tested. As such, the data collected using the 10-cm² cone was grouped together with the data obtained using the 15-cm² cone and collectively fit with a best-fit trendline (case (d) noted in Section 5.4). The parameters obtained from this final curve fit are considered representative of the testing condition, and are included in Table 5.12 for both stress levels and both modes of penetration.

A comparison of the Cone Factor determined from the static penetration testing was also compared to that estimated through cavity expansion theory for tests performed at all three stress levels. A computer program named CONPOINT developed by Salgado (1993) was used to estimate the penetration resistance for both size cone penetrometers using cavity expansion theory. As shown in Table 5.14, the cone factor calculated using CONPOINT is generally less than 16.5% for the tests performed at all stress levels, suggesting that the cone type does not significantly influence the penetration resistance value estimated through cavity expansion theory.

5.7.2 Penetration Resistance in Medium Dense Sands

Included in Figure 5.34 is a comparison of the representative trendlines identified in Section 5.6.2 above and the resulting Cone Factor calculations for static penetration tests performed in the medium dense samples at the low stress state. Similar to the results of the testing in the loose samples, it appears that the Cone Factor is less than 5% at the vertical center of the sample, implying that the penetration resistance measured using the 10-cm² cone was approximately equal to that measured with the 15-cm² cone. Similar results were noted through CONPOINT and cavity expansion theory (Table 5.15). The data collected using the 10-cm² cone was therefore grouped together with the data obtained using the 15-cm² cone and collectively fit with a best fit trendline (case (d) noted in Section 5.4). The parameters obtained from this final curve fit are considered representative of the testing condition and are included in Table 5.12.

5.7.3 Influence of Transducer Location on Pore Pressure Measurements

Presented as Figure 5.35a are pore pressure ratios measured at the U₁ and U₂ locations during penetration tests in loose sands at all stress levels using the 15-cm² cone. The results of both the static and vibratory tests are included in this figure. It can be seen through this comparison that the pore pressure measured at the U₁ location is approximately equal to that measured at the U₂ location for tests performed at all three stress levels. Quantification of any variation in pore pressure measured at the different

element locations is made through the calculation of the element location factor (*ELF*), which is simply the pore pressure measured at the U_1 location less the pore pressure measured at the U_2 location (Figure 5.36). As shown in Figure 5.36, the difference in the magnitude of the pore pressure ratio at the two element locations is minimal ($ELF < \pm 0.02$) for both static and vibratory penetration tests in loose samples at all stress levels. It therefore appears that the magnitude of the induced pore water pressure measured during the penetration test is not dependent on the pore pressure element location for the given cone penetrometers and test conditions. Thus, the pore pressure values measured at the U_2 location with the 15-cm² cone are considered representative of the pore water pressure behavior for the given penetration test, and were used in the analyses presented in Section 5.7.4 related to pore pressure measurements using the 15-cm² cone in loose samples.

As stated in earlier sections, cone penetration testing in the medium dense samples using the 15-cm² cone was limited to static penetration at the low stress levels. Representative pore pressure ratios for both the U_1 and U_2 locations are included in Figure 5.37, along with the difference in the pore pressure values as noted in the preceding paragraph. Similar to the results of the testing in the loose samples, it appears that the excess pore water pressure recorded during penetration is not dependent on the transducer location for the given stress and density condition. The pore pressure recorded at the U_2 location was therefore considered representative of the pore pressure measured during penetration tests for both cone penetrometers.

5.7.4 Pore Pressure Measurements in Loose and Medium Dense Sands

The pore pressure ratios computed for the different cone penetrometers were compared in order to evaluate the influence of the cone type on the pore pressure generated during penetration. The comparisons were made for static and vibratory tests at all stress levels in the loose samples and at the low stress levels in the medium dense samples. The trendlines used in the comparative analysis were noted in Sections 5.6 and 5.7 for both the 10-cm² and 15-cm² cones.

The representative pore pressure ratios determined for both cone penetrometers from penetration tests in loose samples have been presented as Figure 5.38. The results of both the static and vibratory testing has been included for all three stress levels. It is evident from this comparison that the pore pressure ratio measured at the vertical center of the sample using the 15-cm² cone is approximately equal to that measured using the 10-cm²

cone at each stress condition and mode of penetration. The pore pressure ratio data from both penetrometers was therefore grouped together and a best-fit trendline was fit through the collective data set for each stress level (cased (d) noted in Section 5.4). Similar results were noted for tests performed in the medium dense samples at the low stress levels (Figure 5.39). This best fit trendline is the final trendline chosen to represent the pore pressure ratio for the given density and stress condition. A listing of the parameters determined for each stress level has been included as Table 5.13.

5.8 Effect of Testing Sequence on Penetration Resistance

As noted in the Section 5.3, cone penetration tests were conducted in loose and medium dense samples using either a 10-cm² or 15-cm² cone at multiple stress levels, densities, and modes of penetration. Due to the large size and difficulty in preparing a sample and the availability of multiple penetration ports in the top lid of the chamber, penetration tests were performed in samples tested with the 10-cm² cone at both the center and off-center test locations. For reasons stated in Section 5.6, tests using the 15-cm² cone were only performed at the off-center location in samples at the low stress levels.

It was concluded in Sections 5.6 and 5.7 that the test location or cone type did not influence the penetration resistance measurement in loose samples at all stress levels for both modes of penetration. Similar results were noted for tests in the medium dense samples at the low stress level with the 10-cm² cone, while significant lateral boundary effects were noted at the low D_{cc}/d_{cp} testing location for tests performed at the elevated stress levels. Similarly, tests performed in medium dense samples at the low stress level with the 15-cm² cone at the low D_{cc}/d_{cp} testing location revealed significant lateral boundary effects.

The data used in the analyses presented in Sections 5.6 and 5.7 was separated into low D_{cc}/d_{cp} ratio and high D_{cc}/d_{cp} ratio categories for both cone penetrometers, and was not distinguished based on their order in the testing sequence. An investigation was therefore undertaken to determine if the sequence of the penetration tests influenced the penetration resistance measurement within a sample itself and between different samples. The testing sequence in any given sample was held to no specific order, such that multiple combinations of the order of static and vibratory tests were used amongst the different samples.

Presented as Figure 5.40 are normalized penetration resistance values for tests performed in loose samples at low stress levels. The results of both static and vibratory testing are included. Penetration test results from two different samples are included in each of the figures so that an evaluation of the testing order within a particular sample and amongst different samples could be made.

It is shown through Figure 5.40a that both the static penetration resistance measured from the initial test at the vertical center ($z = 0.75m$) of a particular sample is approximately the same as that measured in subsequent tests, even after the sample has been exposed to prior periods of vibration at other testing locations. This behavior was also seen for the vibratory testing (Figure 5.40b), and was noted for all samples analyzed. The surface of the sand sample was surveyed at 7 spots with a precision level at the beginning and end of each test to determine any decrease in height of the sand sample attributed to the penetration of the penetrometer. The survey results revealed a decrease in the height of the sand sample of less than 0.12cm at distances greater than 15cm away from the cone penetrometer, revealing the absence of surficial evidence of subsurface densification at significant lateral distances away from the cone penetrometer. Based on the penetration test results and the survey information, it is suggested that neither the static nor the vibratory penetration resistance measurement was depended on the testing sequence for the tests conducted at the low stress levels. Similar test results were noted for loose samples tested at the elevated stress levels. Thus, multiple data points were obtained from an individual sample, each of which was considered uninfluenced by the test location, testing order, or type of test previously performed.

Presented as Figures 5.41 and 5.42 are the normalized penetration resistance values for tests performed in medium dense samples at low and intermediate stress levels, respectively. Given the analyses presented in the previous sections, only the results of the static and vibratory testing using the 10-cm² cone are included. The results from tests in two different samples are presented in each of the figures for comparative purposes.

It can be seen through Figure 5.41 that the static penetration resistance measured at the vertical center of the sample is approximately the same for all tests in the sample, regardless of the testing order, location, or type of test previously performed. Similar results were noted for the vibratory tests. The survey results also did not reveal a decrease in height of the sand sample of less than 0.15cm at distances greater than 15cm

away from the cone penetrometer. Thus, multiple data points were obtained from an individual sample all of which were considered representative of the sample as a whole.

Presented as Figure 5.42 are plots of the normalized penetration resistance values for tests performed in medium dense samples at the high stress state using the 10-cm² cone. Only the results from the static and vibratory tests performed at the low D_{cc}/d_{cp} ratio location are included in the comparisons. Tests performed at the high D_{cc}/d_{cp} ratio were excluded from the analysis because the penetration resistance values measured at this location were much larger than the values recorded at the low D_{cc}/d_{cp} ratio location.

It is shown through this comparison that the penetration resistance is not dependent on the testing sequence for either the static or the vibratory tests, as shown by the fairly constant penetration resistance ratio at the vertical center of the sample (Figure 5.42). It therefore appears that the penetration resistance measured at the off-center locations is fairly constant for a given mode of penetration and is virtually independent of the testing order or type of test previously performed. Thus, multiple data points were obtained from an individual sample. Similar results were noted for tests performed at the intermediate stress level. However, as stated earlier, the penetration resistance value measured at this low D_{cc}/d_{cp} ratio location is significantly less than the values recorded in tests performed at the sample center (*high D_{cc}/d_{cp} ratio*) and should therefore not be considered representative of the sample as a whole.

5.9 Dummy Cone Tests in Saturated Samples

A series of “dummy cone” tests were performed in loose samples at the low stress levels to evaluate the magnitude of the pore pressure development in the soil away from the penetrating cone. The tests involved inserting the 15-cm² cone into the soil at the center port location (*high D_{cc}/d_{cp} ratio*) to a depth of $z = 0.75\text{m}$ and then penetrating a dummy cone at the off-center port (*low D_{cc}/d_{cp} ratio*) location (Figure 5.43). A lateral distance of 0.35m was present between the two penetrometers. The DA-VT1 data acquisition system was run during the penetration test to record the pore pressure at both transducer locations. For reasons stated in Section 5.7.3, only the pore water pressure measurements at the U_2 location are presented in the following discussion.

The dummy cone consisted of a solid steel rod that was fabricated to a diameter and shape identical to the 15-cm² cone. An accelerometer was mounted in the steel rod at the

same location as in the 15-cm² setup and the vibration was recorded during the penetration by the second data acquisition system. The force and frequency of vibration measured at the accelerometer location mimicked that recorded in the 15-cm² cone during the vibratory penetration tests, suggesting that the vibration transmission capabilities of both the 15-cm² and dummy cones were approximately equal.

Presented as Figure 5.44a is a plot of the pore pressure ratio with depth into the sample from static and vibratory dummy cone tests in loose samples at the low stress level. Due to the stationary nature of the pore pressure measurement location, the pore pressure ratio used in this analysis was created by normalizing the pore pressure measured in the penetrometer by the vertical effective stress at a depth of 0.75m into the sample. This pore pressure value is then used to compute the pore pressure ratio at a depth of 0.75m in the soil as a penetrometer is inserted above and below this depth.

It can be seen from this figure that the pore pressure ratio measured 0.35m away from the penetrating cone is a constant value of about 0.02 during static penetration, which was approximately the same value measured on the actual cone during static penetration (Section 5.7.4). Also included in Figure 5.44 is a plot of the pore pressure ratio with depth in the sample measured during vibratory penetration of the dummy cone. It is evident from this figure that the pore pressure ratio present in the soil laterally away from the penetrometer is much greater than that present during static penetration, revealing a fairly constant value of about 0.44 during penetration of the dummy cone above and below the 0.75m measuring point. This value of the pore pressure ratio is much greater than that measured on the penetrometer during penetration (Section 5.7.4), suggesting that the pore pressure measured by the advancing probe is not indicative of the actual pore pressure in the soil laterally away from the penetrometer. Also, similar to the static penetration tests, the zone of influence of the vibratory penetration is at least $r = 0.35\text{m}$ and $z = 0.75\text{m}$ away from the penetrating device. Assuming $K_o = 0.5$ for the rigid wall condition present during the test, this would suggest that the excess pore water pressure at a depth of $z = 0.75\text{m}$ generated during the penetration of the vibrating probe is approximately 88% of the confining stress in the soil, identifying a potentially unstable soil state. A complete discussion of the pore pressure development during penetration is included in Chapter 6.

5.10 Statistical Analysis of Test Data

A statistical analysis of the test data was performed to validate the comparative analysis presented in Sections 5.6 and 5.7. The analysis consisted of an Analysis of Variance (*ANOVA*) and a regression analysis using the computer program SAS, which allowed for the evaluation of the effects of the testing factors on the normalized penetration resistance values. The independent testing factors considered in the analysis were stress, mode of penetration, testing location, and cone type, while the dependent factor was the normalized penetration resistance. The normalized penetration resistance values used in the analysis were the average values over a depth range from 0.7m to 0.8m. The penetration resistance values measured at these depths were chosen for the analysis based on their minimal influence of the upper and lower boundaries. The analysis was performed for both densities used in the calibration chamber testing.

Table 5.16 shows the results of the ANOVA and regression analysis using a Type III general linear model. The initial hypothesis proposed for the analysis considered that there was no interaction between the independent testing factor and the dependent penetration resistance value, while the null hypothesis was considered if the original hypothesis was statistically proven invalid. Listed in the last column ($Pr>F$) of the table are the probability factors that indicate whether or not the original assumed hypothesis is valid. Low values (<0.05) listed in this column suggest that the assumed hypothesis was rejected in favor of the null, while high values suggest the assumed hypothesis is valid. Based on the statistical analysis, the following conclusions were made:

- a) There is overall evidence of the effects of the vibration on the penetration resistance values
- b) The effect of the vibration on the penetration resistance value is not constant at the different stress levels
- c) The effect of the vibration is not constant for the different densities
- d) The cone type and testing location do not significantly influence the penetration resistance value in loose samples
- e) The cone type and testing location may have impacted the penetration resistance value in the medium dense samples.

A second ANOVA and regression analysis was performed that considered both a mixed model and the differences of the least square means. All possible scenarios of stress, mode of vibration, cone type, and test location were considered in the analysis. Listed in the last two columns of the analytical results presented in Appendix C are the Low and High normalized penetration resistance values for the assumed test condition. These values can be generally considered as the confidence interval of the data used in the analysis. Confidence intervals that include values of zero within their range suggest that there is no statistical evidence of differences between the data, while the reverse is true if zero falls outside of their range. The following conclusions were drawn from the analysis:

Loose Samples

- a) The test location or cone type did not significantly influence the normalized penetration resistance value at any stress level or for either mode of penetration.
- b) Stress does not seem to influence the normalized static penetration resistance value
- c) Stress does influence the normalized vibratory penetration resistance value
- d) The normalized penetration resistance for vibratory penetration tests is statistically different than that measured from static tests at the low and intermediate stress level.
- e) The normalized penetration resistance for vibratory penetration tests is statistically similar to that measured from static tests at the high stress level.

Medium Dense Samples

- a) There is statistical evidence that the test location and cone type influenced the normalized penetration resistance value at all stress levels and both modes of penetration
- b) Stress does not seem to influence the normalized static penetration resistance value for tests at the center location

- c) Stress does influence the normalized vibratory penetration resistance value for tests at the center location
- d) The normalized penetration resistance for vibratory penetration tests is statistically different than that measured from static tests at only the low stress level.

Included in Tables 5.17a and 5.17b are the standard deviations of the loose and medium dense test data computed through the ANOVA and the regression procedures. A general linear model was used for the analysis. The values used in this table were computed for the test conditions ranging from two to four input parameters, with the sample size (and subsequent degrees of freedom) considered for the analysis generally decreasing as the number of testing conditions increases. Based on the results of the analysis, the following conclusions were made:

- a) The analysis considering four input parameters, which reveals a specific testing condition, reveals a maximum fluctuation in the normalized penetration resistance of approximately 15%. This generally agrees with the comparative analysis presented in Sections 5.6 and 5.7.
- b) It was stated earlier that there is no statistical evidence of the influence of the cone type or testing location on the normalized penetration resistance values measured in loose samples. The test data from the different cone types and test locations can therefore be grouped together a given stress and mode of vibration, generating a two input parameter condition that includes stress and mode of vibration. The maximum standard deviation computed for this condition is less than 10%, which generally agrees with the comparative analysis presented in Sections 5.6 and 5.7.
- c) The analyses considering less than four input parameters that do not separate out both stress and mode of vibration (e.g. two parameter analysis that considers only stress and test location) reveal high standard deviations. This suggests that the normalized penetration resistance value is statistically influenced by the stress/mode of vibration relationship. High standard deviations were also observed when the test data from the different testing locations or cone types were grouped together in the analysis, further suggesting that the

penetration resistance value is statistically influenced by the cone type and testing location.

5.11 Representative Trendlines

As stated in the preceding sections, a detailed analysis of the calibration chamber test data was undertaken to determine representative trendlines for the penetration resistance and pore pressure ratios for each density, stress level, and mode of penetration. The analyses included an evaluation of the effects of the lateral boundary and cone type on the measured penetration resistance and pore pressure values. A review of the influence of the pore pressure transducer location on the measured pore pressure values was also performed.

The penetration resistance curves considered representative for each of the testing conditions are presented as Figures 5.45, while the representative pore pressure ratio curves are presented as Figures 5.46 and 5.47. The parameters associated with each of these penetration resistance ratio and pore pressure ratio trendlines are included in Tables 5.12 and 5.13, respectively. It is these plots and associated trendline parameters that were used in the quantitative analysis of the effects of vibration on the penetration resistance and pore water pressure presented in Chapter 6. The following conclusions were made regarding the representative trendlines:

Loose Samples

A review of the normalized penetration resistance curves presented in Figure 5.45a indicates that the static penetration resistance normalizes to a fairly constant value at the vertical center of the sample for the three stress levels used in the testing. This fairly constant normalized penetration resistance value was generated through a linear normalization procedure, and further suggests that the stress exponent of 1.0 used in Equation 5.1 is viable for the soil type and range of stresses used in the testing.

The normalized penetration resistance at the center of the sample in the vibratory tests is less than that for the static tests for both the low and intermediate stress levels, while the curve representing the vibratory penetration resistance at the high stress level is approximately equal to the static penetration curves. This reduction of the penetration resistance through vibration indicates that the dynamic energy imparted into the soil can influence the penetration resistance value. As shown through the curves, the influence of

this dynamic loading is a function of the effective stress in the soil, with the effect of the vibration decreasing as the effective stress in the soil increases.

The pore pressure ratio plots generated from static penetration tests reveal a negligible excess pore pressure in the center of the sample for all of the stress levels (Figure 5.46a). Similar results were observed for vibratory tests at the intermediate and high stresses, while the tests at the low stress levels reveal an excess pore pressure that was approximately 12% of the confining stress in the soil (Figure 5.46b). However, as noted in Section 5.9, the actual pore pressure measured in the soil at a distance of $r = 0.35\text{m}$, $z = 0.75\text{m}$ was significantly greater than that identified by the cone penetrometer. This suggests that the pore pressure measured by the cone penetrometer during vibratory penetration is not indicative of the actual pore water pressure in the soil mass away from the cone. As shown through cavity expansion theory, the soil near the cone penetrometer is highly deformed during penetration, suggesting that a soil element near the cone penetrometer is at a point of failure during (or prior to) the pore pressure measurement. The soil at this location is at a large strain/steady-state condition adjacent to the penetrometer, where no further volume change will occur with added loading. Any dynamic load imparted into the soil at this point, therefore, does not induce a significant amount of additional strain, which may explain why substantial elevated water pressures were not observed at the pore pressure measurement location during penetration.

Medium Dense Samples

A review of the curves presented in Figure 5.45b reveals a fairly constant static normalized penetration resistance at the vertical center of the sample ($z = 0.75\text{m}$) for all three stress levels. The normalized penetration resistance value for the vibratory tests is dramatically reduced at the low stress level, while the vibratory penetration resistance at the intermediate and high stress levels normalize to values fairly close to that measured during static penetration. Similar to tests performed in the loose samples, the test results in medium dense samples indicate that the influence of the vibration decreases as the effective stress in the soil increases.

The pore pressure ratio plots generated from static penetration tests reveal a negligible excess pore pressure in the center of the sample for all of the stress levels (Figure 5.47). Similar test results were observed for vibratory penetration tests at the intermediate and high stress levels, while a pore pressure ratio of approximately 0.25 was observed at the low stress level.

5.12 Comparison of Static Penetration Resistance Measurements to Theoretical and Empirical Estimations

The preceding sections outline the effects of the testing location and cone diameter on the penetration resistance and pore water pressure measurements in the calibration chamber. As stated earlier, the particular focus of this evaluation was to identify differential boundary effects at the two testing locations prior to the generation of the representative curves for each of the test conditions. Attention was also paid to the effects of the boundary condition on the overall static penetration resistance measured during the testing. This evaluation of the overall magnitude of the boundary effects was made through a comparison of the static penetration resistance values measured during testing to approximated values determined through empirical and theoretical techniques.

5.12.1 Empirical and Theoretical Approaches

Numerous approaches have been developed over the years to attempt to correlate the empirical results of calibration chamber tests to engineering parameters. These parameters are associated with the soil state and stress history, such as the relative density, state parameter, in-situ horizontal stress, and overconsolidation ratio, as well as the soil strength, such as the effective stress friction angle and bearing capacity factors. Although the bulk of these correlations were developed through calibration chamber investigations (e.g. Schmertmann 1976; Villet and Mitchell 1981; Baldi et al. 1986; Been et al. 1986), several were generated through reviews of existing calibration chamber data (e.g. Kulhawy and Mayne 1990; Lunne et al. 1997).

The initial approaches for evaluating the penetration resistance of soil deposits were based on analytical solutions using bearing capacity (e.g. Janbu and Senneset 1974; Durgonoglu and Mitchell 1975) and cavity expansion theories (e.g. Vesic 1972, 1977; Baligh 1976; Mitchell and Keavany 1986). The bearing capacity approach assumes that the soil behaves as a rigid, perfect plastic material and that the failure surface is log spiral in shape. Vesic (1972, 1977) demonstrated that the compressibility, in addition to the friction angle, had a considerable influence on the behavior of sands, and developed an analytical means of incorporating soil compressibility and friction angle into the bearing capacity analysis using cavity expansion theory (Mitchell and Keaveny 1986). Salgado et al. (1997) later used these early versions of cavity expansion theory to develop an analytical approach for estimating the penetration resistance of clean sands in calibration

chamber tests. This approach takes into account chamber size and boundary effects, and can be used to check the validity of the penetration resistance measurements recorded in calibration chambers. General agreements between theoretical and experimental values of $\pm 30\%$ were reported using this approach (Salgado et al. 1997).

Included in this section is a comparison of the penetration resistance measured in the calibration chamber with that estimated using several empirical and analytical based relationships. Representative values of the penetration resistance measured from each of the calibration chamber tests in the loose and medium dense samples are included in Tables 5.14 and 5.15 respectively, along with the soil and stress conditions present during each of the tests. Also included in these tables are estimations of the penetration resistance from an analytical approach based on cavity expansion theory. A computer program CONPOINT developed by Salgado (1993) was used to predict the penetration resistance of the soil using cavity expansion theory for the different stress, density, and boundary conditions present in the testing.

A quantitative comparison of the measured value and that estimated through cavity expansion theory is performed through the use of the Accuracy Ratio (*AR*), which is defined as:

$$Accuracy\ Ratio\ (AR) = \left\{ 1 - \left(\frac{q_{c(Cavity\ Expansion)}}{q_{c(Measured)}} \right) \right\} \cdot 100 \quad (5.5)$$

where $q_{c(Cavity\ Expansion)}$ is the penetration resistance value estimated using CONPOINT and $q_{c(Measured)}$ is the penetration resistance value measured during the penetration test at the vertical center of the sample. A value of the *AR* near zero indicates the measured value is approximately equal to that estimated through cavity expansion theory, while a value approaching 100% suggests the opposite is true.

A comparison of the measured penetration resistance and that estimated through cavity expansion theory was also compared to empirical relationships developed by Kulhawy and Mayne (1990). The first empirical relationship suggested by Kulhawy and Mayne (1990) was developed to determine the relative density of the soil based on the measured penetration resistance, and includes variables such as the vertical effective stress and soil compressibility, overconsolidation, and aging factors. Using values for the compressibility, overconsolidation, and aging factors that were recommended by the

authors, the relationship could be manipulated to show the estimation of the penetration resistance for a given vertical effective stress. This relationship is presented as Equation 5.6 and is referred to as *Method 1* in Figures 5.49 and 5.50:

$$q_c = 34694 \cdot \left(\frac{Dr\%}{100} \right) / \left(\frac{P_a}{\sigma_v'} \right)^{\frac{1}{2}} \quad (5.6)$$

where $Dr\%$ is the relative density of the soil, σ_v' is the vertical effective stress, and P_a is atmospheric pressure (100 kPa).

A second relationship was noted in Kulhawy and Mayne (1990) for estimating the relative density of the soil based on penetration resistance, relative density, and the horizontal effective stress. This relationship was manipulated to generate the following expression:

$$q_c = 17.2 \cdot EXP [Dr\% / 25] \cdot P_a^{\frac{1}{5}} \cdot \sigma_{ho}'^{\frac{4}{5}} \quad (5.7)$$

where σ_{ho}' is the horizontal effective stress and $Dr\%$ is the relative density of the soil. Equation 5.7 is referred to *Method 2* in the q_c estimations presented in Figures 5.49 and 5.50. Considering a $K \sim 0.5$, which was present in most of the calibration chamber tests performed in this study, Equation 5.7 was used to estimate the penetration resistance as a function of vertical effective stress in the soil.

A qualitative comparison of the penetration resistance value measured during the calibration chamber testing to those estimated using cavity expansion theory is presented as Figure 5.48. Plots showing the empirical relationship of the estimated penetration resistance with vertical effective stress presented through Equations 5.6 and 5.7 for loose and medium dense soils are included in Figures 5.49 and 5.50, respectively. Superimposed on these figures are the penetration resistance measurements recorded through the calibration chamber testing and penetration resistance estimations formulated through cavity expansion theory. Also included in Figure 5.49 are penetration resistance measurements recorded by Lhuer (1975) and Caillemer (1975) from calibration chamber tests performed in saturated loose sands at loose density conditions.

5.12.2 Comparative Analysis of Test Results in Loose Sands

The qualitative difference between the penetration resistance values measured during the calibration chamber testing to that estimated using cavity expansion theory is shown in Figure 4.48. It is shown through this comparison that the measured penetration resistance values were similar to that estimated using CONPOINT for the range of densities and stresses considered in the testing. The agreement is especially good for tests at the low and intermediate stress levels. As shown in Table 5.14, AR values determined using Equation 5.6 are generally less than 30% for all of the static tests performed, suggesting that penetration resistance measured during the tests is within the general range of that estimated through cavity expansion theory by using the program CONPOINT.

It can be seen from Figure 5.49 that the penetration resistance measured during the calibration chamber testing in the loose samples falls within the generated using Equations 5.6 and 5.7 for the range of densities used in the testing ($20 < D_r \% < 30$). It also appears that the penetration resistance measurements obtained from the testing approximate the penetration resistance measurements obtained from two other calibration chamber studies (e.g. Lhuer 1975; Caillemer 1975) and that estimated through cavity expansion theory (e.g. Salgado 1993).

5.12.3 Comparative Analysis of Test Results in Medium Dense Sands

The qualitative difference between the measured and estimated penetration resistance values for tests in the medium dense samples is shown in Figure 4.50. It can be seen through this comparison that the measured penetration resistance values were less than estimated using CONPOINT for the range of densities and stresses considered in the testing. As shown through the quantitative comparison using Equation 5.6 (Table 5.15), the penetration resistance measured through the testing is within 30% of that estimated through cavity expansion theory for the intermediate and high stress levels, revealing an overall agreement between the two approaches. At the low stress condition, however, the estimated penetration resistance is 117% to 138% greater than the measured values.

Presented as Figure 5.50 are the penetration resistance measurements recorded during tests performed in medium dense samples as a function of vertical effective stress in the sample. Penetration values estimated using cavity expansion theory and the empirical relationships noted in Equations 5.6 and 5.7 are also included in the figure. It appears from the Figure 5.50 that the penetration resistance measured during the testing

approximates that estimated from cavity expansion theory for the intermediate and high stress conditions. Comparisons made at the low stress conditions, however, did not prove as favorable, and may be related to the absence of a constant vertical boundary during the test at the low stress level.

It appears from Figure 5.50 that the penetration resistance measured during the penetration tests is less than that estimated from the empirical relationships for the range of density conditions present in the testing ($50 < D_r \% < 60$). This difference between the measured and the empirical estimations is particularly evident when the empirical approach defined by Equation 5.6 is considered. The factors contributing to this difference may be related to chamber size and associated boundary effects present when the correlations was developed, but are most likely attributed to grain size distribution, angularity, and compressibility differences between of Light Castle sand and the sand used to form the empirical relationships.

5.13 Summary and Conclusions

Based on the results of the calibration chamber testing, the following conclusions have been made regarding the effects of the degree of saturation, test location, cone type, and vibration frequency on the penetration resistance and pore pressure measurements. The results are summarized as follows:

- a) The static penetration resistance measured at the center of the sample in dry samples was approximately equal to that in saturated samples for static tests performed at similar stress and density conditions. Thus, the results of the tests performed in dry conditions could then be included with saturated tests when best-fit regression curves were formed to represent the test condition.

- b) The vibratory penetration resistance measured at the center of the sample in dry samples was much greater than the values recorded for saturated samples for tests performed at similar stress and density conditions. Vibratory penetration tests performed in dry conditions were therefore not included with the saturated test results when regression curves were formed to represent the test condition.

- c) A comparative analysis of the data obtained from penetration tests in loose samples revealed a similar influence of the lateral boundary at the two test locations for both boundary conditions, both modes of vibration, and all stress states. This behavior was noted for both the 10-cm² and 15 cm² penetrometers, and allowed the test results from both testing locations to be combined so that a best-fit curve could be fit through the collective data for a given test condition and cone penetrometer. The best fit curves for each penetrometer were then compared for a given stress level, revealing a negligible influence of the penetrometer type on the penetration resistance measurement. This allowed the tests data from both penetrometers to be grouped together for a given stress condition and best fit trendlines fit through the collective data set. The curve fit through this collective data set is considered as representative penetration resistance curve for the given stress condition, and was performed for both static and vibratory modes of penetration. The representative curves generated from this process are included in Figure 5.45. The parameters associated with these curves are presented in Table 5.12.
- d) A comparison of the static penetration tests performed at the two test locations in medium dense samples at low stress levels revealed a similar influence of the lateral boundary on the penetration resistance when the 10-cm² penetrometer was used. This behavior allowed the test results from both the low and high D_{cc}/d_{cp} ratios to be combined to form the representative curve for the 10-cm² cone.
- e) A comparison of the static penetration tests performed at the two test locations with the 15-cm² cone in medium dense samples at the low stress state revealed an influence of the lateral boundary on the penetration resistance at the low D_{cc}/d_{cp} ratio that was much larger than that at the high D_{cc}/d_{cp} ratio. The trendline generated for the high D_{cc}/d_{cp} ratio using the 15-cm² cone approximated the representative trendline for the 10-cm² cone and was therefore chosen as the representative trendline for the 15-cm² cone at the low stress condition.
- f) A comparison of the representative penetration resistance curves for the 10-cm² and 15-cm² cones for tests in medium dense samples at the low stress

- states indicated that the penetration resistance was not influenced by the different penetrometers used. This allowed the tests data from both testing locations to be grouped together and best fit trendlines fit through the collective data set for a given penetrometer. The best fit curves for each penetrometer were then compared for a given stress level, revealing a negligible influence of the penetrometer type on the measured pore pressure ratio. This final curve is considered representative of the penetration resistance for the given stress condition. The representative curves generated from this process are included in Figure 5.45. The parameters associated with these curves are presented in Table 5.12.
- g) A comparison of the vibratory penetration resistance recorded at both test locations during tests in the medium dense samples at the low stress state indicates that the effect of the lateral boundary was fairly constant for the two testing locations when the 10-cm² cone was used. This allowed the test results from both the low and high D_{cc}/d_{cp} ratios to be combined to form the best-fit curve for the 10-cm² penetrometer. Since the effects of the test location on the vibratory penetration resistance in medium dense samples at the low stress level was not evaluated for the 15-cm² cone, the curve generated from the analyses using the 10-cm² cone was considered representative for the testing condition. The representative curve generated from this evaluation are included in Figure 5.45 with the associated parameters included in Table 5.12.
- h) Comparisons of the effects of the sample location on the static and vibratory penetration resistance in medium dense sands at the intermediate and high stress conditions were not generated for the 15-cm² cone due to limitations of the calibration chamber. Consequently, the results of the analyses performed for the 10-cm² cone were used to represent the penetration resistance behavior for the medium dense states at the elevated stress states and both modes of penetration.
- i) A comparison of the static penetration resistance recorded at both test locations during tests in the medium dense samples at the elevated stress levels revealed a significant additional influence of the lateral boundary on the penetration resistance at the low D_{cc}/d_{cp} relative to the high D_{cc}/d_{cp} ratio.

Similar results were noted for the vibratory penetration tests at the same test conditions. Consequently, the trendline generated for the high D_{cc}/d_{cp} ratio was chosen as the representative trendline for the particular stress and density condition. The representative curves generated through this analysis are included in Figure 5.45, with the associated parameters presented in Table 5.12.

- j) A comparison of the pore pressure ratios calculated at the different element locations on the 15-cm² cone indicates that the pore pressure measured during penetration was not dependent on the pore pressure transducer location. This behavior was noted for both static and vibratory penetration in the loose samples at all stress levels and for static penetration in the medium dense samples at the low stress levels. The pore pressure measurement at the U₂ location was therefore chosen as the representative location for the penetrometer for all comparative analyses. No evaluation was made for vibratory tests or static tests at the elevated stress levels in the medium dense samples.
- k) An evaluation of the pore pressure ratios determined from penetration tests in loose samples revealed pore pressure ratios that were not dependent on the testing location. This conclusion was made for tests performed using both penetrometers, at all stress levels, and with both modes of penetration. A comparison of the representative pore pressure ratio curves for the 10-cm² and 15-cm² cones was made for each test condition, which indicated that the penetration resistance was not influenced by the different penetrometers used. The test data from both penetrometers was therefore grouped together for a given testing condition and a best fit trendline fit through the collective data set. This final curve is considered as the representative pore pressure ratio curve for the given testing condition. The representative curve generated from this process are included in Figure 5.46 with the associated parameters included in Table 5.13.
- l) An evaluation of the pore pressure ratios determined from penetration tests in medium dense samples at the low stress level revealed a significant additional influence of the lateral boundary on the pore pressure ratio at the low D_{cc}/d_{cp} relative to the high D_{cc}/d_{cp} ratio. This behavior was noted for

both static and vibratory tests using the 10-cm² cone and static tests using the 15-cm² cone. The trendline generated for the high D_{cc}/d_{cp} ratio was therefore chosen as the representative curve for each cone penetrometer. The test data for this testing location from both penetrometers was grouped together for a given testing condition and a best fit trendline fit through the collective data set. This final curve is considered as the representative pore pressure ratio curve for the given testing condition. The representative curves generated from this process have been included in Figure 5.47 with the associated parameters included in Table 5.13.

- m) An evaluation of the pore pressure ratios determined from penetration tests in medium dense samples at the elevated stress levels revealed pore pressure ratios that were not dependent on the testing location. This conclusion was made for tests performed using the 10-cm² cone for both modes of penetration. The final curve generated for each stress level and mode of vibration was chosen as the representative curve for the given testing condition, each of which is included in Figure 5.47. The regression parameters for each of these curves are presented in Table 5.13.
- n) The static penetration resistance measured at the vertical center of a loose sample is approximately the same for all tests in the sample, regardless of the testing order, location, type of test previously performed, or stress level present. Similar results were noted for vibratory tests and static and vibratory tests in medium dense samples at the low stress level using the 10-cm² cone. This suggests that multiple data penetration tests could be performed in a given sample, each of which provides information is assumed to be representative of the sample as a whole.
- o) The penetration resistance measured at the at the off-center (*low D_{cc}/d_{cp} ratio*) locations in medium dense samples at the elevated stress levels is fairly constant for a given mode of penetration and is virtually independent of the testing order or type of test previously performed. Multiple data points could therefore be obtained from an individual sample that can be considered representative of the measured value at the low D_{cc}/d_{cp} ratio. However, as stated earlier, the penetration resistance value measured at this low D_{cc}/d_{cp} ratio location is significantly less than the values recorded in

- tests performed at the sample center (*high D_{cc}/d_{cp} ratio*) and should therefore not be considered representative of the sample as a whole.
- p) The results of a series of dummy cone tests performed with vibration indicates that the pore pressure ratio measured 0.35m away from a penetrating cone is much greater than that measured during static penetration. Induced pore pressure of 88% of the confining effective stress were noted at a distance of 0.35m away from the penetrometer, revealing potentially unstable conditions at or near conditions of liquefaction at the pore pressure measurement location.
 - q) The actual pore pressure measured in the soil at a distance of $r = 0.35\text{m}$, $z = 0.75\text{m}$ was significantly greater than that measured by the cone penetrometer. This suggests that the pore pressure measured by the cone penetrometer during vibratory penetration is not indicative of the actual pore water pressure at distances away from the penetrometer. It is suggested that the soil near the cone penetrometer is highly deformed during penetration such that a soil element near the cone penetrometer is at a point of failure during (or prior to) the pore pressure measurement. The soil at this location is at a steady-state condition adjacent to the penetrometer, where no further volume change will occur with added loading. Any dynamic load imparted into the soil at this point, therefore, does not induce significant further strain in the soil mass, which may explain why significant elevated water pressures were not observed at the pore pressure measurement location during penetration.
 - r) Also, the pore water pressure measured by a vibrating advancing cone is much less than that measured in the soil away from the penetrometer, suggesting that the pore water pressures recorded on the cone itself are not representative of the pore water pressures present in the zone of influence of the penetrometer.
 - s) A statistical critique of the penetration test data using Analysis of Variance and regression analysis procedures confirmed the results of the comparative analysis previously mentioned. The results further suggested that a relatively small standard deviation of the test data was observed for all of

the test conditions analyzed. However, the estimates of the standard deviation should be considered with caution for several of the test conditions due to the limited numbers of degrees of freedom used in with the analysis.

- t) The penetration resistance measured during the calibration chamber testing in the loose samples falls within the estimations from the empirical techniques and agree with the approximations obtained through cavity expansion theory.

- u) 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 small 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.