

**EVALUATION OF CYCLIC RESISTANCE OF PROVIDENCE SILTS USING  
MINI-CONE PENETRATION AND STANDARD PENETRATION TESTS**

**FINAL REPORT**

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16. Abstract Most areas of coastal Rhode Island are underlain by thick layers of non-plastic silt and it is important to know if the existing standard-of-practice liquefaction potential evaluations (e.g. Robertson and Wride (1998) or Seed et al. (1985)) are accurate. The objective of this research was to critically evaluate the applicability of CPT and SPT based approaches to Providence silts. This was accomplished through a laboratory testing program involving the URI mini-cone calibration chamber and cyclic triaxial tests to develop a new relationship between cyclic resistance ratio and tip resistance for Providence silt. The new relationship was compared to the standard-of-practice liquefaction potential evaluation methods from the literature. There was good agreement between the approaches which shows that the existing field-based CPT methods are applicable to Rhode Island silts. This is consistent with previous RIDOT funded research on the liquefaction potential evaluation of silts in Rhode Island (Bradshaw et al. 2007; 2007a; Baxter et al. 2008). An attempt was also made to evaluate SPT-based approaches in silt using the mini-cone and laboratory cyclic data. A $q_c/N_{60}$ correlation was evaluated from two loose silt sites in Rhode Island where SPT and CPTs were performed adjacent to each other. The agreement between blow counts and tip resistance was very poor, most likely due to the small number of tests and small range of in situ densities. Because of the poor agreement, it was not possible to directly evaluate the SPT-based liquefaction evaluation approaches in the study.			
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## 1.0 INTRODUCTION

Field based approaches are typically used to relate the cyclic resistance of soils with *in situ* tests such as the standard penetration test (SPT) and the cone penetration test (CPT). In these methods, penetration test data from sites where earthquakes have occurred are plotted against the estimated cyclic stress caused by the earthquake, and a line is drawn separating data where liquefaction did or did not occur.

Figure 1 shows one such curve based on CPT data (Youd et al. 2001). The boundary between liquefaction and non-liquefaction is considered to be a “clean sand curve” because most of the field cases were recorded in sand deposits with little fines content. In all the field based approaches, corrections are applied to account for soils with varying amounts of fines, typically up to 35%.

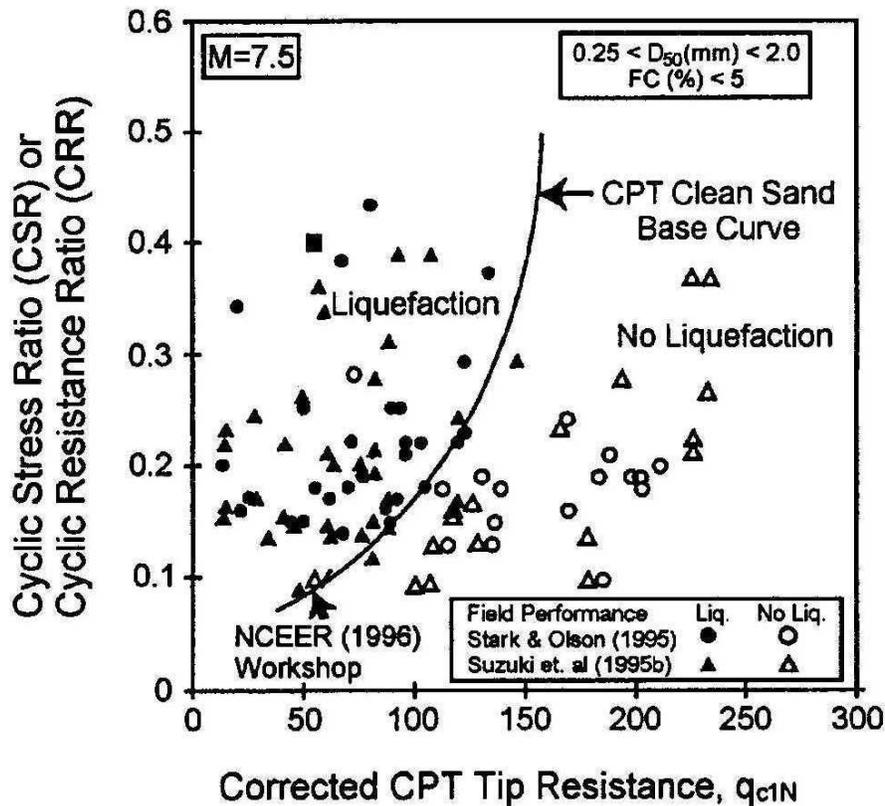


Figure 1. Recommended field based approach for the cyclic resistance of a clean sand deposit from CPT data. Closed symbols represent cases of liquefaction and open symbols cases of no liquefaction (Robertson and Wride 1998; Youd et al. 2001).

Many of the coastal areas surrounding Providence, Rhode Island are underlain by thick deposits of loose, non-plastic silts with fines contents greater than 95%. As such, there is uncertainty in the literature about the applicability of the field based approaches when dealing with pure silts. Recently, there have been several studies performed at the University of Rhode Island (URI) to address this issue, including an evaluation of disturbance during sampling (Page 2004; Baxter et

al. 2008), sample preparation methods for laboratory testing (Bradshaw and Baxter 2007), the development of a soil-specific relationship between shear wave velocity and cyclic resistance (Baxter et al. 2008a), and a detailed site response and liquefaction analysis for a site in downtown Providence (Bradshaw et al. 2007; Bradshaw et al. 2007a).

The primary implications of this work are that existing SPT and CPT based approaches, as outlined in Youd et al. (2001), provide reasonable predictions of cyclic resistance of non-plastic silt when the recommended fines content corrections are applied. The SPT methods in general yield the most conservative results. In addition, it was found that the relationship between shear wave velocity and cyclic resistance is soil specific, and field based approaches using shear wave velocity should not be used.

The objective of this study was to continue to evaluate the applicability of CPT based approaches for evaluating the cyclic resistance of Providence silts. This was accomplished through a laboratory testing program involving mini-cone calibration chamber and cyclic triaxial tests. A mini-cone calibration chamber was built for this study (Franzen 2006; Jasinski 2008) and used to determine a relationship between relative density and tip resistance for the silt (Seher 2008). Results of cyclic triaxial tests performed by Bradshaw (2006) were used to establish a relationship between cyclic resistance and relative density. Combining these two relationships, a laboratory based liquefaction curve for the CPT was generated specifically for the Providence silts.

An attempt was also made to evaluate SPT-based approaches in silt. An SPT-CPT correlation was evaluated from two loose silt sites in Rhode Island. The strategy was to correlate SPT blow counts ( $N_{60}$ ) and CPT tip resistance ( $q_c$ ) from field data and then use the soil specific  $CRR-q_c$  relationship to develop a  $N_{1,60}$ - $CRR$  relationship specific to Providence silts.

## 2.0 BACKGROUND ON CURRENT IN SITU METHODS FOR EVALUATING LIQUEFACTION RESISTANCE

To avoid problems associated with sample disturbance, the trend since the early 1980's has been to use in situ test-based correlations to estimate cyclic resistance of soils (Peck 1979). Cyclic resistance in the field is quantified by the Cyclic Resistance Ratio (*CRR*), which is defined by the ratio of the average horizontal cyclic shear stress required to cause liquefaction to the initial vertical effective stress. These methods are summarized in Youd et al. (2001). However, the methods are briefly presented here to give motivation for the research performed in this study.

### 2.1 SPT-Based Method

The SPT-based approach was initially proposed independently by Seed and Idriss (1971) and Whitman (1971). The current standard-of-practice is described in Youd et al. (2001) and utilizes the data and correlations of Seed et al. (1985) with some modifications. Cyclic resistance ratio is correlated to  $N_{1,60}$ , defined as the SPT blow count corrected to an effective overburden stress of 1 atm (~100 kPa) and a hammer efficiency of 60%. This correlation, which is shown in Figure 2, shows three curves. One curve corresponds to soils having a fines content (*FC*)  $\leq 5\%$ , the second is for soils with *FC*=15%, and the third is for soils with *FC*=35%.

The curves shown in Figure 2 were developed from field evidence of liquefaction (e.g. sand boils, settlements, ground cracking) observed at sites that had experienced an earthquake. For each site, a representative value of cyclic stress ratio *CSR* and  $N_{1,60}$  was selected and those data points are also shown on Figure 2. The *CSR* data used in this figure corresponds to an effective stress of ~100 kPa and an earthquake magnitude (*M*) of 7.5. The *CRR* correlations are defined by the boundaries that reasonably separate data from sites that showed evidence of liquefaction from those that did not. A review of the data which these curves are based indicates that the majority of the soils used in the analysis had a fines content of less than 35%. For soils having a *FC*>35% the procedures recommend using the *FC*=35% curve in Figure 2, as the *CRR* and  $N_{1,60}$  are not expected to change above a limiting fines content of about 35%.

To evaluate the liquefaction resistance of non plastic Providence silt using this method, first a SPT would be performed at a depth of interest to obtain the uncorrected blow counts (*N*). The blow counts are then corrected to a reference hammer energy of 60% and a reference overburden stress of 1 atm (i.e.  $N_{1,60}$ ) by the following expression (e.g. Youd et. Al. 2001; Baxter et al. 2005):

$$N_{1,60} = N \cdot C_N \cdot C_E \cdot C_B \cdot C_R \cdot C_S \quad (1)$$

Where  $C_N$ ,  $C_E$ ,  $C_B$ ,  $C_R$ ,  $C_S$  = correction factors for overburden stress, hammer energy, borehole diameter, rod length, and sampler type. Typical values for these factors are given in Youd et al. (2001) For sandy soils, a grain size analysis would be performed on the sample recovered in the split spoon sampler to determine the fines content (i.e. percent passing the No. 200 sieve). However, considering that the Providence silts have fines contents that are much higher than 35%, the “*FC*=35” curve from Figure 2 would be used to select the *CRR* at the measured  $N_{1,60}$ .

Finally, the  $CRR$  selected from Figure 2 would be corrected to the field conditions and earthquake magnitude using the following equation:

$$CRR = CRR_{100,M=7.5} \cdot K_{\sigma} \cdot K_{\alpha} \cdot MSF \quad (2)$$

where  $CRR_{100,M=7.5} = CRR$  selected from Figure 2,  $K_{\sigma}$  = overburden stress correction factor,  $K_{\alpha}$  = correction factor for sloping ground,  $MSF$  = correction factor for earthquake magnitude. These correction factors are described in detail in Youd et al. 2001.

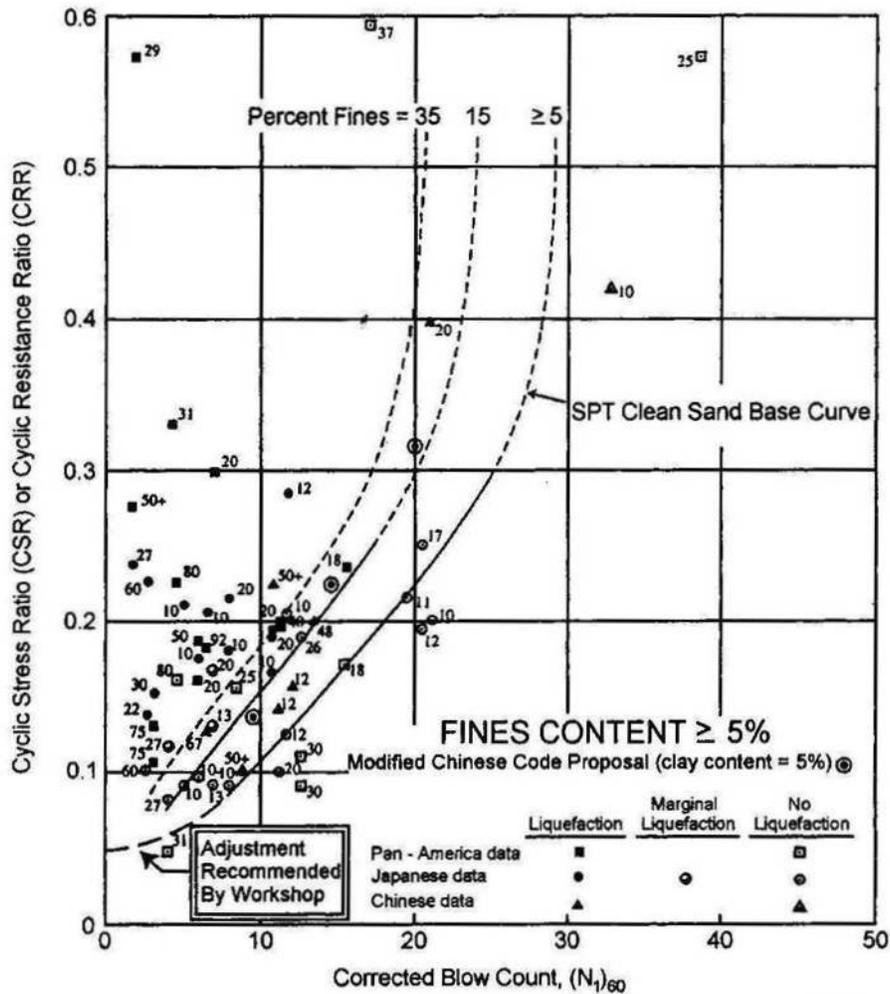


Figure 2. Correlation between  $CRR$  and  $N_{1,60}$  for a vertical effective stress of 100 kPa and an earthquake moment magnitude of 7.5 (Seed et al. 1985; Youd et al. 2001).

## 2.2 CPT-Based Method

The procedure developed by Robertson and Wride (1998) constitutes the current standard-of-practice for evaluating liquefaction potential using the CPT (Youd et al. 2001). This approach correlates *CRR* with cone tip resistance normalized ( $q_{c1N}$ ) to an effective overburden stress of 1 atm (~100 kPa). Like the SPT-based procedure, the cyclic resistance correlation was developed from case histories in relatively clean sands containing less than about 35% fines. The influence of fines is accounted for by adjusting or “correcting” the cone tip resistance to an equivalent clean sand value. The correlation between *CRR* and  $q_{cNI}$  for clean sands is shown in section 1 as Figure 1. The conversion is based on observations of decreased penetration resistance with an increase in fines content.

To evaluate non plastic Providence silt using this method, first a CPT would be performed to obtain a profile of cone tip resistance and sleeve resistance. At the depth of interest, the measured cone tip resistance would be converted to  $q_{c1N}$  using the following expression:

$$q_{c1N} = \left( \frac{q_c}{P_a} \right) \left( \frac{P_a}{\sigma'_{v0}} \right)^n \quad (3)$$

Where  $q_c$  = measured cone tip resistance,  $P_a$  = reference stress (~100 kPa),  $\sigma'_{v0}$  = vertical effective stress where the measurement is taken,  $n$  = exponent. The exponent  $n$  in equation 3 ranges from 0.5 for sands to 1.0 for clays and therefore is estimated to be approximately 0.7 for silts. The measured  $q_{c1N}$  value is then adjusted to obtain an equivalent clean sand tip resistance  $(q_{c1N})_{cs}$  using the following equation:

$$(q_{c1N})_{cs} = K \cdot q_{c1N} \quad (4)$$

where  $K$  = conversion factor. The conversion factor  $K$  depends on the soil type and therefore is correlated to a parameter called the behavior index ( $I$ ) which is estimated from the tip and the sleeve resistance of the cone. A value of *CRR* would then be selected from Figure 2 at the calculated value of  $(q_{c1N})_{cs}$  value. Like the SPT-based method, the *CRR* obtained from Figure 2 would be adjusted to in situ conditions using Equation 2. A detailed description of the CPT-based approach can be found in Youd et al. (2001).

### 3.0 MINI-CONE CALIBRATION CHAMBER TESTING PROGRAM

To date, there has been very little research for evaluating the liquefaction potential of soils with high fines contents (> 35%) using in situ tests. In this study, laboratory mini-cone penetration testing was performed using a self designed calibration chamber and Providence silt with a fines content of ~95%. The overall objective of this project was to develop a relationship between relative density and cone tip resistance for fully saturated silt specimens and to incorporate this relationship with previous research performed at URI to establish a new field-based method for liquefaction potential of Providence silt using the CPT.

This chapter presents details of the laboratory testing program and the URI mini-cone calibration chamber that was built for this study.

#### 3.1 Properties of the Soil Tested

During the last glacial retreat, thick layers of silt were deposited as proglacial lake sediments along much of Rhode Island's coastal areas (Murray 1998). *In situ* densities vary from very loose to very dense. In order to assess liquefaction potential of Providence silt, Bradshaw (2006) collected silt samples from two different sites in the Providence area and performed cyclic triaxial tests on these soils to establish relationships between relative density, shear wave velocity and cyclic resistance. The first site was a housing development in the Olneyville neighborhood of Providence and the second site was located along the Wellington Avenue Freight Rail Improvement Project in Warwick on the north bank of the Pawtuxet River (Jasinski 2008).

For the mini-cone calibration chamber testing program, these soils were blended together to have enough soil to prepare the large specimen and a total of 180 kg was obtained. The specific gravity ( $G_s$ ), minimum and maximum void ratios ( $e_{min}$  and  $e_{max}$ ), and the grain size distribution are shown in Table 1 and Figure 3. The maximum void ratio was determined by pluviation in accordance with ASTM D 4254 Procedure B and the minimum void ratio was determined using a graduated cylinder and allowing a silt slurry to deposit (Franzen 2006; Jansinski 2008).

Table 1. Properties of the silts used in this study (Seher 2008).

Soil	Specific Gravity	% < 0.074 (mm)	% < 0.005 (mm)	$D_{50}$ (mm)	Maximum Void Ratio <sup>a</sup>	Minimum Void Ratio <sup>b</sup>
Providence Silt	2.75	98	17	0.013	1.15	0.59

a. Maximum void ratio determined by placing a slurry and allowing it to settle in a graduated cylinder.

b. Minimum void ratio determined from a modified compaction test (ASTM D 1557).

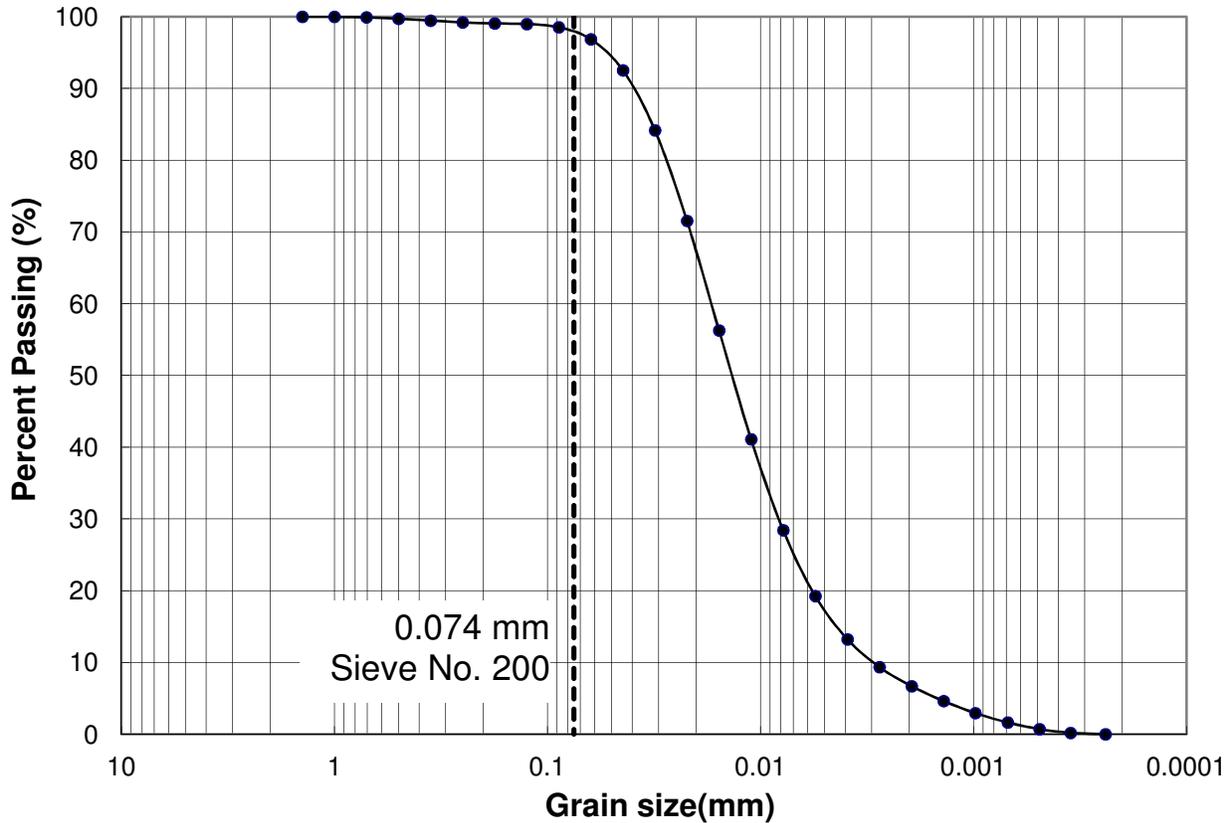
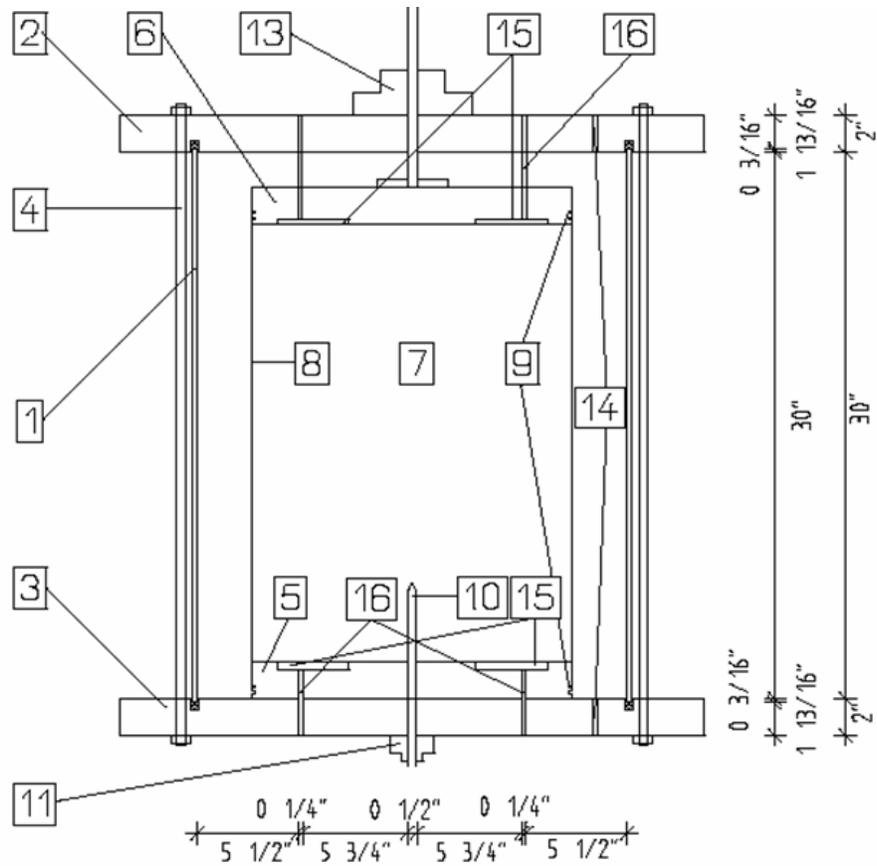


Figure 3. Grain size distribution of silt used in this study (Seher 2008).

### 3.2 URI Mini-Cone Calibration Chamber

A schematic and photograph of the URI mini-cone calibration chamber is shown in Figures 4 and 5. The chamber was designed and constructed by Franzen (2006) and Jasinski (2008). In principle, it is very similar to standard triaxial testing equipment. It is capable of applying an isotropic working pressure up to 700 kPa to a 56 cm tall x 45 cm diameter sample that is contained within a flexible membrane. The chamber system is mounted on a steel frame table approximately 82 cm from the working floor surface. The table spans over a 120 cm deep trench which allows room for the system’s hydraulic ram mounted within a reaction frame to be suspended from the bottom of the chamber table into the trench. The mini-cone was mounted in the baseplate of the chamber and pushed upwards into the sample using a hydraulic piston.

This chamber is designed with the ability to apply backpressure to the sample, provide a constant lateral stress boundary via a flexible membrane (i.e. BC1 boundary conditions), a cone to chamber diameter ratio of 40, and can be expanded to apply anisotropic consolidation stresses. Cell pressure and back pressure were applied using a standard triaxial pressure panel.



<b>1</b>	Chamber Wall	<b>9</b>	O-Rings
<b>2</b>	Chamber Top Cap	<b>10</b>	Cone Penetrometer
<b>3</b>	Chamber Bottom Cap	<b>11</b>	Pressure Sealing Bushing
<b>4</b>	Threaded Rod	<b>12</b>	Consolidation Rod
<b>5</b>	Sample Bottom Cap	<b>13</b>	Pressure Bushing (future)
<b>6</b>	Sample Top Cap	<b>14</b>	Inlet/Outlet Ports
<b>7</b>	Sample	<b>15</b>	Porous Stones
<b>8</b>	Flexible Membrane	<b>16</b>	Drainage Ports

Figure 4. Schematic of University of Rhode Island Mini-Cone Calibration Chamber (Franzen 2006).

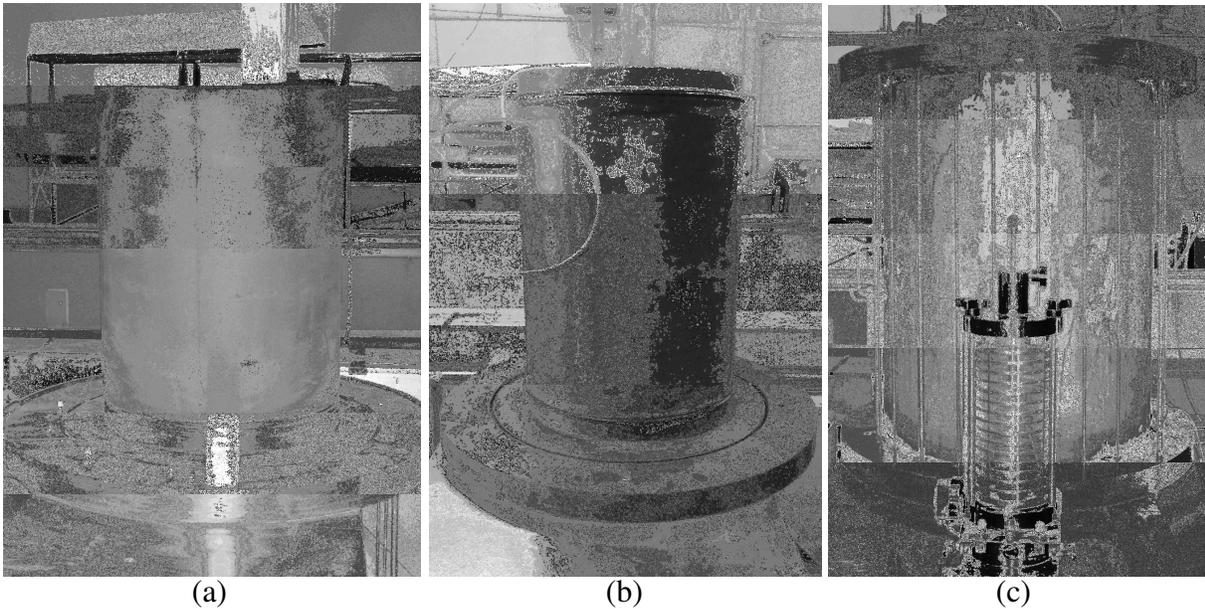


Figure 5. a.) 45 cm diameter, 56 cm high sample of non-plastic silt after sample preparation, b.) the sample encased in a rubber membrane, and c.) the sealed chamber prior to application of cell and back pressure (a standard triaxial cell is shown for scale).

### 3.3 FUGRO Mini-Cone

A  $1 \text{ cm}^2$  piezo-cone penetrometer was purchased from FUGRO Engineers B.V., Netherlands, for use in the calibration chamber tests (Figure 6). This mini-cone is the smallest electric piezo-cone cone commercially available. Three integrated transducers are able to measure tip load, friction sleeve load and pore pressure. The tip and friction load cell are connected in series, so that the first load cell measures only the tip load and the second load cell measures tip and friction sleeve load. The cone has a diameter of 1.13 cm, which corresponds to a base area of  $1 \text{ cm}^2$ . On the shoulder of the tip ( $u_2$  location according to Lunne et al. (1997)), an o-ring shaped porous stone connects the pore pressure transducer to the outside. The friction sleeve, mounted right behind the porous o-ring, moves independently of the tip and is only connected to the second load cell. The load limits of the cone load cell and sleeve load cell are 5 kN, where the load limit for the pore pressure transducer is 10 MPa.

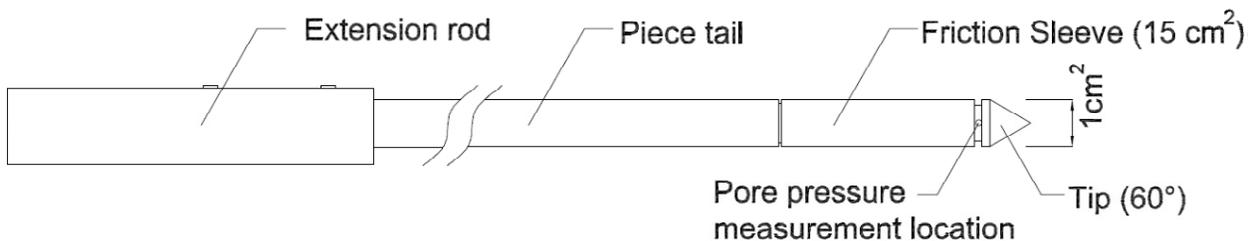


Figure 6. Schematic of FUGRO mini-cone penetrometer used in this study.

To operate the cone, a proprietary connection box is attached to the cone via an eight wire cable. The connection box requires a power input of 15 - 25 Volts DC. The transducers in the cone are powered with AC voltage. The transducers change resistance proportionally to the actual load condition and output a signal in the range of about -35 to 900 mV.

### 3.4 Mini-Cone Thrust System

The thrust system for the mini-cone consists of an aluminum frame holding a hydraulic piston (457 mm stroke), which is bolted to the bottom cap of the cell (Figure 7). When the bolts holding the aluminum frame are loosened, the entire frame can be swung aside to allow mounting of the cone. Once the cone is inserted in the housing attached to the base of the cell, the aluminum frame is swung back into place, the hydraulic piston is placed underneath the cone and the bolts are retightened. On top of the hydraulic piston a load cell and a “cup” fitting are placed. The load cell is used for monitoring the load on the cone in real time during penetration as a back up to the load cells mounted within the cone. The “cup” fitting acts as a hinge to prevent bending moments in the cone during penetration.

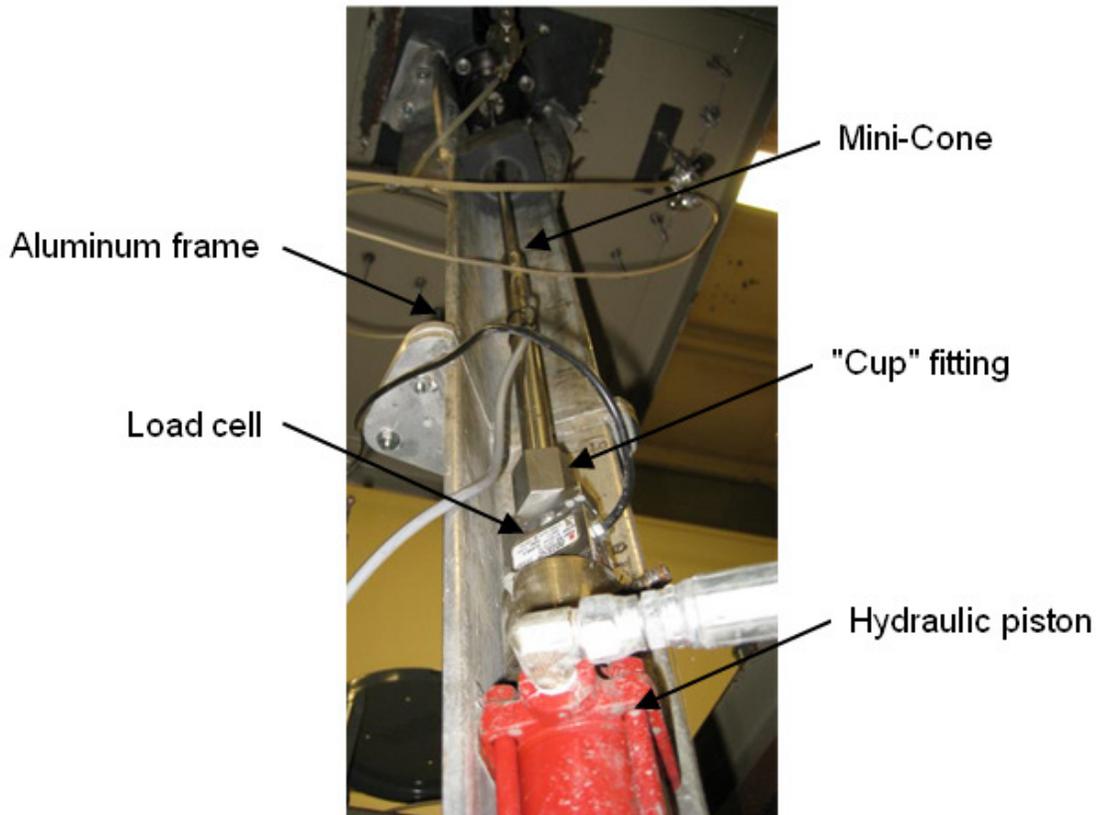


Figure 7. Mini-cone thrust system that is mounted beneath the calibration chamber.

A 10 MPa hydraulic pump (DYNEX Rivett Corp.) powers the hydraulic piston. To control and calibrate cone penetration rate to the required 2 cm/s, a needle valve is used. The feed rate is monitored using a Celesco PT 1A-50-Dn-10K-C25 linear displacement transducer.

### 3.5 Data Acquisition System

LabVIEW 7.1 was used to monitor and record the data obtained from the mini-cone penetration tests. The data acquisition card (NI PCI 6110) was installed in a standard desktop PC and connected to a BNC breakout box (NI BNC 2110) (Figure 8). Four channels of data were recorded: three signals from the cone (tip, sleeve, and pore pressure) and a fourth signal from the displacement transducer. The sample rate for each channel was 100 Hz.



Figure 8. Data acquisition system used for the mini-cone testing involving a desktop PC equipped with a National Instrument 6110 DAQ card.

### 3.6 Sample Preparation Methodology

Samples were prepared using a moist tamping method (Ladd 1978). In this approach, samples are compacted in layers, and either the compactive effort or layer density is adjusted for each layer to achieve uniform samples. Bradshaw and Baxter (2007) showed that the molding water content used during tamping has a significant influence on the cyclic resistance of silts. The strengths of samples tamped at an initial saturation ( $S$ ) of about 55% matched the strengths of both normally consolidated samples prepared from a slurry, as well as overconsolidated specimens trimmed from a block sample of Providence silt. At lower molding water contents, however, the cyclic resistance was significantly higher due to differences in fabric. Therefore, all the samples tested in this study (both the mini-cone tests and the cyclic triaxial tests) were prepared to an initial degree of saturation of 55%.

The density of the samples were measured several different ways for each test. After sample preparation, the total height and the circumference was measured at several locations along the sample. The overall bulk density was calculated from the known weight of the sample and the measured volume. The density of each layer following compaction was also measured directly from height and weight measurements. After cone penetration testing, small constant volume “plug” samples were taken from each layer during disassembly of the sample to verify the density measurements.

#### 4.0 ASSESSMENT OF LIQUEFACTION POTENTIAL OF SILT FROM MINI-CONE PENETRATION TESTS

This section presents the results of the mini-cone calibration chamber tests, which were used to understand the relationship between relative density and tip resistance for the Providence silt. These results were combined with a cyclic resistance - relative density relationship developed by Bradshaw (2006) to develop a silt-specific relationship between cyclic resistance and cone penetration resistance. This data is then compared to existing field based approaches from the literature to evaluate their suitability for assessing the liquefaction potential of the Providence silts.

##### 4.1 Results of the Mini-Cone Calibration Chamber Tests

The results of the 10 mini-cone calibration chamber tests are summarized in Table 2. Relative densities of the samples ranged from 30% to 85%, and all the samples were consolidated isotropically to an effective stress of 100 kPa. Six samples were saturated using a back pressure of 300 kPa, and four samples were tested at the molding water content (i.e. unsaturated). In all cases it is believed that the penetration tests occurred under drained conditions.

Also shown in Table 2 are the average tip resistance ( $q_c$ ), sleeve friction ( $f_s$ ), and friction ratio ( $R_f$ ) for each test. These values were obtained by averaging the cone data from 10 to 45 cm within the samples.

Figure 9 shows detailed results from the test performed on a sample prepared to a relative density of 61%. The plots of tip and sleeve resistance show some variation corresponding to the layers formed during compaction of the samples, but are otherwise fairly uniform. The pore pressure response during penetration was approximately 300 kPa, which was the back pressure used in this test. The relative density of the sample was calculated from the overall volume and mass of the sample (shown as “Bulk” density in Figure 10) as well as from the measured density of each layer during compaction (“Layer”).

Table 2. Summary of mini-cone penetration test results.

Relative Density (%)	$q_c$ (MPa)	$f_s$ (MPa)	$R_f$ (%)	Cell Pressure (MPa)	Back Pressure (MPa)	Effective Stress (MPa)
30	2.16	0.022	1.02	0.1	0	0.1
30	1.45	0.015	1.03	0.4	0.3	0.1
50	4.83	0.047	0.98	0.1	0	0.1
58	4.97	0.048	0.96	0.4	0.3	0.1
60	5.72	0.067	1.17	0.1	0	0.1
61	2.25	0.021	0.92	0.4	0.3	0.1
65	6.08	0.047	0.78	0.4	0.3	0.1
77	8.09	0.081	1.00	0.4	0.3	0.1
84	18.45	0.144	0.78	0.1	0	0.1
85	15.56	0.136	0.87	0.4	0.3	0.1

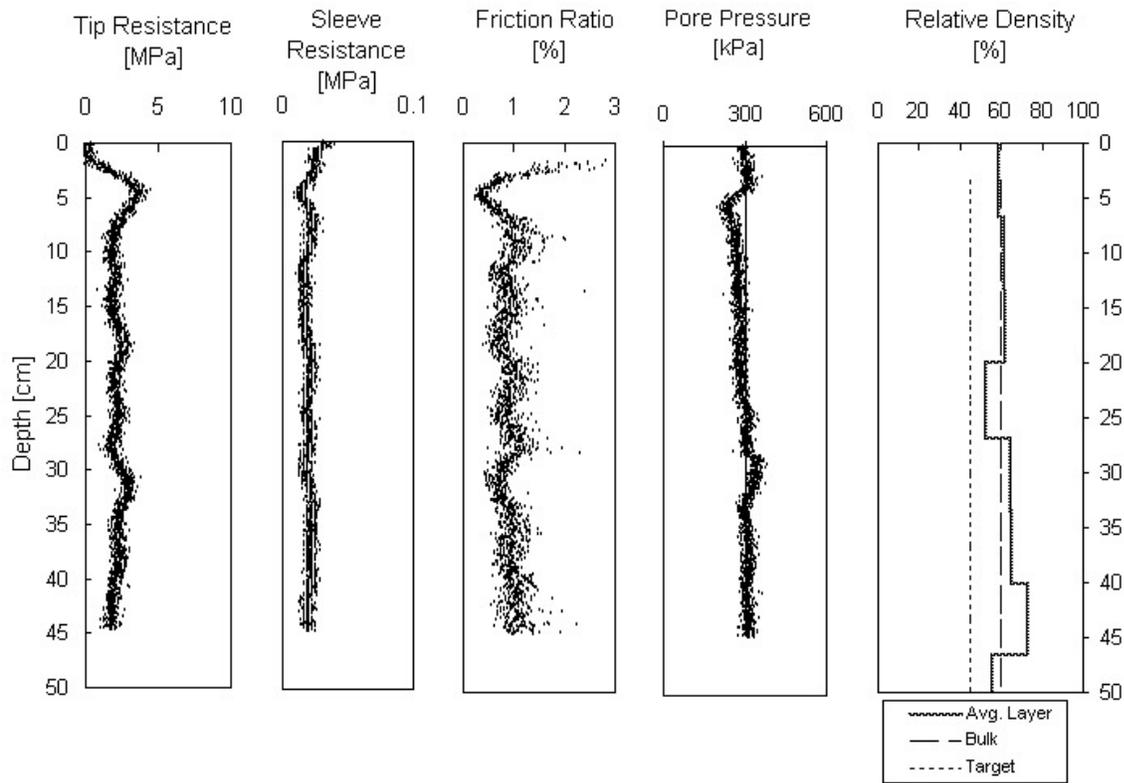


Figure 9. Mini-cone calibration test results for a sample of Providence silt prepared to a relative density of 61%.

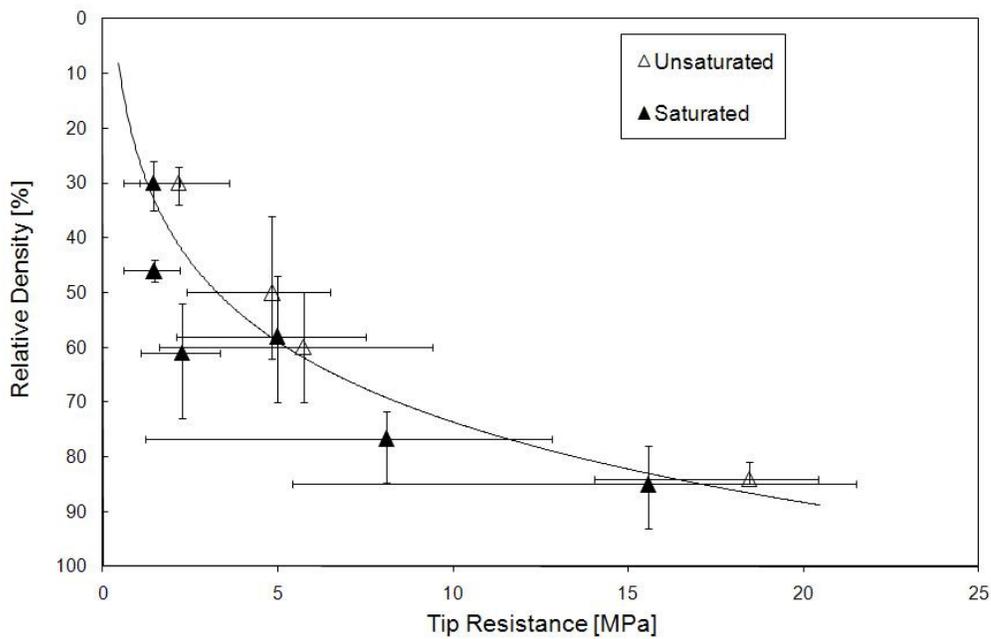


Figure 10. The relative density-tip resistance relationship derived from the 10 mini-cone calibration chamber tests. Error bars are included on each data point to illustrate the variation in measured tip resistance and relative density observed in each test.

## 4.2 Soil Specific $CRR-q_c$ Relationship

Dr. Aaron S. Bradshaw (personal communication, 2008) provided unpublished data for evaluating a relationship between relative density and cyclic resistance ratio. Bradshaw (2006) performed cyclic triaxial tests on silts from different sites in Rhode Island: the Old Farmer's Market in Providence, Wellington Avenue in Warwick, and Olneyville. The silt from two of the sites (Farmer's Market and Wellington Ave) was blended together by Franzen (2006) for chamber testing in this study. The objective of the study performed by Bradshaw was to evaluate the liquefaction potential of silts using shear wave velocity to link field and laboratory results, and the results were presented in an earlier RIDOT report (Bradshaw and Baxter 2008). The cyclic triaxial tests were performed at an effective confining stress of 100 kPa and different relative densities, ranging from 42 to 83%. The cyclic resistance ratio (CRR) of the silt was determined using 5% double amplitude strain as the failure criterion, and the data was corrected for field conditions, based on the assumption of  $K_o = 0.45$  (Baxter et al. 2008a).

Figure 11 shows the results of these tests for the samples of silt from the Wellington Ave. site, the Old Farmer's Market, and the Olneyville site. In each figure, the cyclic resistance is plotted versus the number of cycles of loading required to cause liquefaction, and the data is grouped according to relative density.

Most field based approaches make corrections to assess the liquefaction resistance for a "standard" earthquake of Magnitude 7.5 (called  $CRR_{7.5}$ ). When using laboratory data, the resistance of a Magnitude 7.5 event is typically considered to be equivalent to the cyclic resistance ratio at 15 cycles of shaking. Therefore, from Figure 11, the  $CRR$  values corresponding to 15 cycles of shaking for each level of relative density were obtained or estimated and plotted in Figure 12.

A best-fit line through the data presented in Figure 12 relating the  $CRR_{7.5}$  to relative density can be written as

$$CRR_{7.5} = 0.0213 e^{0.0293(Dr)} \quad (4)$$

Using relative density as the link between the calibration chamber and cyclic triaxial test results, the cyclic resistance corresponding to the measured tip resistances in Table 2 were calculated using Equation 4. These results are shown in Figure 13.

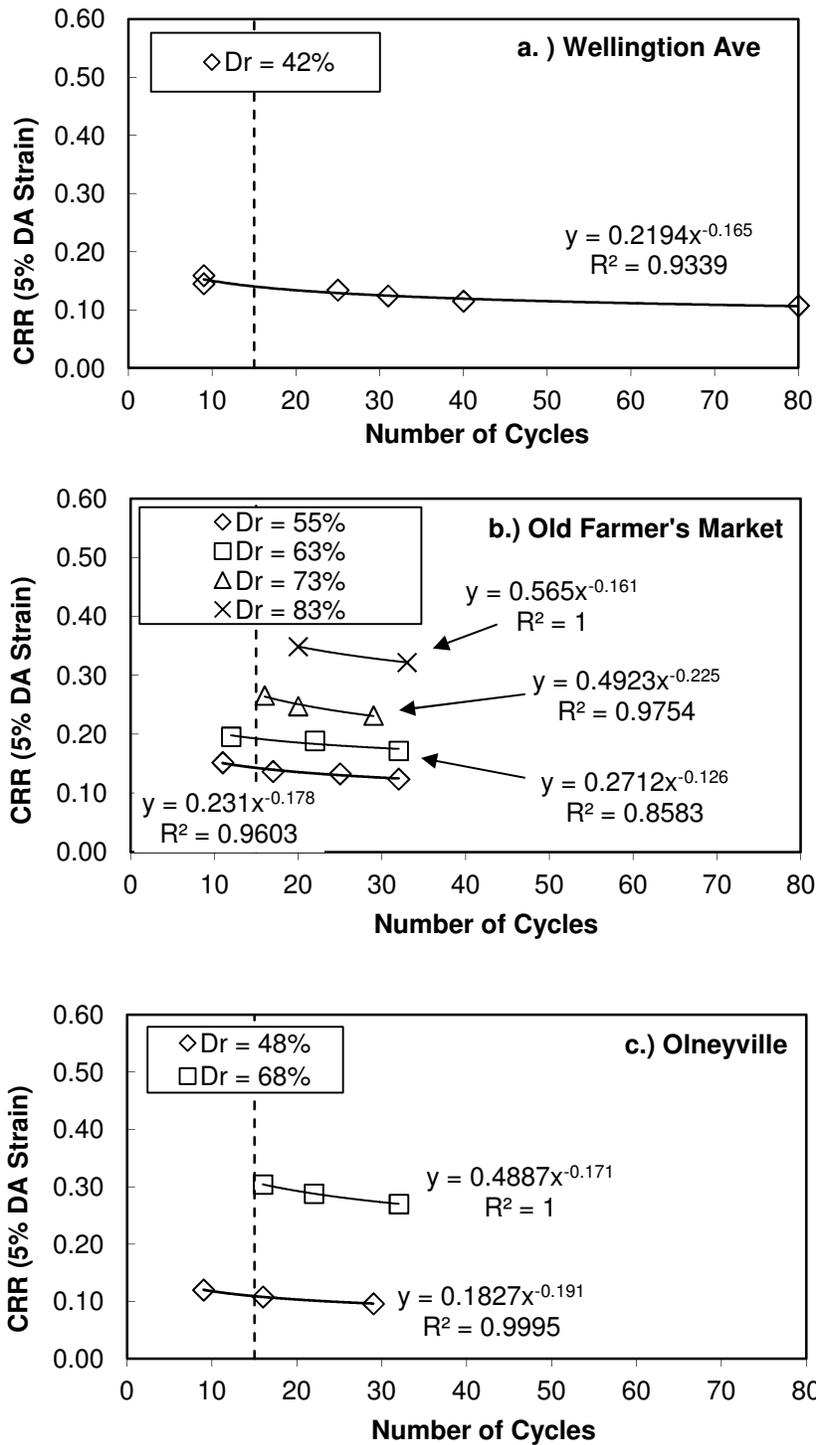


Figure 11. Results of cyclic triaxial tests on samples of silt at different relative densities from a.) Wellington Ave., b.) the Old Farmer's Market, and c.) Olneyville. The vertical dashed line in each plot shows the cyclic resistance ratio (CRR) at 15 cycles of shaking, which was used to develop Figure 12.

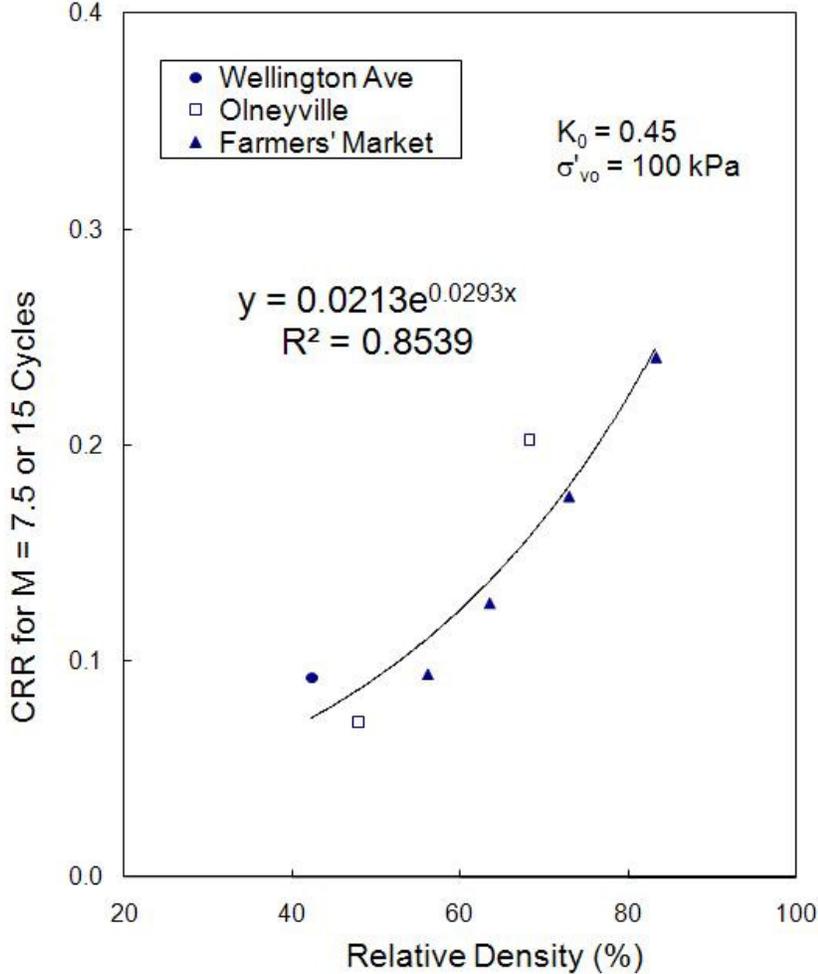


Figure 12. Relationship between cyclic resistance ratio and relative density from cyclic triaxial tests for the Providence silts used in this study.

### 4.3 Comparison with Existing Field Based Approaches

The Providence silt-specific relationship developed from the mini-cone calibration chamber and cyclic triaxial tests was compared to two existing field based liquefaction approaches from the literature. The approach developed by Robertson and Wride (1998), summarized in section 2.2, is considered to be the state-of-the practice (Youd et al. 2001). It is the most widely used field based method utilizing the cone penetration test. Moss et al. (2006) proposed a probabilistic approach for assessing liquefaction resistance from cone data.

Both methods require normalizing the tip resistance,  $q_c$ , to an in situ vertical effective stress in order to estimate the  $CRR_{7.5}$ . This creates an issue because the calibration chamber tests were consolidated isotropically, which is not representative of in situ conditions. Because  $q_c$  is known to be primarily a function of horizontal effective stress (and relative density), it was assumed that the calibration chamber test results performed at an isotropic stress of 100 kPa were equivalent to

in situ tests at a vertical effective stress of 222 kPa and a horizontal effective stress of 100 kPa (i.e.  $K_o= 0.45$ ). Thus, the  $q_c$  values in Table 2 were normalized using 222 kPa (Seher 2008), and the resulting estimated  $CRR$  values from each method are shown in Figure 13 along with the silt specific results from the mini-cone penetration tests.

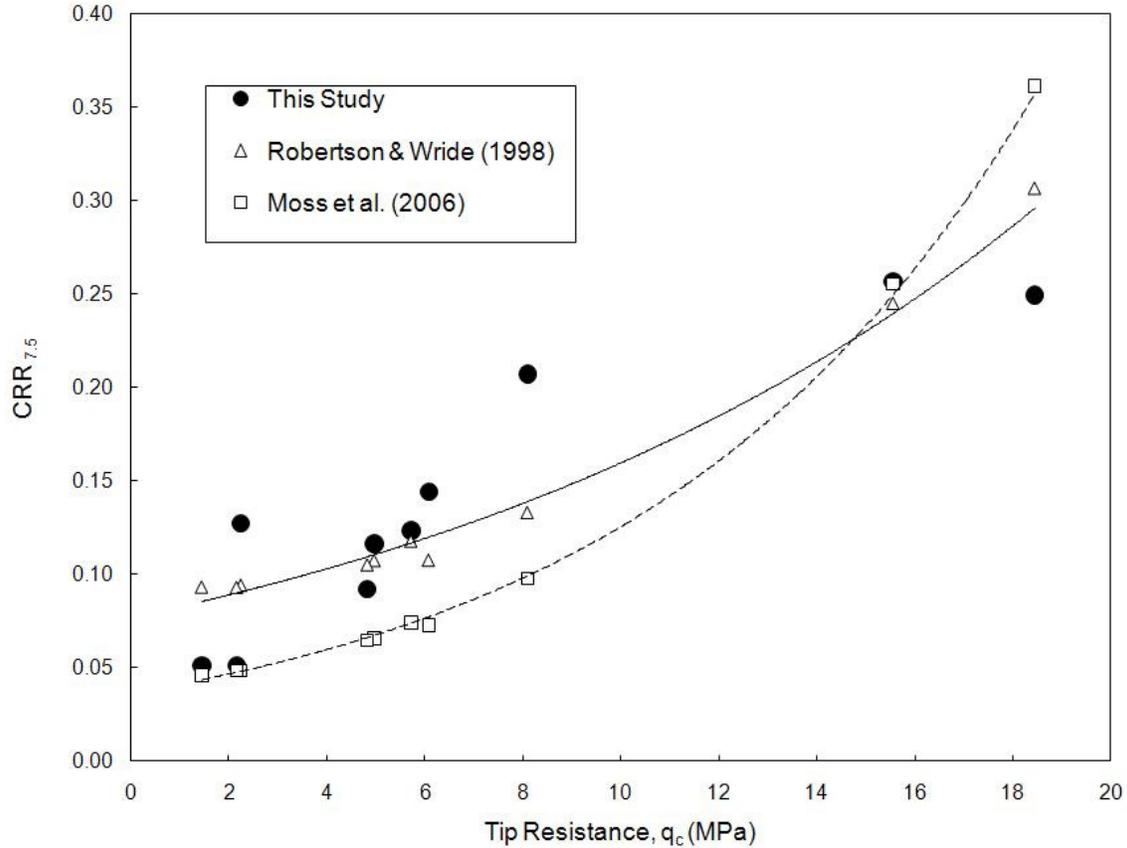


Figure 13. Comparison of liquefaction resistance curves for Providence silt from mini-cone calibration chamber and cyclic triaxial tests (this study) and published field based methods.

There is reasonable agreement between the existing field based approaches and the results of the laboratory based study. This is encouraging for sites where the fines content is significantly greater than 35%, and the **implications of this study are that the existing CPT-based approaches developed by Robertson and Wride (1998) and Moss et al. (2006) provide reasonable predictions of the cyclic resistance of non-plastic silt when the recommended fines content corrections are applied.**

## 5.0 EVALUATION OF A RELATIONSHIP BETWEEN SPT BLOW COUNTS AND CPT TIP RESISTANCE FOR PROVIDENCE SILT

A correlation between SPT blow counts and CPT tip resistance ( $q_c/N_{60}$ ) is presented in this chapter based on data from two silt sites in Rhode Island, where SPT borings were conducted adjacent to CPT soundings.

The objective of this effort was to further evaluate the applicability of SPT-based liquefaction assessment methods from the literature (Youd et al. 2001). Bradshaw et al. (2007) showed that the existing SPT-and CPT-based approaches provide reasonable predictions of cyclic resistance of Providence silt when the recommended fines content corrections are applied. In that study, the cyclic resistance ratio (*CRR*) for the silts at the Old Farmer's Market site in Providence was estimated from SPT- and CPT-based approaches and compared to the *CRR* estimated from a soil-specific relationship developed at URI using cyclic triaxial tests with shear wave velocity measurements.

In this section, the strategy was to correlate SPT blow counts ( $N_{60}$ ) and CPT tip resistance ( $q_c$ ) from field data and then use the soil specific *CRR*- $q_c$  relationship developed in section 4.2 to develop a  $N_{1,60}$ -*CRR* relationship specific to Providence silts.

### 5.1 Existing Tip Resistance - Blow Count Relationships from the Literature

The Standard Penetration Test is the most commonly used in situ test in North America, and most conventional foundation design is based on the SPT N-value. Despite the fact that the CPT is increasingly becoming more popular due to its ability to continuously profile soil layers and the higher repeatability, the base of CPT data is still smaller than for the SPT. Geotechnical engineers have considerable experience in design using SPT blow counts and therefore it is common to evaluate local SPT-CPT correlations to use CPT data in existing SPT data based design correlations. Robertson et al. (1983) correlated CPT tip resistance to SPT blow count as a function of the mean grain size  $D_{50}$  (Figure 14). Most of the blow count data used in Figure 14 was obtained using a donut hammer, and the authors estimated the average efficiency of the hammer system to be 55%. The ratio of  $q_c$  to  $N_{55}$  for a mean grain size of 0.01 mm (corresponding to an approximate value of  $D_{50}$  for Providence silt) is approximately 2.2. Note that the unit used for the tip resistance is in bars, with 1 bar ~ 0.1 MPa.

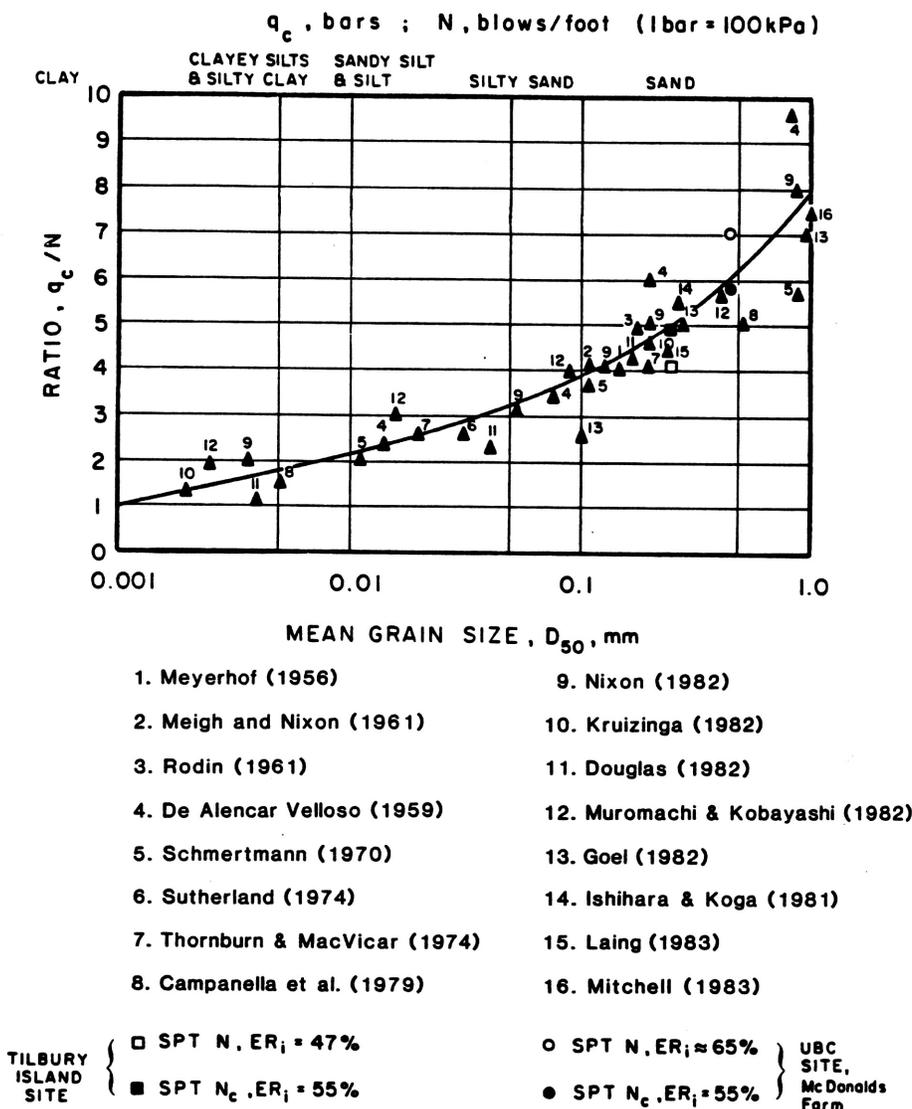


Figure 14. Variation of the ratio of CPT tip resistance and SPT blow count with mean grain size for 16 different sites from Robertson et al. (1983).

Jefferies and Davies (1993) also correlated tip resistance to SPT N-value in order to calculate an equivalent  $N_{60}$  value from CPT data only. The ratio of  $q_c$  to  $N_{60}$  is shown in Figure 15. Similar to the work of Robertson et al. (1983),  $q_c/N_{60}$  is shown as a function of mean grain size. For a mean grain size of 0.01 mm, a ratio of approximately 0.2 MPa/(blows/300 mm) is estimated, which is consistent with the correlation of Robertson et al. (1983).

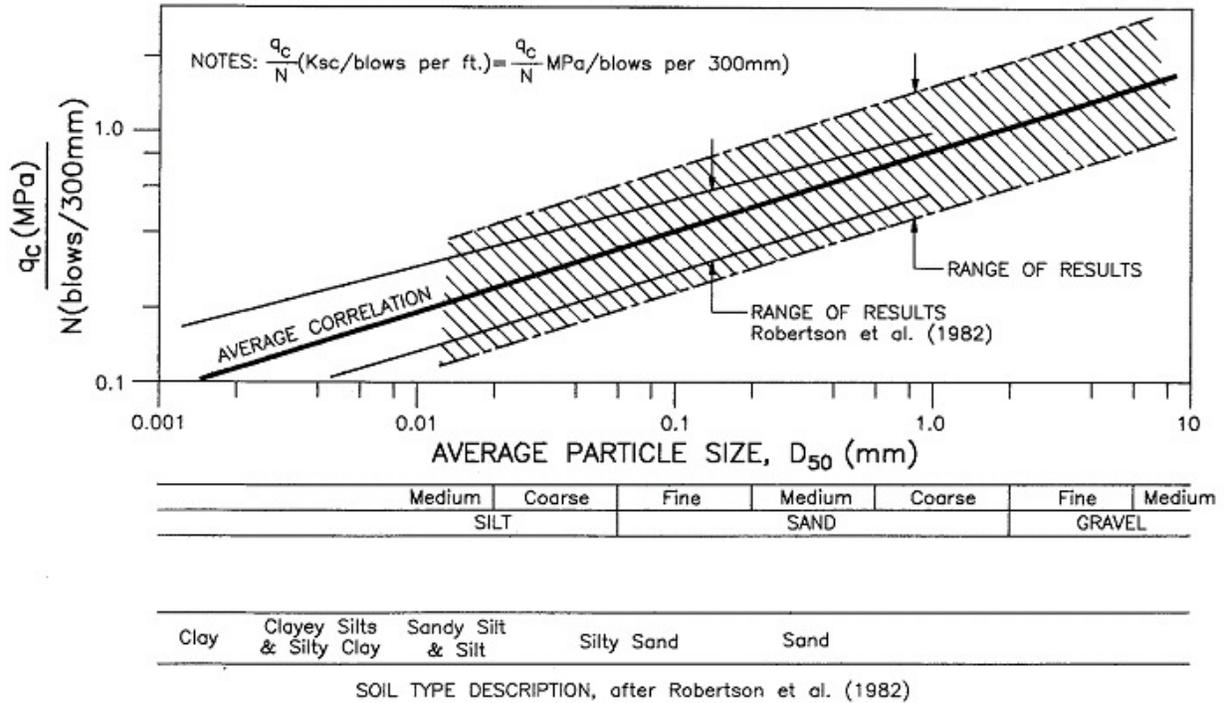


Figure 15. Variation of the ratio of CPT tip resistance and SPT blow count with mean grain size from Jefferies and Davies (1993).

## 5.2 SPT-CPT Correlation for Providence Silt

SPT and CPT data was obtained from the following two silt sites in Rhode Island:

- Old Farmer's Market, Providence
- Wellington Ave Railroad Bridge, Warwick Cranston

At the Old Farmer's Market site, located on Harris Avenue in downtown Providence, four sets of SPT and CPT soundings were performed in 2006. The standard penetration tests were performed with a donut hammer and a standard split-spoon sampler with the inside liner removed. The efficiency of the donut hammer system was measured by Heller and Johnsen Inc. using a Pile Driving Analyzer, PAK Model manufactured by Pile Dynamics, Inc., and ranged from 30% to 40% with an average of 37%.

The Wellington Avenue Railroad Bridge site was part of a larger Freight Rail Improvement Project of the Rhode Island Department of Transportation. For this site, no dynamic energy measurements were conducted, however a safety hammer was used. A total of nine CPT soundings were performed adjacent to standard penetration tests.

The CPT tip resistance for both sites was averaged over 30 cm intervals in the silt layers at the depths corresponding to the depths of the standard penetration tests. The SPT blow count were corrected to 60% of the theoretical free-fall hammer energy using a measured efficiency of 37%

for the Old Farmer's Market and an assumed efficiency of 60% for the Wellington Ave. data. The resulting tip resistance ( $q_c$ ) and blow count ( $N_{60}$ ) measurements are shown in Figure 16.

The agreement between blow counts and tip resistance for these two silt sites was very poor, most likely due to the small number of tests and small range of in situ densities. Because of the poor agreement, it was not possible to directly evaluate the SPT-based liquefaction evaluation approaches in the study.

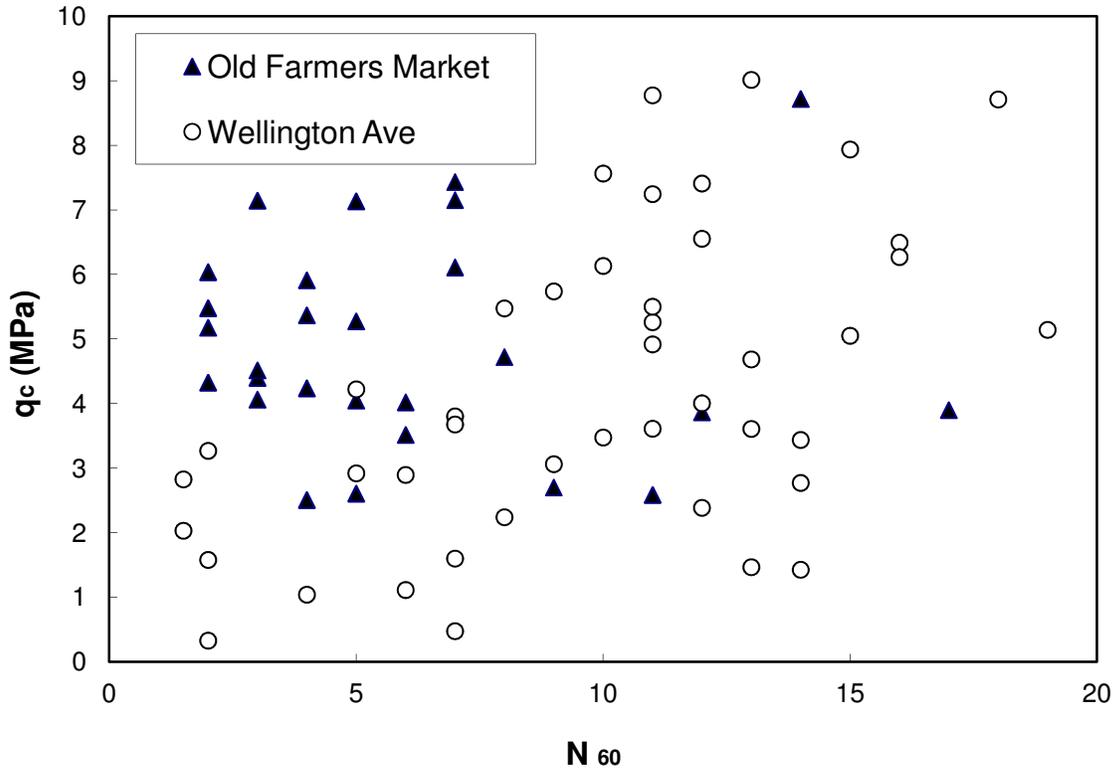


Figure 16. CPT tip resistance ( $q_c$ ) and SPT blow counts ( $N_{60}$ ) taken at adjacent locations at two non-plastic silt sites in Rhode Island.

## 6.0 CONCLUSIONS

The objective of this paper was to critically evaluate the applicability of CPT-based liquefaction resistance approaches to non-plastic silts commonly found in Rhode Island. Ten mini-cone calibration chamber tests on saturated and unsaturated specimens of Providence silt were conducted to determine a relationship between relative density and tip resistance. These results were combined with a cyclic resistance - relative density relationship obtained from a previous study, and a new relationship between cyclic resistance ratio and tip resistance for Providence silt was developed. The new relationship was compared to field based approaches proposed by Robertson and Wride (1998) and Moss et al. (2006). There was reasonable agreement between the approaches which **supports the use of the existing field-based CPT methods for assessing the liquefaction potential of non-plastic silts.**

This work is consistent with other studies by the author on the liquefaction potential of non-plastic silts, which can be found in the following references:

1. Baxter, C.D.P., Bradshaw, A.S., Green, R.A., and Wang J. (2008). A New Correlation Between Cyclic Resistance and Shear Wave Velocity for Silts, *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, 134(1), pp. 37-46.
2. Bradshaw, A.S., Green, R.A., and Baxter, C.D.P. (2007). A Rational Approach for Evaluating Seismic Demand and Resistance at a Silt Site in Rhode Island, *Boston Society of Civil Engineers' Civil Engineering Practice Journal*, 22(1), pp. 5-18.
3. Bradshaw, A.S., Baxter, C.D.P., and Green, R.A. (2007). A Site-Specific Comparison of Simplified Procedures for Evaluating Cyclic Resistance of Non-Plastic Silt, *GeoDenver 2007*, Geotechnical Special Publication 160, ASCE.

An attempt was also made to evaluate SPT-based approaches in silt using the mini-cone and laboratory cyclic data. An  $q_c/N_{60}$  correlation was evaluated from two loose silt sites in Rhode Island where SPT and CPTs were performed adjacent to each other. The agreement between blow counts and tip resistance was very poor, most likely due to the small number of tests and small range of in situ densities. Because of the poor agreement, it was not possible to directly evaluate the SPT-based liquefaction evaluation approaches in the study.

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## 8.0 NOTATION

The following symbols were used in this report:

$C_N$	= Standard Penetration Test (SPT) correction factor for overburden stress
$C_E$	= SPT correction factor for hammer energy
$C_B$	= SPT correction factor for borehole diameter
$C_R$	= SPT correction factor for rod length
$C_S$	= SPT correction factor sampler type
CPT	= Cone Penetration Test
$CRR$	= cyclic resistance ratio
$CRR_{7.5}$	= $CRR$ corresponding to a $M=7.5$ earthquake
$CRR_{100,M=7.5}$	= $CRR$ corresponding to an effective stress of 100 kPa and a $M=7.5$ earthquake
$CSR$	= cyclic stress ratio
$D_{50}$	= median grain size
$D_r$	= relative density
$f_s$	= sleeve friction
$FC$	= fines (% passing the No. 200 sieve) content
$I$	= behavior index used for converting tip resistance to a clean sand value
$K$	= soil type dependent factor for converting tip resistance to a clean sand value
$K_o$	= lateral earth pressure coefficient at rest
$K_\sigma$	= overburden stress correction factor
$K_\alpha$	= correction factor for sloping ground
$M$	= moment magnitude of an earthquake
$MSF$	= correction factor for earthquake magnitude (Magnitude Scaling Factor)
$N$	= Standard Penetration Test (SPT) blow counts (uncorrected)
$N_{60}$	= SPT blow counts corrected for 60% hammer efficiency
$N_{1,60}$	= SPT blow counts corrected to 1 atm (~100 kPa) and 60% hammer efficiency
$n$	= exponent for normalizing tip resistance
$P_a$	= reference stress of 1 atm (~100 kPa)
$q_c$	= cone tip resistance
$q_{c1N}$	= dimensionless cone tip resistance normalized to 1 atm (~100 kPa)

$(q_{cNI})_{cs}$	= normalized equivalent clean sand tip resistance
$R_f$	= friction ratio ( $f_s/q_c$ )
$\sigma'_{v0}$	= initial vertical effective stress
$S$	= degree of saturation
SPT	= Standard Penetration Test
$u_2$	= pore pressure measured on the shoulder of the cone penetrometer