Chapter 3

Experimental Testing Program

3.1 Introduction

The focus of this chapter is to describe the engineering properties of the sand used in the study and to outline the equipment and testing program used in the investigative analysis. The chapter begins with a summary of the index and strength testing properties of the sand used in the study. Descriptions of the different cone penetrometers, vibratory units, other equipment used in the testing are then presented. The calibration procedures and corresponding calibration factors generated for each of the pieces of equipment that had testing sensors is also included. A discussion of the problems encountered during the testing regarding the influence of temperature on pore pressure measurements is also presented. The chapter is concluded with the presentation of typical results of the vibratory motion recorded during penetration tests using both the rotary turbine and counter rotating mass vibrators.

3.2 Index Properties of Light Castle Sand

Light Castle sand was used for all of the calibration chamber testing performed as part of this study, mainly due to the large supply readily available at the testing facility. Light Castle sand was used in other research studies at Virginia Tech (e.g. Filz and Duncan 1992; Porter 1998, Gomez et al. 1999). Light Castle sand has a grain shape and distribution similar to Monterey 0 sand, which has been widely used in liquefaction evaluation analyses (e.g. Silver et al. 1976). Light Castle sand is a poorly graded quartz sand (*SP*) consisting predominantly of subangular to subrounded particles. Scanning electron microscope photographs of a grab sample from the sand stockpile are shown in Figure 3.1, while a grain size distribution curve is presented as Figure 3.2. Also included in Figure 3.2 is the grain size distribution curve defined by Silver et al. (1976) for Monterey 0 sand and the zone of liquefiable soils defined by Ishihara (1985). As shown through this comparison, the Light Castle sand used in the study has a grain size distribution almost identical to that of Monterey 0 sand and falls within the zone of liquefiable soils suggested by Ishihara (1985).

Specific gravity and maximum and minimum density tests were also performed as part of the study. Table 3.1 is a summary of the index testing performed for Light Castle sand. Also included in this table are the corresponding properties for Monterey 0/30 sand given by Porter (1998). All of the index testing performed as part of the investigation was in accordance with ASTM procedures.

3.3 Strength Testing of Light Castle Sand

3.3.1 ICU Triaxial Tests

Estimations of the strength parameters of the soil were obtained from information available in the literature and from monotonic and cyclic triaxial testing performed in the laboratory. Porter (1998) performed a series of monotonically-loaded isotropically consolidated triaxial tests (*ICU*) on Light Castle sand to evaluate the effects of the testing procedure, testing equipment, and applied correction factors on the undrained steady-state shear strength. Some of the tests performed as part of his study were on lose samples within the loose density range considered in this investigation, the results of which are considered herein. Monotonically loaded ICU triaxial tests were performed on samples air pluviated to medium dense densities as part of this study to determine the strength parameters of the soil at the higher density state and further the information related to the undrained steady-state strength generated by Porter (1998).

ICU triaxial tests were performed on medium dense samples as part of this investigation. The samples were 71mm in diameter by 152mm tall and were formed through an air pluviation technique. Each of the samples was pluviated into a latex membrane that was positioned within a forming mold. A relative density of 55% was used to simulate the average relative density present in the calibration chamber testing. An end platen was then placed over the specimen top and the membrane was secured over the platen, resulting in complete separation of the sample from the outer air surface. The sample was then subjected to a vacuum of 12 kPa to keep the sample intact once the mold was removed. The sample was then placed into the triaxial cell, which was sealed and filled with water. The vacuum was removed and the sample was purged with CO_2 to displace any air entrapped within the soil voids. The sample was subjected to a confining stress and then inundated with de-aired water. The confining stress and backpressure were then increased until a B-value greater than 0.95 was achieved. The sample was consolidated to the desired effective stress and then sheared at a constant strain rate of 0.1%/min.

Presented in Figure 3.3a are the effective stress paths presented by Porter (1998) for a series of ICU triaxial tests on samples at a relative density of 22%. Presented as Figure 3.3b are the test results determined through this study for samples at a relative density of 55%. The peak friction angles determined through this testing are 30.8^o and 40.5^o for the loose and medium dense conditions, respectively, while the steady-state friction angles were 29.1^o and 28.9^o. As shown in Figure 3.3, a significant post peak strength loss was only observed in the medium dense samples at the intermediate and high stress levels, suggesting that the *flow liquefaction* condition defined by Robertson and Fear (1997) was not encountered in the loose samples using the ICU testing procedure.

Included as Figure 3.4 is the steady-state friction angle suggested by Porter (1998) for Light Castle sand (i.e. $\phi = 29.1^o$). Superimposed on this plot are the undrained steady-state strengths determined through the ICU testing performed as part of this study. As shown through the comparison, a good agreement exists between the test data from the two different sources.

Figure 3.5 is the steady-state line formulated by Porter (1998) for Light Castle sand. Also included in the plot are test data generated by Porter (1998) for loose samples and data obtained from this investigation for medium dense samples. The position of the medium dense samples relative to the steady-state line suggests that each of the samples would tend to dilate during shear, which is further indicated by the stress path presented in Figure 3.3. However, the magnitude of any reduction in pore water pressure observed through the test data is considerably less than that suggested by the horizontal distance from the steady-state line, particularly for samples tested at the low and intermediate stress levels. Similar observations are noted for the contractive behavior of the loose samples. Thus, the concept of the steady-state line did not provide a reliable estimation of the volume change or pore pressure behavior during loading for the Light Castle sand.

3.3.2 Cyclic Triaxial Testing

Cyclic triaxial tests were performed to evaluate the behavior of Light Castle sand during dynamic loading. The triaxial system used in the testing is a completely automated closed-loop feedback system that is controlled by a five-channel signal processor. A full discussion of this system is presented in Polito (1999). Software run through a personal computer was developed specifically for the testing equipment to control both the signal processor and the data acquisition system. The software can be used to run drained and undrained tests on monotonic or cyclically loaded samples. The sample in any of these tests can be consolidated to either isotropic or anisotropic stress states. The data acquisition system also automatically checks the B-value of the sample during the backpressure saturation stage of the test and converts the recorded data to an ASCII file format. Five different testing parameters are measured during the test by the five-channel signal processor. The parameters recorded during the test include the axial load, which is measured through a load cell, and the axial displacement, which is recorded through an electronic LVDT. The confining pressure and effective confining pressure (which takes into account the magnitude of the backpressure) are also measured during the test using pressure transducers.

The reconstituted samples tested in the investigation were prepared using an air pluviation technique previously mentioned for the monotonic ICU triaxial tests on the medium dense samples. A cyclic load based on sinusoidal waveform motion applied at a frequency of 1 Hz was used for all of the testing. Each of these samples was consolidated to an effective stress of 110 kPa and then sheared at cyclic stress ratios ($\sigma_d/2\sigma'_{(consol)}$) ranging from 0.12 to 0.18 for the loose samples and 0.16 to 0.22 for the medium dense samples.

The results of the cyclic triaxial testing on samples prepared at the loose density are presented as Figures 3.6 through 3.8. As shown through these diagrams, the pore water pressure increases and the effective stress decreases during the cyclic loading, identifying the *cyclic softening* behavior defined by Robertson and Fear (1995a). The accumulation of this water pressure and the subsequent reduction in effective stress eventually leads to a state where the applied shear stress equals the shear strength of the soil. The soil at this point begins to exhibit large amounts of strain, which accumulates with added loading cycles. The combination of the applied cyclic load and the negligible shear stress present in the soil prior to the load application results in a shear stress reversal during the test, which eventually leads to periods where the effective confining stress is zero. Further evidence of this pore pressure increase and subsequent decrease in effective stress is shown through the *p′ vs q* diagrams presented in Figure 3.9, which clearly show that the stress path of the soil moves to the left during shear. As identified by the tests, the number of cycles needed to reach the point where collapse of the soil structure is initiated decreases as the shear stress applied to the soil increases. Similar results were identified for tests performed on the medium dense samples, the results of which are presented as Figures 3.10 through 3.14.

Presented as Figure 3.15 are the plots of the cyclic stress ratio versus the number of cycles to failure for both the loose and medium dense samples. Failure was defined for each of the tests as the initial point where strength loss was initiated and the soil exhibited a double amplitude strain of 2% over a one-cycle period. Similar strain criteria were noted by Ishihara (1993) for liquefaction based analysis using cyclic triaxial testing. This definition of failure differs from the commonly used stress based criteria where failure is defined as the point when the effective confining stress in the soil is zero. It should be noted that the effective stress in the sample did not equal values of zero at this point and that the pore pressure ratio ($\Delta u/\sigma_3'_{(initial)}$) values were much less than 1.0. This value was chosen as the initial point of failure because the decrease in effective stress with added strain beyond this point was always very rapid, sometimes reaching changes in effective stresses of greater than 60 kPa within a tenth of a cycle period.

A comparison of the level of the effective stress in the soil prior to the rapid loss in strength is presented as Figure 3.16 for the two soil densities. The effective stress in the soil at this point ($\sigma_3'_{(c)}$) was normalized by the initial confining stress ($\sigma_3'_{(o)}$) to show the percent of effective stress in the soil relative to the initial amount. A listing of these values is included in Table 3.2 for each test. An inspection of Figure 3.16 reveals that the ratio of the final to the initial effective stress increases with the cyclic stress ratio for a given relative density, indicating that the higher loads applied to the soil can cause rapid strength loss at confining stresses closer to the initial stress level. Similarly, for a given CSR, this ratio for the medium dense condition is substantially less than that for the loose condition, revealing that the potential for rapid strength loss is much larger for soil in the loose state. Thirdly, for a given ratio, a higher CSR is needed to induce large strains at the higher density state.

As shown through this analysis, the generation of excess pore water pressure and the subsequent rapid loss in strength is dependent on the input load applied to the soil mass. This principle is further considered in Chapter 6 through an evaluation of the energy imparted into the soil through vibration and the ability of the soil to resist strength loss when exposed to dynamic loading.

Figures 3.17 and 3.18 show the stress-strain hysteresis loops generated during the cyclic triaxial testing on loose and medium dense sands, respectively. The hysteresis loops for all of the CSR's used in the testing are included in the figures. Each hysteresis loop was used to compute the dissipated energy per unit volume of soil during triaxial testing by using a modified form of the relationship proposed by Towhata and Ishihara (1985). The relationship is:

$$DE = \frac{1}{2}\sum_{i=1}^{n-1}(\sigma_{d\,(i+1)} + \sigma_{d\,(i)}) \cdot (\varepsilon_{(i+1)} - \varepsilon_{(i)}) \qquad (3.1)$$

where *DE* is the dissipated energy per unit volume of soil, $\sigma_{d(i)}$ is the deviator stress applied during the cyclic loading at time step *i*, $\varepsilon_{(i)}$ is the axial strain at time step *i*, and *n* is the number of data points. DE is a measure of the energy absorbed by the volume of soil during loading, but is represented by units of stress (i.e. kJ/m^3 = kN-m/m^3 = kN/m^2 = kPa). The relationship presented in Equation 3.1 does not consider the influence of the confining pressure on the energy capacity of the soil. Several investigations were noted in the literature that attempt to account for this influence by normalizing the DE by the initial confining stress (e.g. Simcock et al. 1983; Figueroa et al. 1994). This normalized energy value is referred to as the normalized dissipated energy (*NDE*) for this study.

The NDE is generated through strain in the soil and is accumulated during the test, as noted through the summation, and can be represented graphically for each of the different tests. Presented as Figure 3.19 is the NDE generated during the tests as a function of the number of cycles present during the loading. It can be seen from each of the figures that the shape of the NDE curve is characterized by an exponential function, where the rapid increase in the NDE corresponds to the initiation of strength loss and large strains in the sample. It is also evident that the NDE at this point of failure, which can also be considered as the energy capacity, decreases as the CSR applied to the soil increases and the number of cycles needed to reach failure decreases (Figure 3.20). This suggests that the energy absorbed by the soil prior to failure is dependent on the stress applied to the soil mass (*CSR*), and possibly suggests that the soil has a higher energy dissipation capacity when exposed to low CSR's than to high CSR's. The severity of this behavior seemed to be more evident as the density of the soil increases. A listing of the NDE capacity and the number of cycles to failure is presented in Table 3.2.

3.4 Equipment Used in Calibration Chamber Testing

3.4.1 Cone penetrometers

Two cone penetrometers were used in the investigation. Schematics of both cone penetrometers are presented in 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.

The first penetrometer was a triple element piezocone penetrometer loaned by Fugro Geosciences, Inc. of Houston, TX (Figure 3.21). This cone had a 60^o conical area of 15-cm^2 and a friction sleeve area of 200 cm^2. Electrical strain gauge load cells are located at both the cone tip and sleeve locations to measure the tip resistance and sleeve friction. Each unit has a maximum load capacity of 150 kN. The load cell at the sleeve location is a subtraction type load cell, which records the summation of the loads applied to both the tip and sleeve during penetration. Thus, the load applied to the sleeve is determined by simply subtracting the voltage recorded at the tip from that recorded at the sleeve.

Keller model number PA-8/8820 pore pressure transducers are positioned on the cone face (U_1) and shoulder (U_2) of the cone, while a Kistler model number 4043A50 transducer is located at the sleeve (U_3) location. Either a ceramic or polyethylene filter provided by the manufacturer was located over the transducers. The transducers located at the U_1 and U_2 locations were installed specifically for the project to remove the influence of temperature on the transducer and corresponding pore pressure values. A complete discussion of these temperature effects is included in Section 3.6. Electrical problems were encountered during the testing with the pore pressure transducer at the U_3 location. The data recorded at this location were therefore omitted from all analyses

A Topward Electric Instrument Co, LTD model 2000 power supply was used to supply a 15V excitation voltage to the cone penetrometer. This excitation voltage activated an internal signal conditioner, which distributed the voltage and then returned a

5V reference signal common to all channels. The voltage signal from each of these channels measured during the penetration test was then directed towards a Keithley 2000 multimeter, which converted the signal to the digital form read by the data acquisition unit (Figure 3.22).

The second penetrometer used in the testing was loaned by Georgia Tech for the project. This penetrometer has a 60^o conical base area of 10-cm^2, a friction sleeve area of 150 cm^2, and an 89kN capacity (Figure 3.21). It is capable of measuring the load at both the tip and sleeve locations through strain gauge load cells that act independently of one another. The pore water pressure is measured on the cone at the U_2 location through a Data Instruments type AB transducer. A polyethylene filter was positioned over the transducer during all of the penetration tests. An ET Tech PSR-6C six unit power supply was used to provide a 15V excitation voltage to the load cells at the tip and sleeve locations and a 5V excitation voltage to the pore pressure transducer. The voltage response measured at each one of these load cells/transducers was then directed towards the Keithley 2000 multimeter, which converted the signal to the digital form needed for the data acquisition system (Figure 3.22).

The diameter of the rod used in the testing varied for the different cone penetrometers so that an adequate seal was maintained at the top lid location during penetration tests in samples with an elevated backpressure. This seal was not maintained if a gap was generated between the rod and top lid after the cone penetrometer was inserted into the sample. An EW cone rode was used with the 10-cm^2 cone while a specially fabricated rod was designed for testing with the 15-cm^2 cone. A schematic of the specially designed rod and the fitting that attaches the rod to the 15-cm^2 cone is presented as Figure 3.23.

3.4.2 Vibratory System

The vibratory system designed for the project provides a dynamic excitation to the cone penetrometer during penetration. Three different dynamic sources were developed and used in the testing. Unless otherwise noted, the machining of all of the fittings and accessory components in each of the systems was performed in the machine shops on the Virginia Tech campus. Similarly, the rotating mass vibrator was built for the project using Virginia Tech facilities.

All of the vibratory units were contained within either a steel or aluminum housing. The lower portion of this housing was mounted on top of a 1m section of cone rod, which was then attached on the lower end to the cone penetometer (Figure 3.24a). The upper portion of this housing was rigidly attached to the hydraulic jack used to push the cone penetrometer. Karman Rubber model K175 rubber vibration isolators were placed in the midpoint of the connector rods in the housing to minimize the upward propagation of the vibration into the hydraulic jack and maximize the downward propagation of the vibration into the cone rod. Four Kistler model 9031A load cells were attached to the housing base plate directly below the vibratory unit to measure the magnitude of the force and the frequency of the dynamic load generated by the vibratory units (Figure 3.24a). A Kistler model 8602A500 accelerometer was also installed in the cone rod directly above the penetrometer sleeve to determined the vibratory force and frequency imparted into the soil (Figure 3.24b).

The Kistler load cells used in the vibration analysis are piezoelectric force transducers that respond well to dynamic loading. The voltage output from each of these load cells is directed into a Kistler 4-Gang Connector Box, which averages the four signals and generates one voltage output (Figure 3.25). The voltage output from this box is directed into a Kistler model 5004 Dual Mode Amplifier, which amplifies and transmits the signal to the data acquisition system. The Dual Mode Amplifier also serves as the power source for load cells. Kistler model 1635A2 low noise cables were used in all of the voltage transmission lines to reduce the noise and minimize the voltage influence from other electrical sources.

A Kistler model 5112 Piezotron Coupler served as the power supply for the accelerometer (Figure 3.25). The voltage output from this accelerometer was amplified using a Keithley Metrabyte MB40-02 100x amplifier and then directed into the data acquisition unit through a Kistler model 1601BSP low capacitance cable. The voltage signal from both the load cell and accelerometer were observed during each test using a Tectronics TDS 430A oscilloscope.

The initial vibrator used in the testing was developed by Georgia Tech as part of this study. The unit was based on a pneumatic impulse design where a 0.357 kg mass attached to a piston was elevated and driven into a steel plate (Figure 3.26). Compressed nitrogen moving into and out of a solenoid valve was used to drive the piston. A timer located in a control box was used to control the rate of motion of the impact, which was limited to frequencies between 1 and 5 Hz. Impulse load tests conducted in an MTS machine using a high speed data acquisition system revealed that the force imparted onto the penetrometer tip through the impact motion was less than 4N. Tests performed in the calibration chamber and field tests results reported by Wise (1998) and Schneider et al. (1998) using this unit did not reveal a reduction in vibratory tip resistance when compared to static tests. As such, a limited number of penetration tests were performed with this unit.

The second vibrator used in the calibration chamber testing was loaned to the project by ARA Associates, Inc. of South Royalton, VT. The vibrator is manufactured by BES Technology, Inc. of Brunswick, OH and is available commercially. The unit is based on an eccentrically loaded mass design where compressed air is directed into the system and forced through a narrow chamber at the edge of the eccentrically loaded mass (Figure 3.27). This airflow turns the barrel containing the eccentrically loaded mass about a fixed axis that is oriented in the horizontal direction. Thus, both horizontal and vertical components of the motion are present during most of the cycle of the rotating mass. The unit operates at a fairly constant frequency and force for input air pressures above 550 kPa and flow rates above 0.4 m^3/min. A 5.66 m^3/min trailer-mounted air compressor was rented for the testing to achieve these rates. Values of air pressure and flow rate below these minimum values either did not generate enough force inside the vibratory unit to turn the eccentrically loaded mass or generate a vibratory motion that was constant with respect to force or frequency.

The third vibratory unit used in the calibration chamber testing was built for the project (Figure 3.28). The source of vibration is similar to that of the second vibrator, only a second counter rotating mass was added to the system with a horizontal component of motion equal and opposite to that of the first rotating mass. Thus, the horizontal component of motion is zero and the net vertical motion is twice that generated by a single rotating mass. The vertical vibratory force generated by the unit is controlled by the placement of a known mass at the same eccentricity and location on the gear so that both masses meet at the same point at the same time during the rotation. Thus, force and frequency combinations ranging from 0.2kN to 1.9kN and 5Hz to 60Hz, respectively, can be generated with the unit since both the mass and the frequency of motion are adjusted independently of one another.

The rotating mass noted in the previous paragraph is attached to a 127mm diameter gear through a 9.5mm steel shaft and a Lovejoy Spider connection. The steel shaft is imbedded into the center of the gear through a metal insert and key connection. A second gear and associated eccentric mass is attached to the first gear at the gear edge and to a 9.5mm steel shaft and metal insert at the center. Each gear is fixed on both sides to a steel bearing jacket. This bearing jacket is raised off of the underlying aluminum housing plate by a 25.4mm aluminum block so that the gear is free to rotate about its axis. A Gast 1UP-NRV-3A air motor is used to rotate the gears.

3.4.3 Data Acquisition System

Two data acquisition systems were used in the testing. The first data acquisition system (*DA-VT1*) was designed to record the time, displacement, tip resistance and pore water pressure generated during the penetration test. Although the system was modified slightly for each of the cone penetrometers used in the testing, the overall setup of the system remained the same. The voltage output from the cone penetrometer was directed into a Keithley 2000 multimeter, which converted the analog signal generated by the cone to a digital form. The Keithley meter is a nine channel meter, so the voltage outputs from all of the channels in the cone were simultaneously directed into the meter without significant delays between the readings. The digital signal was then transmitted to a laptop computer, which was recorded and stored at a sampling rate of 3 readings/sec. A computer program VTCone written in the QuickBasic computer language was used to run the data acquisition system.

A second data acquisition system (*DA-VT2*) was used to record the vibration generated by the vibrator during the dynamic penetration tests. The system was designed to record the vibration measured at both the load cell and accelerometer locations for a 5-second interval as the cone approached the center of the sample. The voltage output from both the Dual Mode Amplifier and the Piezotron Coupler were directed into a Keithley Metrabyte STA-16 (*DAS-16*) screw terminal access board, which acts as a bridge between the analog input signal and the data acquisition board located in a personal computer. A Keithley DAS-16 high performance analog and digital I/O data acquisition board was used for the project, which allowed for load cell and accelerometer measurements at a sampling rate of 1000 readings/sec. The software Labtech Notebook Pro was used to run the data acquisition system.

3.4.4 Other Accessory Equipment

Procedures were undertaken to saturate the cone penetrometer prior to the penetration tests to ensure that the response the transducer mimicked the response of the water pressure. The procedure involved placing the pore pressure elements and a 75% glycerin, 25% water solution in a small PVC pressure vessel and then subjecting the vessel to a vacuum of 97 kPa for a minimum of one hour. An apparatus consisting of a rubber 51mm Flexible Rubber Drain Coupling and a 51mm to 102mm PVC Pipe Increaser was developed to aid in the saturation process (Figure 3.29). The cone was placed in the saturation device and sealed along the shaft with steel hose clamps. The deaired water and pore pressure elements were then poured into the cup of the PVC pipe so that the pore pressure element and transducer housing were completely submerged. A syringe was then used to insert the fluid into the cavities of the transducer housing to displace any entrapped air. The element and tip were then assembled while submerged and a latex membrane was placed over the cone tip and pore pressure element. The liquid was removed from the apparatus and the cone was taken directly to the push frame.

3.5 Calibration of Instrumentation Used in the Testing

3.5.1 Load Cells and Transducers in Cone Penetrometers

The load cells and transducers in the cone penetrometers were calibrated in the laboratory to determine the calibration factor needed to convert the analog signal into the required CPT parameters. The linearity, hysteresis, zero shift, and cross talk of the signals were also evaluated. The calibration factor noted for each of the measuring devices is defined by the slope of calibration curve. Any y-intercept noted in the figures is perceived as the residual voltage present in the instrument, which is generally zeroed out prior to the computation of the CPT parameter. The calibration factors determined from the testing are included in Table 3.3. The calibration curves corresponding to each of the calibration factors are included in Appendix A.

The setup used to generate the calibration factor for the tip and sleeve load is presented as Figure 3.30a. An MTS machine was used to apply an incremental load to the cone face for the 15-cm^2 cone and to the cone face and sleeve for the 10-cm^2 cone. The voltage output for the load cells was recorded for each of the load increments and a best fit linear regression line was fit through the data. The voltage output of the pore pressure transducer was also recorded during the loading of the load cell to evaluate the magnitude of cross talk between the load cells and transducers.

Each cone penetrometer was also positioned in the MTS machine with the rotary turbine and counter rotating mass vibrators at the top to determine if the load cell at the tip of the cones was capable of identifying the cyclic loads generated by the vibratory unit. If so, the dynamic load imparted into the soil at the tip location could be measured directly with the cone penetometer. The DA-VT2 data acquisition unit was modified and used in the investigation because of the high sampling rate associated with the system. The results of the investigation revealed that the load cell at the tip did not accurately identify the dynamic load imparted onto the tip for either cone, especially for the higher frequencies of motion associated with the rotary turbine vibrator.

The pore pressure transducers were calibrated in a miniature pressure chamber built for the project. A schematic of the chamber is presented as Figure 3.30b. The cone was placed in the chamber and sealed above the friction sleeve through a series of o-rings located in the top plate of the unit. A top plate was developed for each cone penetrometer due to the different diameters of the units. The cone penetrometer was then subjected to incremental increases in pressure while the voltage outputs from the tip and sleeve load cells and the pore pressure transducer(s) were recorded.

The calibration test performed in the pressure vessel also provided information related to the magnitude of the *unequal end area effects* noted by Lunne et al. (1997). The unequal end area effect is associated with the influence of the water/air pressure on the shoulder area behind the cone and is specific to each penetrometer (Figure 3.31). The correction for the unequal end area effects is represented by the following expression:

$$q_t = q_c + u_2(1 - a) \tag{3.2}$$

where q_t is the corrected cone resistance, q_c is the measured cone resistance, u_2 is the pore water pressure measured at the shoulder location, and a is the unequal end area ratio, which is the ratio of the cross sectional area of the load cell or shaft to the projected area of the cone (Lunne et al. 1997). The value of a was determined experimentally by comparing the measured q_c to the applied water pressure, as shown in Figure 3.32. The value of a determined for the 10-cm^2 cone is 0.71 while the value for the 15-cm^2 cone is

0.78, both which fall in the range of values reported by Lunne et al. (1997) of 0.55 to 0.90.

The load cells and transducers were calibrated in the laboratory on three-month cycles to evaluate fluctuations in the calibration factors. No significant change was observed in the factors for any of the load cells or transducers. Similarly, each of the load cells and transducers exhibited a fairly linear behavior during cycles of loading and unloading, suggesting that the hysteresis present in the instrument was minimal. The no- load voltage output of the pore pressure transducers in both cone penetrometers drifted slightly over long periods of time, but this value was zeroed out prior to the test and therefore did not impact the magnitude of the pore pressure reading. Finally, the voltage response in the pore pressure transducers during loading of the sleeve or tip was minimal for both cones, suggesting that the voltage cross talk between the different measurement devices was minimal.

3.5.2 Load Cells and Accelerometers in Vibration System

The load cells and accelerometer used in the vibratory testing were calibrated using an MTS machine in the laboratory. The calibration factor for the load cells was defined as the slope of the applied load versus voltage response curve. Any y-intercept noted in the analysis is related to the static load applied by the MTS machine prior to the application of the cyclic load. This value is generally zeroed out prior to the computation of the cyclic load and should therefore have no bearing on the calibration factor and the subsequent estimation of the dynamic load. The linearity and hysteresis of the output signals were evaluated during the testing. The calibration factors for the load is included in Table 3.3. It should be noted that the calibration factor determined through the testing was based on a defined setting of the Dual Mode Amplifier. The settings of this unit at the time of the calibration are listed on the calibration curve presented in Appendix A.

A schematic of the setup used to calibrate the Kistler load cells is presented as Figure 3.33a. An MTS machine was used for the testing. The load cells were attached to the MTS load cell through a rigid connection so there was no compliance between the two units. A nominal static load was initially applied to the system and then a cyclic load was applied at a 5 Hz frequency for 5 seconds. The data acquisition system was used in the testing to record the voltage response of both the Kistler and MTS load cells at a sampling rate of 1000 readings/sec. The calibration test was performed using dynamic loads of 0.88 kN, 1.78 kN, and 2.67 kN. A best-fit linear regression line was fit through the data and the calibration factor used in the testing was the average value from all three tests.

The calibration factor for the accelerometer was provided by the manufacturer prior to the testing. This factor was checked through the setup noted in Figure 3.33b. The bottom plate of the vibratory unit containing the load cells were fixed to the base plate of the MTS machine using C-clamps. A small section of EW rod containing the accelerometer at the far end was threaded into the plate attached to the load cells. The system was oscillated at 5, 10, and 20 Hz frequencies and the voltage response of both the load cell and accelerometer were noted. When the setup moves freely, the force measured by the load cell should be equal to the mass times acceleration of the rod, provided that a rigid connection exists between the load cell and the rod.

Presented as Figure 3.34 is a portion of the time history from the accelerometer calibration check. The force estimations using Newton's Second Law of Motion ($F = m*a$) are noted in Figure 3.34a while the force measured at the load cell is presented as Figure 3.34b. The regression curve fit through force estimations from the accelerometer is superimposed on the data in both Figures 3.34a and 3.34b. It is shown through this comparison that the force estimations from the accelerometer is approximately the same as that measured in the load cell, which verifies the calibration factor provided by the manufacturer. The calibration factor used in the testing is included in Table 3.3.

The calibration factors for both the load cells and accelerometer were verified in the laboratory on three-month cycles, revealing fairly constant values. Similarly, each of the load cells and transducers exhibited a fairly linear behavior during cycles of loading and unloading, suggesting that the hysteresis present in the instrument was minimal.

3.5.3 Displacement Transducer and LVDT

The displacement transducer used to measure the travel distance and rate of the cone penetrometer was calibrated in the laboratory by determining the voltage output of the unit for known extensions of the wire cable. The calibration for the unit is presented in Table 3.3. The calibration curve generated during the test is included in Appendix A.

The LVDT used to measure the displacement of the bottom sample plate during the application of the vertical pressure was also calibrated in the laboratory using a Trans-

Tek model 0353-0000 LVDT. The calibration for the unit is presented in Table 3.3. The calibration curve generated during the test is included in Appendix A.

3.6 Temperature Effects on Pore Pressure Measurements

The initial 15-cm^2 cone penetrometer used in the calibration chamber testing had Keller Model PA-8-200 pore pressure transducers at both the cone face (U_1) and shoulder (U_2) locations. These transducers are capable of withstanding extremely high pressures, and were installed into the unit by the manufacturer for a previous deep-sea application. A penetration test performed with this unit in a dry Light Castle sand sample revealed elevated water pressures at the U_1 location, suggesting that the voltage output generated by the transducer was influenced by factors other than the pressure exerted on the internal diaphragm. The influence of the transmission of axial load to the transducer, filter type and wear, and temperature were all evaluated in the laboratory as suspect reasons for the erroneous pore pressure values. The results of the laboratory investigation revealed that axial loads applied directly to the pore pressure element did not influence the voltage output from the pore pressure transducer. Calibration chamber tests using specially fabricated aluminum and carborundum filters at the U_1 location also revealed a pore pressure response similar to that using a ceramic element. However, a series of submergence tests performed with the penetrometer revealed that the pore pressure response of the transducer was dependent of the temperature of the cone penetrometer. The submergence tests consisted of submerging the cone into a 152mm deep water bath and measuring the voltage output of both the U_1 and U_2 transducers with time using the DA-VT1 data acquisition unit. The temperature of the water bath was then fluctuated and the test was repeated. The temperature of the cone was then reduced to room temperature (18.2^{o}C) prior to the start of each test. The maximum temperature increase (ΔT) was set at approximately 29^{o}C, which corresponds to the maximum measured temperature increase noted by Zuidberg (1988) during field penetration tests in sands.

The results of the submergence tests are presented in Figure 3.35. Also included in this figure are the results of a calibration chamber test conducted in the dry Light Castle sand. It can be seen through Figure 3.35 that the U_1 pore pressure transducer was highly sensitive to temperature, as indicated by the fluctuating pore pressure response (voltage output) at different temperatures. The tests also reveal a delay in the voltage response with respect to time of submergence, with the shortest delay occurring at the highest temperature. This time delayed transducer response was also noted during the calibration chamber test.

Corrective measures to account for this thermal shock behavior involved replacing the Keller PA-8-200 transducers with Keller PA-8/8820 transducers. This remedial activity took place at the Fugro Geosciences Inc. office in the Netherlands due to the proprietary nature of the cone. Submergence tests performed with the cone and new transducers revealed a negligible fluctuation in the voltage output with temperature (Figure 3.35).

3.7 Vibratory Response During Testing

As noted in Section 3.3.2, the dynamic motion generated by both the rotary turbine and counter rotating mass vibrators was monitored through load cells positioned directly beneath the base plate of the vibrator and by an accelerometer located near the cone tip. These instruments were added to the penetration system midway through the testing program. The vibration measurements were recorded by the DA-VT2 data acquisition unit for a 5 second period when the penetrating cone reached the vertical center of the sample.

3.7.1 Rotary Turbine Vibrator

A representative force time history at the load cell location is presented as Figure 3.36. The force measurement was offset 5kN for comparative purposes. The Fourier transform of this dynamic motion is also included in the figure. Vibration measurements at the load cell location reveal an average force output of approximately 1.5kN (340lbf) at a nearly sinusoidal frequency between 125Hz and 135 Hz (Table 3.4).

A summary of the average force and frequency of motion measured by the load cells for each of the tests is included in Table 3.4. The magnitude of force listed in this table represents the double amplitude motion generated by the unit. The standard deviation of the force values relative to the mean is only 0.27, suggesting that the force generated by the unit was fairly constant between tests. Any variations that did exist were most likely attributed to variations in the rate of airflow brought into the vibratory unit from the air compressor. Only the first fundamental mode of the vibration was recorded in the testing, most likely because the sampling rate of the data acquisition system was not high enough to identify the higher modes of vibration.

Vibration measurements at the accelerometer (tip) location reveal an average peak acceleration of approximately 6000 cm/sec^2 at a frequency almost identical to that recorded by the load cells (Figures 3.36 and 3.37, respectively. An estimation of the dynamic force at the tip was made using an expression derived from the principles of 1-D wave propagation through a homogeneous, isotropic, linear elastic rod:

$$F(t) = \frac{v(t) \cdot E \cdot A}{c} \tag{3.3}$$

where *F(t)* is the force generated by the propagating wave as a function of time, *v(t)* is the particle velocity, *E* is Young's modulus, *A* is the cross sectional area of the bar, and *c* is the wave velocity. Similar expressions are used to determine the compressional force generated by a propagating wave during pile driving (e.g. Yokel 1982). The area used in this analysis was based on the cross sectional area of the bar and the particle velocity was determined by integrating the acceleration time history (Figure 3.36). The values of Young's Modulus and wave velocity used in the analysis were those reported by Richart et al. (1970) for steel.

A comparison of the force measured at the load cell and the force estimated at the tip using Equation 3.3 is presented as Figure 3.38 for a short time increment during the test. As shown through this comparison, the force estimated at the load cell is approximately equal to that at the tip, suggesting that there is minimal loss of force through material damping during the propagation of the wave through the rod. This also suggests that the material properties gathered from Richart et al. (1970) accurately represent the material properties of the system, and further indicates that the non-continuous nature of the rod system does not significantly impact the propagation abilities of the wave.

A more precise measurement of the wave velocity (c) can be made by dividing the distance of propagation (L) by the phase difference between the force recorded at the load cell and the acceleration recorded at the tip (Δt), provided the sampling rate of the data acquisition system adequately characterizes the shape and frequency of the curve (Figure 3.39). Given the high frequency of the wave motion and the relatively few sampling points within the cycle of the wave, this approach was not used and the representative value suggested by Richart et al. (1970) was used for the analysis.

3.7.2 Counter Rotating Mass Vibrator

The counter rotating mass vibrator was used to evaluate the effects of the frequency of vibration on the penetration resistance of the soil. The vibrator was designed so that the mass attached to the rotating gear system could be adjusted to maintain a constant dynamic force for different frequencies of rotation. A summary of the force and frequencies of motion generated by the unit for different penetration tests is presented as Table 3.5. The magnitude of force listed in this table represents the double amplitude motion generated by the unit.

As shown through the table, the average force of vibration at the load cell was approximately 1.5kN (350lbs) for all tests, which was identical to the force generated by the rotary turbine vibrator. The frequency of motion noted in Table 3.5 for the load cell location was identified by performing a Fourier transform of the force time history. As shown in the representative transform, multiple frequencies of vibration were identified during each of the tests (Figure 3.40).

The natural frequency of the rod system was calculated using procedures derived in Richart et al. (1970). Both fixed-free and fixed-fixed end conditions were considered in the analysis to bound the end conditions that change during the test. The analysis was performed for the first three fundamental modes of vibration, which were approximately 25, 75 and 90 Hz, respectively. As shown through Figure 3.40, each of these frequencies are present in the Fourier transform of the vibratory motion, which suggests that the motion identified by the load cells is related to both the motion induced by the vibrator and the first three fundamental periods of the rods. The largest peak in this transform was generally associated at the first mode of vibration for each of the tests, suggesting that the first mode of vibration represents the predominant vibration frequency generated by the vibratory unit. Thus, the frequency noted in the Table 3.5 is the first fundamental mode of vibration noted through the transform.

Vibration measurements at the tip location reveal a peak acceleration of approximately 6000 cm/sec^2 and frequencies and modes of vibration similar to that recorded by the load cells (Figures 3.41 and 3.40, respectively). This similarity in the vibratory response at the two measurement locations further confirms that the higher modes of vibration are associated with the dynamic properties of the rod. An estimation of the dynamic force at the tip made using Equation 3.4 reveals that the force at the load cell is approximately equal to that at the tip, revealing a minimal loss of force through material damping during the propagation of the wave through the rod (Figure 3.42).

The rotating gears used in the vibrator were made of 1018 steel. After a considerable number of tests, the teeth on the gears began to wear and the small amounts of play developed between the components. The addition of this play to the system altered the position of the mass during the rotation of the gear, which subsequently added a horizontal component to the motion. A predominant frequency of vibration was not observed through the Fourier transforms, so the unit was dismantled and a new gear system installed. Although this seemed to correct the problem, it is anticipated that testing errors associated with gear wear will always be present unless a gear system is installed that is made of a high strength steel or is constantly lubricated as the gears rotate.

3.8 Summary and Conclusions

Included in the previous sections is a comprehensive summary of the index and strength properties of Light Castle sand. Also included were detailed descriptions of the equipment used in the calibration chamber testing. The following conclusions are made:

a) The Light Castle sand used in the testing is similar in gradation, shape, and composition to Monterey 0 sand, which is often used in liquefaction oriented investigations.

b) Estimations of the steady-state strength envelope using the data from the medium dense samples agree well with that estimated by Porter (1998) based on loose samples.

c) The proximity of the initial states of the soil to the estimated steady-state line does not accurately approximate the pore pressure response of the soil during shear, adding questions to the approach of using the steady-state line established from ICU test data to estimate volume change and pore pressure behavior during loading.

d) The cyclic triaxial testing allows for the estimation of the normalized dissipated energy (*NDE*) during the dynamic loading of the soil specimen. The results of the testing indicate that the NDE at failure is dependent on the CSR applied to the soil, and possibly suggests that the full energy dissipation capacity of the soil is not mobilized at high CSR values.

e) The initial pore pressure transducers in the 15-cm^2 cone penetrometer were highly susceptible to thermal effects generated by friction during penetration. These transducers were replaced with thermally compensating models that do not generate voltage fluctuations with temperature.

f) The dynamic load generated by the vibrators was monitored directly below the vibrator by load cells and at the cone tip through an accelerometer. The force at the tip location was approximately equal to that generated by the vibratory units at the load cell, revealing a minimal loss of motion from propagation through the rod.

g) The internal load cell in the cone at the tip location did not accurately measure the dynamic load generated by the vibratory units. A dynamic load cell at this location would allow for the direct measurement of the dynamic load imparted into the soil at the tip location.

h) The motion associated with the counter rotating mass vibrator was not purely sinusoidal. This is most likely due to imprecise machining of the parts associated with the unit, which could not be avoided due to the absence of sophisticated equipment used in the manufacturing process.

i) The natural modes of vibration of the rod system were identified during the testing with the counter rotating mass vibrator. The first mode of vibration was almost always the most predominant and was therefore considered the motion generated by the vibratory unit.