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Use of In-Situ Tests to identify Soil Behavior Type and Liquefaction Susceptibility of SCCP Soils

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USE OF IN-SITU TESTS TO IDENTIFY SOIL BEHAVIOR TYPE AND LIQUEFACTION SUSCEPTIBILITY OF SCCP SOILS

by

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ABSTRACT

For many years, the Cone Penetrometer Test (CPT), Flat Plate Dilatometer Test (DMT) and Standard Penetration Test (SPT) have been used as in-situ tools to assess the liquefaction potential of soils. Given the importance of evaluating liquefaction potential in the South Carolina Coastal Plain (SCCP), research was conducted to study the soil behavior of soils prone to liquefaction, develop site specific correlations between SPT, DMT and CPT testing parameters and evaluate the liquefaction susceptibility of the soils in the SCCP. The SCCP sites studied in this thesis are Sampit (SAM), Gapway (GAP), Hollywood (HWD), Four Hole Swamp (FHS) and Fort Dorchester (FD). Normalized Cone Tip Resistance, Q, versus Normalized Friction Ratio, F and Material Index, $I_{D,}$ versus Dilatometer Modulus, E_D; charts were used to determine the soil behavior of soils prone to liquefaction. The soil behavior obtained from these charts was compared to the USCS results. From this analysis, the source sand layers at SAM, GAP, HWD and FD were found to be liquefiable, however, the source sands at FHS were considered as non-liquefiable due to the high fines content. A new DMT soil behavior chart is proposed based on the soil behavior of source sands which were classified according to physical measurements of relative densities obtained from laboratory tests on high quality soil samples. This chart was found to be in good agreement with the CPT soil behavior chart. The soil characteristics of the overburden layer and the current prediction of the water table indicated that the formation of sandblows is unlikely to occur at the Fort

Dorchester site in future seismic events. CPT and DMT tests were also used herein to develop site-specific correlations between Q-K_D and Q-E_D/σ'_{vo} for different types of soils. SPT-DMT correlations were also established for all soil types in the SCCP and were compared to previously published correlations. New correlations between these parameters were also developed for source sands at each site as well as for the combined source sands from all the five sites. Published relations between average I_c and B_q values were used to determine the soil susceptibility to liquefaction. Finally, a comparison between the geotechnical properties of the sites studied herein to sites where no liquefaction features have been found indicated that the sites studied herein are currently more susceptible to liquefaction than the other sites. Further research is required to evaluate the liquefaction potential at these sites.

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CHAPTER 1

INTRODUCTION

1.1 Overview

Cone Penetration Tests (CPT), Flat Plate Dilatometer Test (DMT) and Standard Penetration Tests (SPT) have been performed at five paleoliquefaction sites in the South Carolina Coastal Plain (SCCP) as a part of a larger study to characterize the engineering properties of the soils at these sites and evaluate their potential for liquefaction (Talwani et al., 1999; Talwani and Schaeffer, 2001; Hu et al., 2002a and Hasek, 2014). Liquefaction at these sites was triggered by strong ground motions from prehistoric earthquakes. Due to the vast damage caused by earthquakes, the ability to predict the soil behavior of soils prone to liquefaction and evaluate the potential for ground surface disturbance is a major concern.

1.2 Summary of SCCP Research to Date

Paleoliquefaction features in the SCCP have been studied since the early 1980s. Prehistoric earthquakes have been attributed to findings of over 100 sandblows near Charleston, Georgetown, Myrtle Beach, Bluffton and Hilton Head areas (See Figure 1.1). Talwani et al. (1999), Talwani and Schaeffer (2001) observed that these sandblows were caused by earthquakes that occurred over a period of 6000 years. Hu et al. (2002a) analyzed SPT, CPT and shear wave velocity tests performed at the Sampit (SAM), Gapway (GAP), Ten Mile Hill (A and B) sites to evaluate liquefaction potential. Soil samples were also collected to classify the soil and obtain the percentage of fines. The paleoliquefaction features at these sites in the SCCP were estimated to have been associated with earthquakes of magnitudes ranging from 5.3 to 7.8 and peak ground accelerations ranging from 0.14 to 0.42 g by Hu et al. (2002a). Leon et al. (2006) developed new empirical boundary curves to estimate the Cyclic Resistance Ratio (CRR) of aged soils and found that when compared to using relations developed for Holocene soils to find CRR, CRR of SCCP soils was underestimated by as much as 60%. Hasek (2014) analyzed geotechnical parameters at three additional sites: Hollywood (HWD), Four Hole Swamp (FHS) and Fort Dorchester (FD) and studied the CRR obtained from triaxial testing of high quality soil samples.

Williamson (2013) studied the geotechnical properties from DMT data at SAM, GAP, HWD, FHS and FD and established correlations between CRR and DMT derived from CRR-SPT and CRR-CPT correlations specific to SCCP to serve as boundary curves between unliquefiable soils and soils that are prone to liquefaction. These DMT data along with the CPT and SPT data collected at the five sites will be used herein to further study the soil behavior and evaluate liquefaction susceptibility in the SCCP.

1.3 Research Objectives

Given the importance of evaluating liquefaction potential in the SCCP the purpose of this research is to 1) study the soil behavior of soils prone to liquefaction, 2) develop site specific correlations between SPT, DMT and CPT testing parameters, and 3) evaluate the liquefaction susceptibility of the soils in the SCCP. The five sites studied in this thesis are Sampit, Gapway, Hollywood, Four Hole Swamp and Fort Dorchester. The geotechnical properties of the source sand layer are of particular interest to be able to understand the current and prehistoric liquefaction potential.

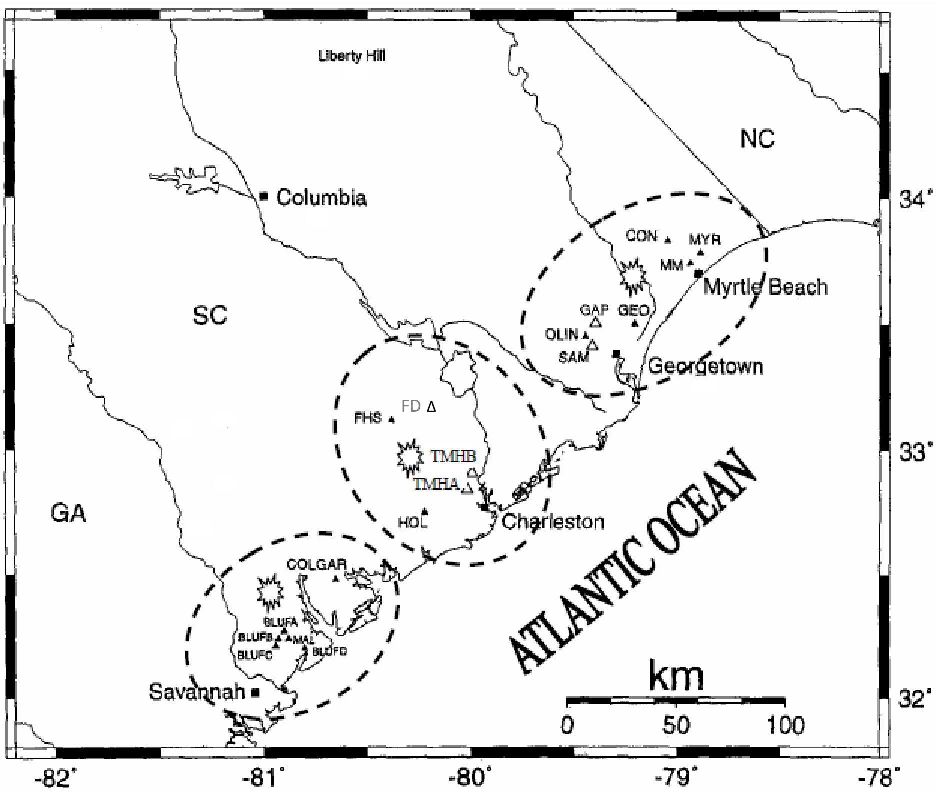


Figure 1.1 Locations of Paleoliquefaction Features in the South Carolina Coastal Plain (after Hu et al. 2002a, as shown in Williamson, 2013)

To study the soil behavior of the soils prone to liquefaction, data from CPT and DMT tests were used in this research. Normalized Cone Tip Resistance versus Normalized Friction Ratio and Dilatometer Modulus versus Material Index charts will be used to find the Soil Behavior Type and compare them to the USCS method of soil classification obtained from grain size distribution. The Soil Behavior Charts proposed by Robertson (1990) and Marchetti et al. (1980) were used to reflect the mechanical characteristics of the soil; a different approach than a soil classification based on grain size distribution and Atterberg limits. Zones 5 and 6 of the CPT based chart represent clean sands to sands and silt mixtures, soils which are generally considered to be potentially liquefiable soils. Whether the CPT data of the source sand layers plot within the specified zones will be determined from the CPT based chart. The soil behavior of source sands and the overburden layer will be studied to understand whether the sandblows will form in future seismic events. Furthermore, the physical measurements of relative densities from laboratory tests will also be used to characterize the soil behavior of source sands.

The in-situ data that was obtained by Hasek (2014) will be used to develop site specific correlations between DMT and CPT and DMT and SPT testing parameters for the SCCP soils. The CPT and DMT data will be used to develop correlations between Q-K_D and Q-E_D/σ'_{vo} parameters for all fine grained soils and for all soil types respectively. These newly acquired correlations will then be compared to previous published correlations. SPT-DMT correlations will be developed for three different soil types: silts, clays and sands and compared to the correlations found by Hajduk (2006) specific to the Charleston region in the SCCP. In addition to these results, new correlations between the CPT-DMT and SPT-DMT parameters will also be established for the source sand layers at each site as well as for combined source sands from all five research sites.

I_c and B_q values from CPT test data will be further analyzed by using the CPT based susceptibility charts provided by Hayati and Andrus (2008a) to evaluate whether the source sand at each site is susceptible to liquefaction or not. Lastly, a comparison will be made between the in situ data from the sites studied herein where there is evidence of liquefaction to sites studied by Geiger (2010) where there is no evidence of liquefaction.

1.4 Thesis Outline

The thesis is organized in six chapters as follows. Chapter 2 presents an overview of the five geotechnical sites studied in this thesis. The in situ testing procedures, existing correlations between DMT-CPT and DMT-SPT parameters and methods used to determine soil behavior type and liquefaction susceptibility of soils are also presented. Chapter 3 addresses the CPT and DMT methodologies used to determine soil behavior type for SCCP soils. Chapter 4 presents the DMT-CPT and DMT-SPT correlations developed for different soil types in the SCCP and compares them to existing correlations between DMT-CPT and DMT-SPT test parameters. Chapter 5 presents an analysis of the liquefaction susceptibility at the five sites in the SCCP using CPT based charts by Hayati and Andrus (2008a). Finally in Chapter 6, conclusions are drawn and recommendations for future work are given.

CHAPTER 2

BACKGROUND

2.1 Introduction

This chapter gives a summary of the five geotechnical investigation sites in the South Carolina Coastal Plain. The in situ testing procedures and assumptions that are used in reducing the experimental data for each test are presented. These tests include the dilatometer test, cone penetration test and standard penetration test. Previous work presented by other researchers and existing correlations between different test parameters are also summarized.

2.2 Site Descriptions

2.2.1 Sampit Site

The Sampit site is situated about 9.2 miles west northwest of Georgetown, South Carolina. As discussed by Williamson (2013), the elevation above mean sea level varies from 37 to 43 ft (11.3 to 13.1 m) and the topography gently inclines towards the northwest direction. The geographical test locations and the locations of the three sandblows in the drainage ditch at the Sampit site are presented in Figure 2.1.

Hu et al. (2002) studied the data from six SCPT and six SPT tests (SAM-01 through 06). Three SCPT tests (SAM-SCPT-1 through 3), two SPTE tests (SAM-SPTE-1 and 2), and a DMT test (SAM-DMT) were studied by Hasek (2014). Williamson (2013) analyzed the data at SAM-SPTE-1, SAM-SCPT-1 and SAM-DMT and performed index tests on soil samples obtained from SAM-SPTE-1. In addition to the test locations analyzed by Williamson (2013), this thesis also includes data from SAM-SCPT-2 and SAM-SCPT-3 of Hasek (2014).

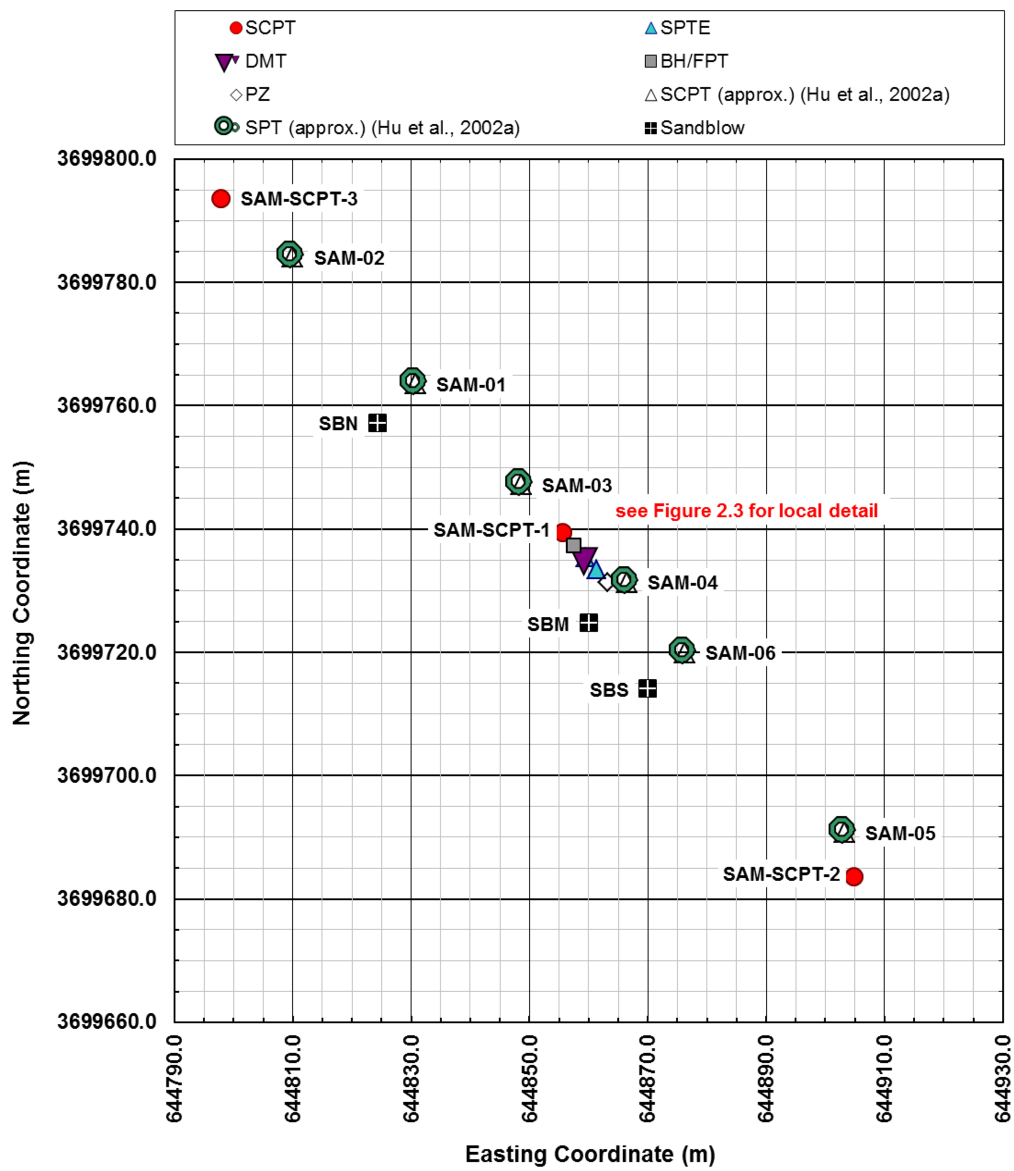


Figure 2.1 Exploration and Test Locations at the Sampit Site (after Hasek, 2014 as shown in Williamson, 2013)

Williamson (2013) identified the source sand layer to be from 9 to 22 ft (2.7 to 6.7 m) deep. The source sand layer is overlain by a 9 ft (2.7 m) layer consisting of poorly graded sand with silt. The groundwater table was located within this layer at a depth of 6.5 ft (1.9 m) below the ground surface. Below the source sand layer, lies a 9 ft (2.7 m) thick clay layer that overlies a silty sand layer beginning at a depth of 31ft (9.4 m) below the ground surface.

2.2.2 Gapway Site

The Gapway site is situated about 9 miles northwest of Georgetown and approximately 1.2 miles north of the Sampit site as shown in Figure 2.2. The ground elevation ranges from 13 to 16 ft (3.9 to 4.9 m) above mean sea level and the topography is relatively flat. Figure 2.3 presents a map of the locations of the in situ tests performed at the Gapway site. All the tests were conducted in the vicinity of four sandblows.

The CPT test (GAP-CPT-1) closest to the DMT (SAM-DMT) and SPT test (GAP-03) were studied by Williamson (2013). Soil samples obtained from GAP-03 were tested for grain size distribution by sieve analysis as reported by Hu (2001). In addition to the data from Williamson (2013), this work examines two CPT test locations (GAP-SCPT-2 and GAP-SCPT-3) of Hasek 2014 and SPT data (GAP-03) of Hu (2001). The site comprises of a 3 ft (0.9 m) mixed sand layer underlain by a 1 ft (0.3 m) clay layer.

The source sand which extends from a depth of 4 to 7 ft (1.2 to 2.1 m) was delineated by Hu (2001) and Williamson (2013). The source sand was underlain by an 8 ft (2.4 m) clay layer and coarse sand beginning at a depth of 15 ft (4.6 m). The groundwater table at Gapway was measured at a depth of 4 ft (1.2 m) below the ground surface (Hasek, 2014).

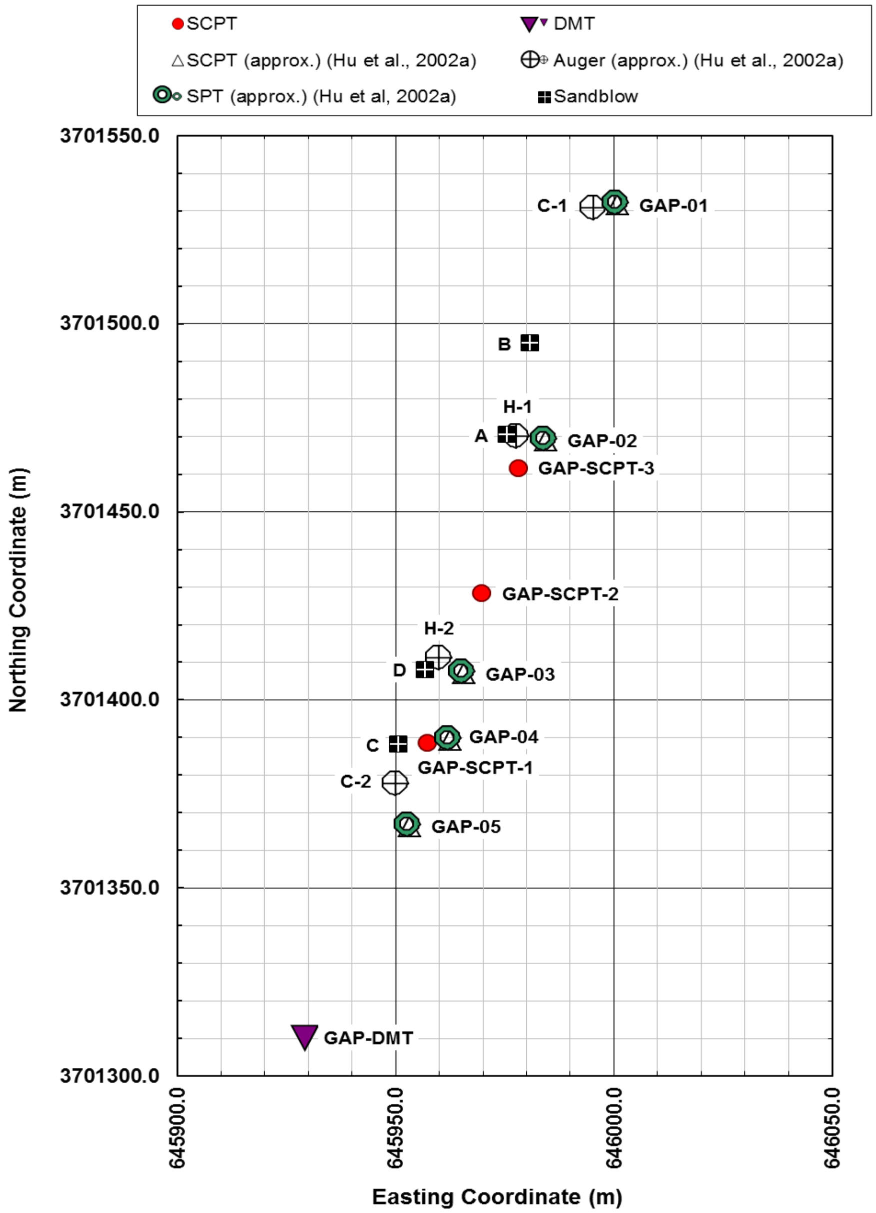


Figure 2.3 Exploration and Test Locations at the Gapway Site (after Hasek, 2014 as shown in Williamson, 2013)

2.2.3 Hollywood Site

The Hollywood site is situated about 0.5 miles northeast of the town of Hollywood, South Carolina (See Martin, 1990; Williamson, 2013 and Hasek, 2014). The ground elevations vary from 28 to 35 ft (8.5 to 10.7 m) above mean sea level and the topography gently inclines from east to west direction. The geotechnical exploration points and field tests conducted at Hollywood site are presented in Figure 2.3.

The work by Williamson (2013) includes 1 DMT test (HWD-DMT), 1 CPT test (HWD-CPT-4) and 1 SPT test (HWD-SPTE-1). These tests were conducted in close proximity to each other and were used in this study as well. Two other CPT tests (HWD-CPT-5 and -6) studied by Hasek (2014) are also studied in this work.

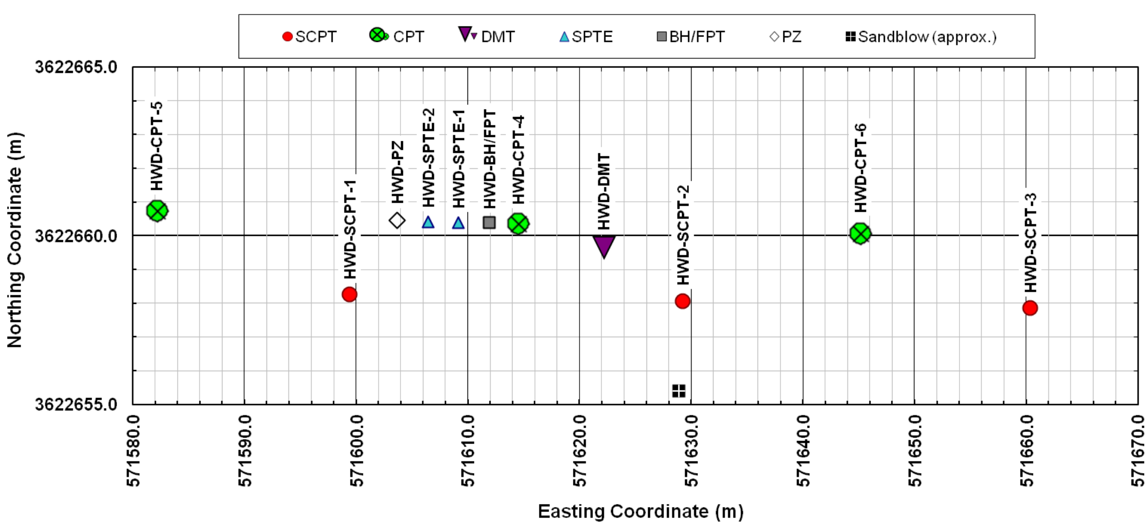


Figure 2.3 Exploration and Test Locations at the Hollywood Site (after Hasek, 2014 as shown in Williamson, 2013)

The site geology includes a 9 ft (2.7 m) of silty sand layer underlain by the source sand which extends from 9 to 14 ft (2.7 to 4.3 m) and silty, clayey sand beginning at 14 ft (4.3 m) below the ground surface. The ground water table depth was estimated at 9 ft (2.7 m) below the ground surface.

2.2.4 Four Hole Swamp Site

The Four Hole Swamp site is situated about 2.6 miles east of Dorchester, South Carolina near the intersection of State Highways 78 and 178. The site is situated on the easternmost boundary of Waste Management's Oakridge Landfill area (Williamson 2013 and Hasek, 2014). The ground elevation ranges from 57 to 72 ft (17.4 to 21.9 m) above mean sea level and the topography gently inclines towards northeast. The in situ tests conducted at different test locations are shown in Figure 2.4.

At this site, three SCPT tests (FHS-SCPT-1 through -3), two SPT tests and a DMT test (FHS-DMT) have been performed (Hasek, 2014). A piezometer (FHS-PZ) was used to measure the ground water levels at the site (Hasek, 2014). Williamson (2013) studied the results from FHS-SPTE-1, FHS-SCPT-1 and FHS-DMT. Soil samples obtained from FHS-SPTE-1 were used to perform index tests. This study addresses all the tests analyzed by Williamson (2013) in addition to FHS-SCPT-2 and FHS-SCPT-3.

The source sand was indicated by Williamson (2013) to be approximately 6 ft (1.8 m) deep ranging at a depth of 9 to 15 ft (2.7 to 4.6 m). A 9 ft (2.7 m) thick silty, clayey sand lies above the source sand and clayey sand lies beneath the source sand starting at a depth of 15 ft (4.6 m). The ground water table was measured approximately at 9 ft (2.7 m) below the ground surface.

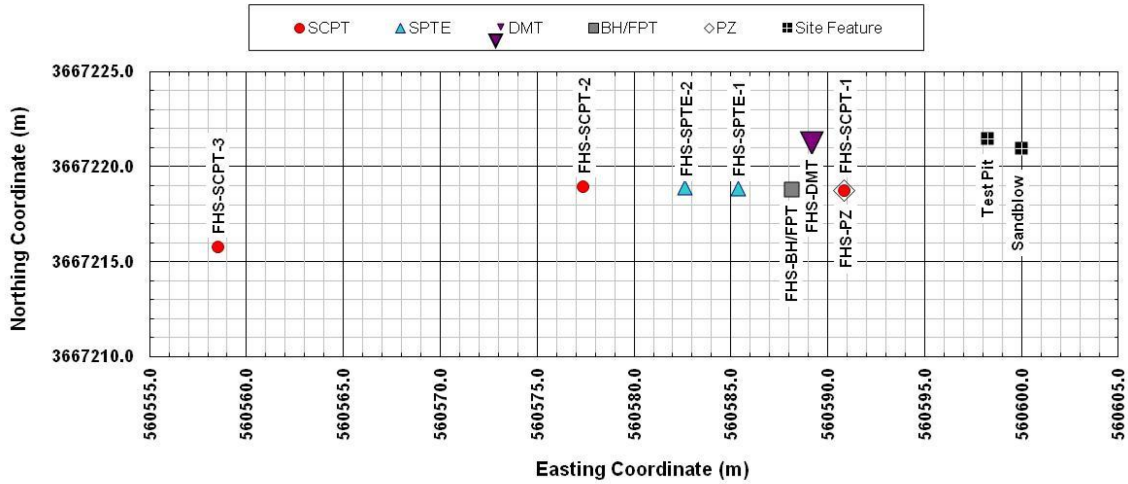


Figure 2.4 Exploration and Test Locations at the Four Hole Swamp Site (after Hasek 2014, as shown in Williamson, 2013)

2.2.5 Fort Dorchester Site

As described by Talwani et al. (2001), the Fort Dorchester site is situated on the banks of Ashley River at the Colonial State historic site in Summerville, South Carolina. The ground elevation ranges from mean tide elevation of 3 ft (0.9 m) to about 27 ft (8.2 m) above mean sea level and the topography gently inclines to the west and south towards the Ashley River. Figure 2.5 shows the locations of all the in situ tests performed at the Fort Dorchester Site.

At this site, 3 CPT tests, 5 SCPT tests, 3 vibracores, 2 DMT tests and 1 piezometer were performed at locations shown in Figure 2.5. Williamson (2013) analyzed the data from two CPT tests (FD-SCPT-1 and FD-SCPT-2) and DMT tests (FD-

DMT-EW and FD-DMT-NS) where one test was conducted with the dilatometer plate oriented at east and west direction and the other one oriented north and south direction. Index testing was performed on samples obtained from vibracore FD-VC-1. This work further studies the results from test locations previously studied by Williamson (2013). CPT test locations FD-SCPT-3 and FD-CPT-7a are also examined in this thesis.

Figure 2.5 Exploration and Test Locations at the Fort Dorchester Site (after Talwani et al. 2011)

The site consists of a 5 ft (1.5 m) of silty clay layer underlain by 3 ft (0.9 m) of clayey sand, 8 ft (2.4 m) of source sand, 2 ft (0.6 m) of silty sand and sandy silt starting at a depth of 18 ft (5.5 m) below the ground surface. As reported by Williamson (2013), the source sand layer varies from a depth of 8 to 16 ft (2.4 to 4.9 m). Although, it is predicted that the water table was much closer to the ground surface during paleoseismic events, the current water table depth was measured at 17 ft (5.2 m) below the ground surface.

2.3 In Situ Test Methods

2.3.1 Dilatometer test

The dilatometer test was first introduced in Italy by Silvano Marchetti (Marchetti et al., 2001). Today it is used in over 40 countries worldwide. The dilatometer test is conducted by pushing a flat stainless steel blade into the ground at a rate of 0.02 m/sec and pushing is stopped at the desired depth of testing. The dilatometer consists of a circular membrane situated on one side of a flat steel blade which expands horizontally into the soil using nitrogen gas pressure via pneumatic tubes connected to a control unit. The control unit includes a pressure regulator, pressure gauge, an audio visual signal and vent valves.

As described by Marchetti (2001), the test is initiated by inserting the dilatometer vertically into the ground using field equipment such as drilling rigs. When the desired depth is reached at intervals of every 1 ft, pushing is halted. At this point the membrane is flush with the blade and there is no horizontal displacement. The dilatometer is then allowed to expand and deform. This expansion and deformation continues until the membrane inflates 0.05 mm into the soil to indicate the lift off pressure reading (p_0). The lift off pressure is also defined as the "A pressure". The pressure on the membrane is again applied until it reaches a displacement of 1.1 mm. The corresponding pressure at this point is called the full expansive pressure (p_1) and is also referred as the "B pressure". After the pressures are recorded, the membrane is allowed to return back to its original position. An optional reading known as closing pressure (p_2) or "C pressure" is then recorded at zero deformation. Both readings A and B are taken in about 60 seconds. The entire process is then repeated at the next 1 ft (0.3 m) interval. Correction factors ΔA and ΔB are applied to the pressure readings from the test to overcome membrane stiffness (Marchetti et al. 2001). The pressure readings from the DMT ΔA and ΔB along with zero correction of the pressure gauge (Z_m) can be used to obtain values p_0 and p_1 using the following equations presented by Marchetti et al. (2001):

$$p_0 = 1.05(A - Z_m + \Delta A) - 0.05(B - Z_m - \Delta B) \quad 2.1$$

$$p_1 = B - Z_m - \Delta B \quad 2.2$$

The pressure readings p_0 and p_1 obtained from DMT can be correlated to various geotechnical indexes and coefficients. The primary correlations include the material index (I_D), the horizontal stress index (K_D), and the dilatometer constrained modulus (E_D). Marchetti's (1980) equations for determining these properties are as follows:

$$I_D = (p_1 - p_0) / (p_0 - u_0) \quad 2.3$$

$$K_D = (p_1 - p_0) / \sigma'_{v0} \quad 2.4$$

$$E_D = 34.7\ (p_1 - p_0) \quad 2.5$$

A soil behavior type chart was introduced by Marchetti et al. (1980) to classify soils based on the relationship between I_D and E_D as shown in Figure 2.6. Marchetti (1980) suggested that I_D values reflected the mechanical behavior of soil. In general, I_D

values have the following range: $0.1<I_D<10$. The soil type was identified as $I_D<0.6$ for clays, $0.6\leq I_D\leq 1.8$ for silts and $I_D>1.8$ for sands as shown in Figure 2.6. Note that I_D is not recommended to be used in classifying soils based on grain size distribution and plasticity. K_D can be used to estimate several soil parameters such as K_0 and ϕ' and is a key parameter from the DMT. Marchetti (1980) suggested that the K_D value for Normally Consolidated clays is $K_{D,NC}$ is approximately 2. The K_D profile is similar in shape to the Over Consolidation Ratio profile and therefore it is helpful in understanding the soil deposit and stress history in clays (Marchetti (1980)). Williamson (2013) used Monaco et al.'s (2005) liquefaction criteria of $K_D\leq 5$ for liquefiable sands and verified that this method was not applicable to SCCP soils because very few data points in the source sand region met the $K_D\leq 5$ limit. E_D lacks information on stress history and can be used only in combination with K_D and I_D.

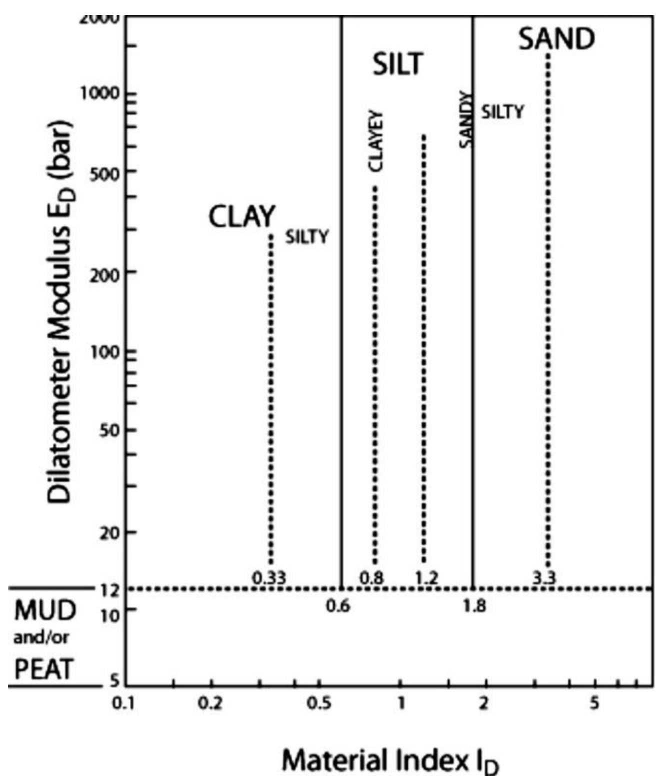


Figure 2.6 Soil behavior type chart (after Marchetti et al. 1980)

2.3.2 Cone Penetration Test

The cone penetration test involves an electric piezocone penetrometer which is hydraulically pushed into the soil at a constant rate of 2 cm/sec (ASTM D-5778). Load cells behind the cone and near the sleeve are used to determine the cone penetration tip resistance (q_c) and sleeve friction (f_s). Pore water pressure (u_2) is measured behind the cone with a pressure transducer. The total force acting on the cone (Q_c) divided by the area of the cone (A_c) gives the cone resistance (q_c). The total force acting on the friction sleeve (F_s) divided by the surface area of the sleeve gives the sleeve friction (f_s).

The cone tip resistance (q_c), sleeve friction (f_s) and pore pressure (u_2) measurements from CPT can be used to estimate various index properties and determine subsurface stratigraphy. To evaluate liquefaction potential, the CPT parameters need to be normalized to identify soil behavior type (SBT). The index properties included are stress normalized cone penetration resistance (Q), normalized friction ratio (F), normalized cone pore pressure ratio (B_q) and soil behavior type index (I_c). Robertson (2009) recommended the following equations for determining these dimensionless values:

$$Q = [(q_t - \sigma_{v0}) / P_a)] (P_a / \sigma'_{v0})^{n} \qquad 2.6$$

$$F = [f_s / (q_t - \sigma'_{v0})] * 100 \qquad 2.7$$

$$I_c = [(3.47 - \log Q)^{2} + (1.22 + \log F)^{2}]^{0.5} \qquad 2.8$$

$$B_q = (u_2 - u_{0)} / (q_t - \sigma_{v0}) \qquad 2.9$$

where P_a is a reference stress of 100 kPa, σ_{v0} is the total overburden stress, σ'_{v0} is the effective overburden stress and q_t is the field cone penetration resistance at the tip. The exponent n varies from 0.5 for sand to 1 for clay. The hydrostatic pore pressure u_0 is calculated by multiplying the depth below the groundwater table by the unit weight of water.

Soil behavior type index, I_c, can be found using the following three step iterative method proposed by Robertson and Wride (1998). Firstly, Q is calculated by assuming value of n equal to one. The I_c values are then determined. If all the results of I_c are greater than 2.6, then the soil is considered too clay rich to liquefy and no further evaluation of these soils is required. However a second iteration is necessary if there are I_c values less than 2.6 after the first iterative step. The characteristic of such soils are more granular so an exponent of n=0.5 is applied to the next set of calculations for Q, I_c, F and B_q. The new I_c values are then examined. For the recalculated I_c values $\leq$ 2.6 the soil is considered as nonplastic and granular and these values should be used in the liquefaction evaluation. For values >2.6 a final iteration is done for soils likely to be silty and possibly plastic. The resulting I_c values are determined by assigning an intermediate exponent of n=0.7 to the calculation. Finally, the subsequent I_c values at the end of the three step iterative process are used in the liquefaction evaluation.

Robertson et al. (1990) suggested a Q-F Soil Behavior type chart to reflect the mechanical behavior of soil as shown in Figure 2.7. According to the chart, Robertson (2009) identified that the CPT normalized friction ratio, F was strongly influenced by soil sensitivity whereas Q was strongly influenced by OCR for clay like soils. In Figure 2.7, potential liquefiable zones fall within Zone 5, 6 and 7 which consists of sand mixtures with little fines. Robertson and Wride's (1998) liquefaction criteria F<1.0% and $(q_{c1N})_{cs}$<160 indicated that soil is susceptible to liquefaction. Note that $(q_{c1N})_{cs}$ is clean sand equivalent normalized CPT tip resistance for soils. I_c can be used to define the boundaries in the CPT SBT chart between different soils types: Clays (I_c>2.95), Silts (2.05≤I_c≤2.95) and Sands (I_c<2.05).

Robertson and Wride's (1998) liquefaction criteria I_c>2.6 and B_q>0.5 are used to indicate whether a soil is too clay rich to liquefy. Youd et al. (2001) recommended that soils with I_c of 2.4 to 2.6 needed to be tested to evaluate their liquefaction susceptibility because the cutoff of I_c>2.6 was overly conservative for some soils. Based on Robertson and Wride (1998)'s and Youd et al. (2001)'s findings, Hayati and Andrus (2008a) proposed a liquefaction susceptibility chart as shown in Figure 2.8. This chart indicated that soils with I_c<2.4 and B_q<0.4 are considered to fall in the susceptible zone while soils with I_c>2.6 and B_q>0.5 fell into the non-susceptible zone. Soils were considered to be moderately susceptible in between these limits and additional testing is required to determine susceptibility to liquefaction. The correlation in the chart I_c>5.7-2.3B_q can be used to identify sensitive fine grained soils.

Kulwawy and Mayne (1990) suggested a formula for estimating relative density:

$$D_r^2 = q_{c1} / 305Q_c.Q_{OCR}.Q_A \qquad 2.10$$

where

q_{c1} = Dimensionless normalized cone resistance

= $(q_c/p_a) / (\sigma'_{v0}/p_a)$

Q_c = Compressibility factor

$0.91 < Q_c < 1.09$

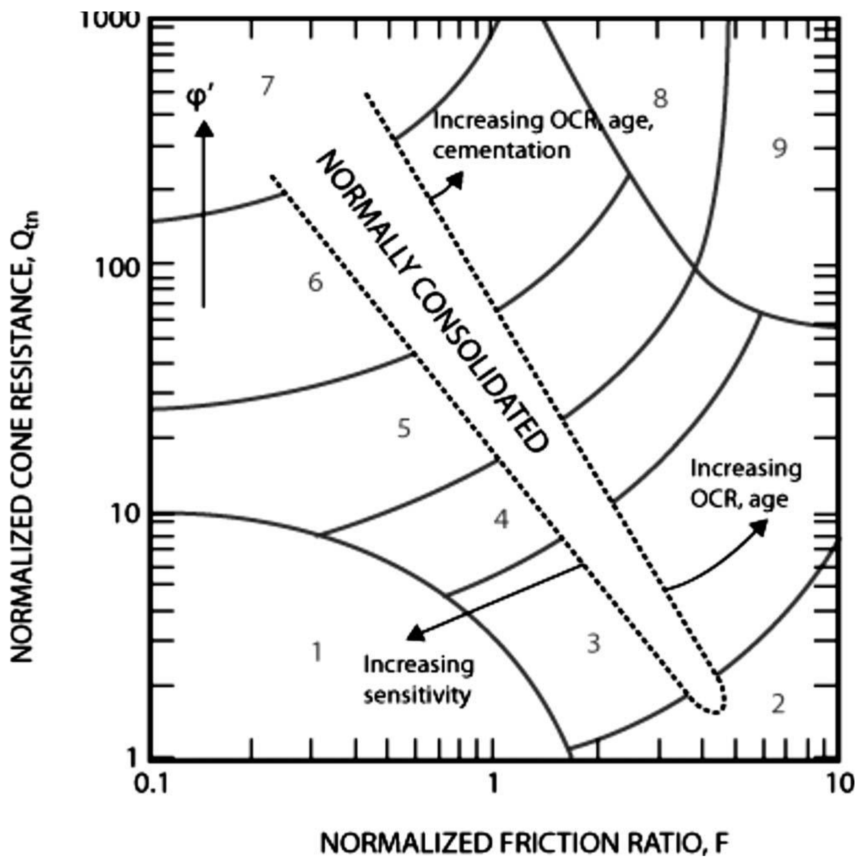
Q_{OCR} = Overconsolidation factor

= $OCR^{0.18}$

For normally consolidated sands OCR=1.

Q_A = Ageing factor

= 1.2 + 0.05 log (t/100)



Zone	Soil Behavior Type	Zone	Soil Behavior Type
1.	Sensitive, fine grained;	6.	Sands: clean sands to silty sands
2.	Organic soils, peats	7.	Gravelly sand to sand;
3.	Clays: clay to silty clay;	8.	Very stiff sand to clayey sand;
4.	Silt mixtures: clayey silt to silty clay;	9.	Very stiff fine grained
5.	Sand mixtures: silty sand to sandy silt;		

Figure 2.7 Normalized Soil Behavior Chart for CPT (after Robertson, 1990)

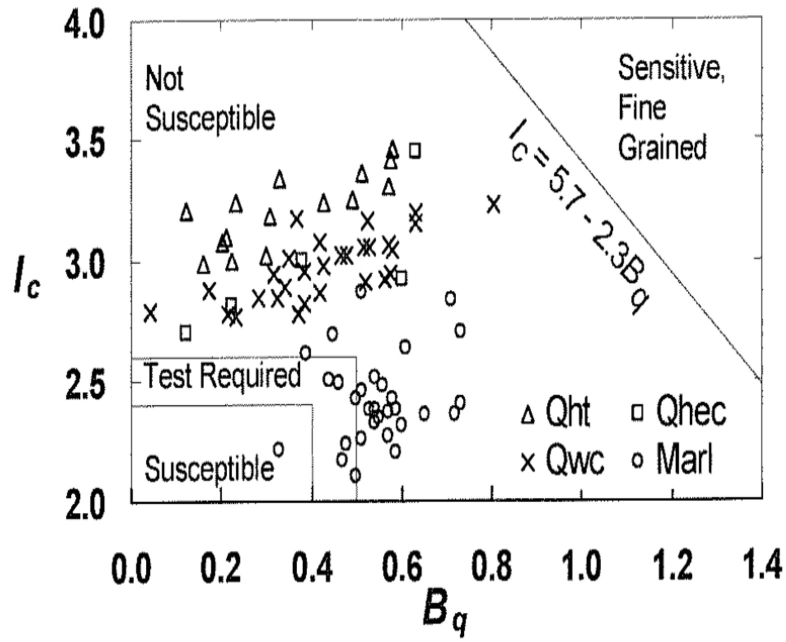


Figure 2.8 Liquefaction Susceptibility Chart (after Hayati and Andrus, 2008)

2.3.3 Standard Penetration Test

The Standard Penetration Test involves a 140 lb hammer repeatedly falling through a distance of 760 mm (30 in.) on an anvil connected to drill rods and a split spoon sampler (ASTM D1586). The split spoon sampler is driven 6 in. (150 mm) into the ground and the number of blows required for the sampler to penetrate each 6 in. (150 mm) up to a depth of 18 in. (457 mm) is recorded. As the drill rods are pulled out of the borehole and the sampler is lowered into the borehole, soil falls into the borehole. This disturbs the soil and hence the blow count in the upper 6 in. (150 mm) is discounted. The number of blows for the second and third 6 in. (150 mm) intervals is added together and is termed as the “Standard Penetration Resistance” or the N value for that particular range of depth. The N value can be used to estimate the relative density of the subsurface soil and provides empirical geotechnical correlations to determine approximate shear strength properties of soils.

The SPT blow count N used for geotechnical explorations is affected by various factors such as overburden pressure, hammer type, blow rate, drill length, type of anvil, use of liners or bore hole liquid. N is first corrected for energy loss by normalizing N to a standard energy of 60%. Youd et al. (2001) recommended the following equation to account for N_{60}:

$$N_{60} = N\, C_E C_B C_R C_S \qquad 2.11$$

where N is the measured standard penetration resistance; C_E is correction for hammer energy efficiency; C_B is a correction factor for bore hole diameter; C_R is a correction factor for rod length; and C_S is a correction for samplers with or without liners.

N_{60} is further corrected with a factor C_N to account for increasing overburden pressure. Kayen et al. (1992) recommended the following equation to determine the correction factor:

$$C_N = 2.2 / (1.2 + \sigma'_{v0}/P_a) \qquad 2.12$$

where P_a is atmospheric pressure equal to 100kPa. Youd et al. (2001) provided the following equation to determine the overburden stress-corrected blow count $(N_1)_{60}$:

$$(N_1)_{60} = N_{60}\, C_N \qquad 2.13$$

A correction to $(N_1)_{60}$ was applied to account for the behavior of soil with high fines content to that of clean sand. This is termed $(N_1)_{60cs}$:

$$(N_1)_{60cs} = \alpha + \beta\,(N_1)_{60} \qquad 2.14$$

where α and β are coefficients determined by the following relationships:

$$\alpha = 0 \qquad \text{for } FC \leq 5\% \qquad 2.15$$

$$\alpha = \exp[1.76 - (190/FC^2)] \quad \text{for } 5\% < FC < 35\% \qquad 2.16$$

$$\alpha = 5.0 \quad \text{for } FC \geq 35\% \qquad 2.17$$

$$\beta = 1.0 \quad \text{for } FC \leq 5\% \qquad 2.18$$

$$\beta = 0.99 + (FC^{1.5}/1000) \quad \text{for } 5\% < FC < 35\% \qquad 2.19$$

$$\beta = 1.2 \quad \text{for } FC \geq 35\% \qquad 2.20$$

and FC is the fines content

Youd et al. (2001) recommended that soil is too dense to liquefy when $(N_1)_{60cs} \geq 30$.

2.3.5 Correlations

2.3.5.1 CPT-DMT Correlations

A review of the literature revealed a series of DMT-CPT correlations for sand-like and clay-like soils. Sand-like soils were determined based on $I_C \leq 2.6$ and $I_D > 1$ while clay-like soils were determined based on $I_C > 2.6$ and $I_D < 1$ (Marchetti (1980), Robertson and Wride (1998) and Robertson (2009)).

Robertson et al. (1988) provided evidence that horizontal stress index K_D increased slightly with an increase in soil sensitivity due to development of high pore pressures around the DMT probe during penetration. Based on this evidence, Robertson (2009) proposed a relationship for fine grained clay like soils between horizontal stress index, K_D and normalized cone penetration resistance, Q, by combining OCR, K_D and Q relations given by Marchetti (1980) and Kulhawy and Mayne (1990)

$$K_D = 0.88\,(Q)^{0.64} \qquad 2.21$$

Similarly, Robertson et al (2009) also developed a relation for fine grained soils between K_D and Q by combining OCR, K_D and Q relations given by Marchetti (1980) and Wroth (1984) and Ladd (1991):

$$K_D = 0.8\ (Q)^{0.80} \qquad 2.22$$

Schneider (2008) recommended a series of relations between (u_2 / σ'_{v0}) and Q for insensitive clays as shown below. These relationships were based on the assumption that DMT lift off pressure (p_0) was equal to the CPT measured pore pressure (u_2) around the DMT probe.

$$u_2 / \sigma'_{v0} = \beta\ (Q)^{0.95} + 1.05 \qquad 2.23$$

$$\text{where} \quad K_D = u_2 / \sigma'_{v0} \qquad 2.24$$

$$K_D = \beta\ (Q)^{0.95} + 1.05 \qquad 2.25$$

where, on average, $\beta = 0.3$.

Schneider (2008) also presented the following correlation between (u_2 / σ'_{v0}) and Q for excess CPT pore water pressures in sensitive clays as shown below.

$$K_D = 0.67\ (Q)^{0.91} + 1.1 \qquad 2.26$$

Mayne and Liao (2004) suggested two relationships for piedmont residual soils (silty sands to sandy silts) between DMT modulus E_D and corrected resistance measured at the tip q_t, and E_D and net cone resistance, q_{net}, respectively:

$$E_D = 5\ q_t \qquad 2.27$$

$$E_D = 5\ (q_t - \sigma_{v0}) \qquad 2.28$$

where $q_{net} = (q_t - \sigma_{v0})$ and $q_t >> \sigma_{v0}$.

Robertson (2009) presented the normalized form and a general form according to the above equations is shown as follows:

$$E_D / \sigma'_{v0} = 5\ Q \quad 2.29$$

$$E_D / \sigma'_{v0} = \alpha\ Q \quad 2.30$$

where, α is a factor similar to the variation of CPT modulus factor, $\alpha_{E,}$ and varies with relative density, age and stress history. Robertson (2009) predicted that α=5 was a reasonable average for a wide range of soils from coarse grained soils to fine grained soils where 5<Q<200.

Tsai et al. (2009) provided correlations using DMT and CPT test data in Holocene soils which are presented below:

$$(q_{c1N})_{cs} = 0.4K_D^3 - 7.7K_D^2 + 56K_D - 20: \quad R^2 = 0.39 \quad 2.31$$

$$(q_{c1N})_{cs} = 0.00078E_D^3 - 0.095E_D^2 + 5E_D + 7; \quad R^2 = 0.54 \quad 2.32$$

The following CPT-DMT correlations for the source sand zones in the five geotechnical sites previously studied by Williamson (2013) are shown below:

$$(q_{c1N})_{cs} = 0.037K_D^3 - 1.431K_D^2 + 19.787K_D + 12.525; \quad R^2 = 0.52 \quad 2.33$$

$$(q_{c1N})_{cs} = 0.0004E_D^3 - 0.069E_D^2 + 4.079E_D + 35.033; \quad R^2 = 0.44 \quad 2.34$$

2.3.5.2 DMT-SPT Correlation

Several correlations between DMT and SPT are presented in the literature. Tanaka and Tanaka (1998) proposed the following correlation between standard measured blow count N and horizontal stress index E_D for sands:

$$N = E_D\ (MPa) / 2.5 \quad 2.35$$

The following relationships between N_{60} and E_D based on I_D values were provided by Hajduk (2006) for three different soil behavior types.

$$N_{60} = E_D\ (MPa) / 1.08 \qquad I_D < 0.6; \qquad R^2 = 0.697 \qquad 2.36$$

$$N_{60} = E_D\ (MPa) / 2.65 \qquad 0.6 \leq I_D \leq 1.8; \qquad R^2 = 0.679 \qquad 2.37$$

$$N_{60} = E_D\ (MPa) / 2.43 \qquad I_D > 1.8; \qquad R^2 = 0.598 \qquad 2.38$$

where equations 2.31, 2.32 and 2.33 represented correlations for clays, silts and sands respectively. Hajduk (2006) used a quantitative comparison procedure chart to establish the above correlations between E_D and N_{60} for the three different soil behavior types. Hajduk (2006) also compared his data to Tanaka and Tanaka (1999) which showed a good general agreement between the parameters.

Tsai et al. (2009) presented correlations for a wide range of soil types between normalized clean sand corrected factor $(N_1)_{60cs}$ and E_D shown in equation below.

$$(N_1)_{60cs} = 0.00022E_D^3 - 0.02E_D^2 + 0.9E_D + 3; \qquad R^2 = 0.53 \qquad 2.39$$

$$(N_1)_{60cs} = 0.185K_D^3 - 2.75K_D^2 + 17K_D - 15; \qquad R^2 = 0.40 \qquad 2.40$$

Williamson (2013) provided SPT-DMT correlations for the source sand zones in the five geotechnical investigation sites studied in this thesis which is shown below:

$$(N_1)_{60cs} = 0.023K_D^3 - 0.403K_D^2 + 2.813K_D + 0.581; \qquad R^2 = 0.66 \qquad 2.41$$

$$(N_1)_{60cs} = 0.0015E_D^3 - 0.0878E_D^2 + 1.6144E_D + 2.2918; \qquad R^2 = 0.31 \qquad 2.42$$

2.4 Summary

This chapter presented an overview of the five geotechnical investigation sites in the SCCP where DMT, CPT and SPT were performed. General descriptions of each of the in situ testing procedures were provided. Correlations between DMT and CPT test parameters and DMT and SPT test parameters found in the literature were summarized. These include the correlations between K_D and Q presented by Robertson (2009) and

Schneider (2008) for fine- grained soils, the correlations between E_D and Q by Mayne and Liao (2004) for a wide range of soils, and the correlations between E_D and N_{60} by Hajduk (2006) for silts, clays and sands. The SCCP data will be compared to these correlations in Chapter 4 and used to develop, new site specific correlations. The methods used to determine the Soil Behavior type from DMT data (Marchetti, 1980) and CPT data (Robertson, 1990) were summarized and will be used to find the soil behavior types for the soils at the sites in the SCCP (See Chapter 3). The method to assess liquefaction susceptibility from CPT test data developed by Hayati and Andrus (2008) was also summarized and will be used in Chapter 5 to evaluate the liquefaction susceptibility of the soils at each of the five sites studied in this thesis.

CHAPTER 3

SOIL BEHAVIOR TYPE

3.1 Introduction

This chapter presents the methodologies used for CPT and DMT analysis to characterize the soil behavior type of soils of five geotechnical investigation sites. The CPT and DMT data were used to develop a soil stratigraphy for each site. A comparison between the methodologies is presented to identify the differences in classifying soils for a particular site. The source sand layer delineated by Williamson (2013) was further analyzed to check the consistency of potential liquefiable zones at each of the test locations presented in this study.

3.2 Soil Behavior Type from CPT

The test locations at each site used for CPT analysis are listed in Table 3.1. CPT parameters q_t and f_s were plotted with depth for all test locations at each site. The corresponding pore pressure measurements are also shown with depth in separate figures. Soil layers at each site were delineated by Williamson (2013) using the SCPT test location in close proximity to the DMT and SPTE samples for index testing. The soil behavior classification chart by Robertson (1990) was used to determine the soil behavior type of soils found in each layer of the soil profile at each site. Closed symbols were used to represent Q and F values calculated for the CPT test location closest to the DMT at depths where DMT data were obtained while open symbols denote Q and F values for all the CPT test locations (see Table 3.1) calculated at each depth.

Table 3.1 Summary of Test Locations used in CPT Analysis

Site	Test Locations			
Sampit	SAM-SCPT-1	SAM-SCPT-2	SAM-SCPT-3	
Gapway	GAP-SCPT-1	GAP-SCPT-2	GAP-SCPT-2	
Hollywood	HWD-CPT-4	HWD-CPT-5	HWD-CPT-6	
Four Hole Swamp	FHS-SCPT-1	FHS-SCPT-2	FHS-SCPT-3	
Fort Dorchester	FD-SCPT-1	FD-SCPT-2	FD-SCPT-3	FD-CPT-7a

3.2.1 Sampit

SAM-SCPT-1 was used to delineate the soil layers at Sampit. As shown in Figure 3.1, there are four distinctive layers in the Sampit soil profile labelled as A, B, C and D. Layer A extends from the ground surface down to a depth of approximately 9 ft (2.7 m). The ground water table is assumed to be approximately at 6.5 ft (1.9 m) below the ground surface for all test locations. The CPT measured pore pressure shown in Figure 3.2 does not rise above the hydrostatic pore pressure indicating Layer A soil mostly varies from clean sand to silty sand (Zone 6) as suggested by the CPT based soil identification chart (Robertson, 1990) shown in Figure 3.3. However, the soil in this layer that is above the ground water table falls within Zone 7 suggesting a soil behavior type that varies from gravelly sand to sand.

Layer B is the soil layer below 9 ft (2.7 m) which extends down to a depth of 22 ft (6.7 m). This soil layer was delineated as the source sand layer by Williamson (2013).

From Figure 3.3, it is seen that most of the data plots within Zone 6, the region of clean sand to silty sand. However, there is a slight variation in soil behavior for test location SAM-SCPT-3. In the upper part of the layer, the soil behavior type indicates a small fraction of fines due to low tip resistances and the data plots within Zone 3 through 5. However, most of the data which are from the lower part of the layer plots in Zone 6 which is similar to that of SAM-SCPT-1 and SAM-SCPT-2. This layer showing high tip resistance and low pore pressures indicate that the soil behaves as silty sands to sands. Note that for all the three test locations, $(q_{c1N})_{cs}$<160 which indicates that the soil layer is susceptible to liquefaction as per Robertson and Wride (1998).

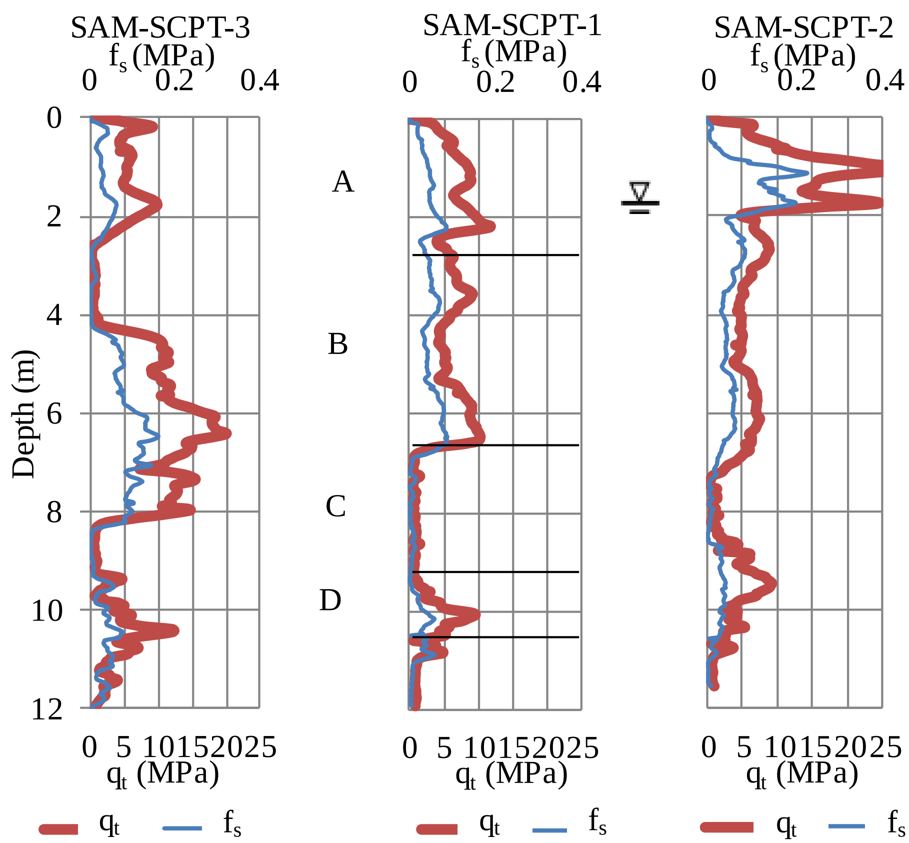


Figure 3.1 Soil Stratigraphy from CPT Data (q_t and f_s) at the Sampit Site.

Layer C extends from 22 to 31 ft (6.7 to 9.4 m) deep. As shown in Figure 3.3, most of the data plots within Zone 4 to 6 and hence the soil varies from clay to silty sand. The soil behavior in SAM-SCPT-1 shows nearly zero penetration resistance and CPT measured pore pressures are greater than the hydrostatic pore pressure (see Figure 3.2). Therefore, it can be inferred from SAM-SCPT-1 that it has considerable amount of fines. SAM-SCPT-2 and SAM-SCPT-3 show a mixture of sands, silts and clays due to the variation in tip resistance and sleeve friction.

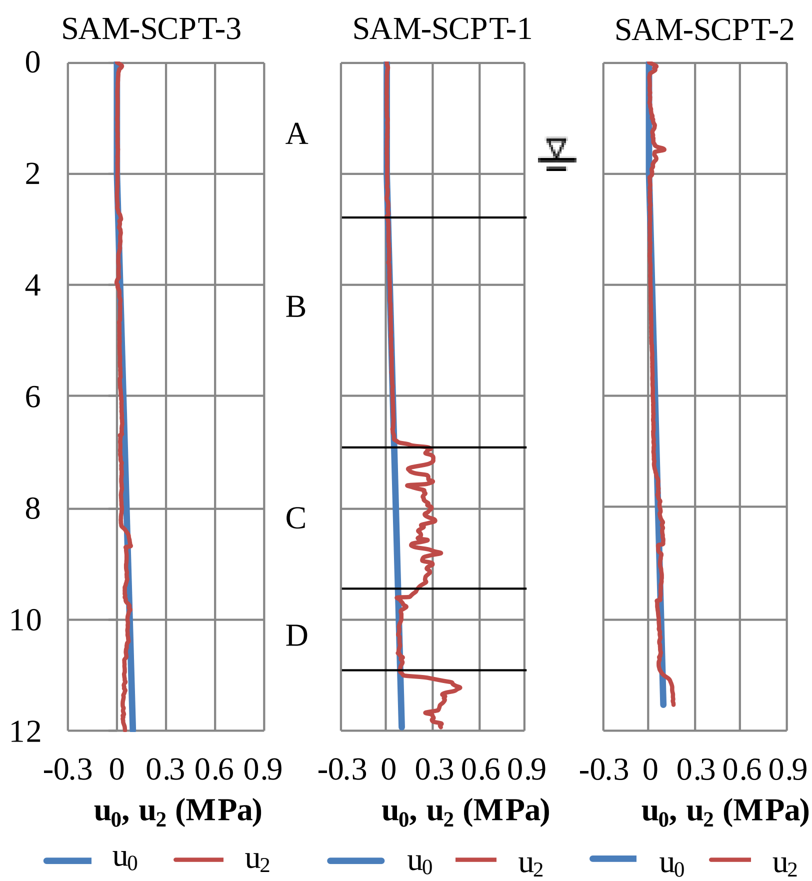
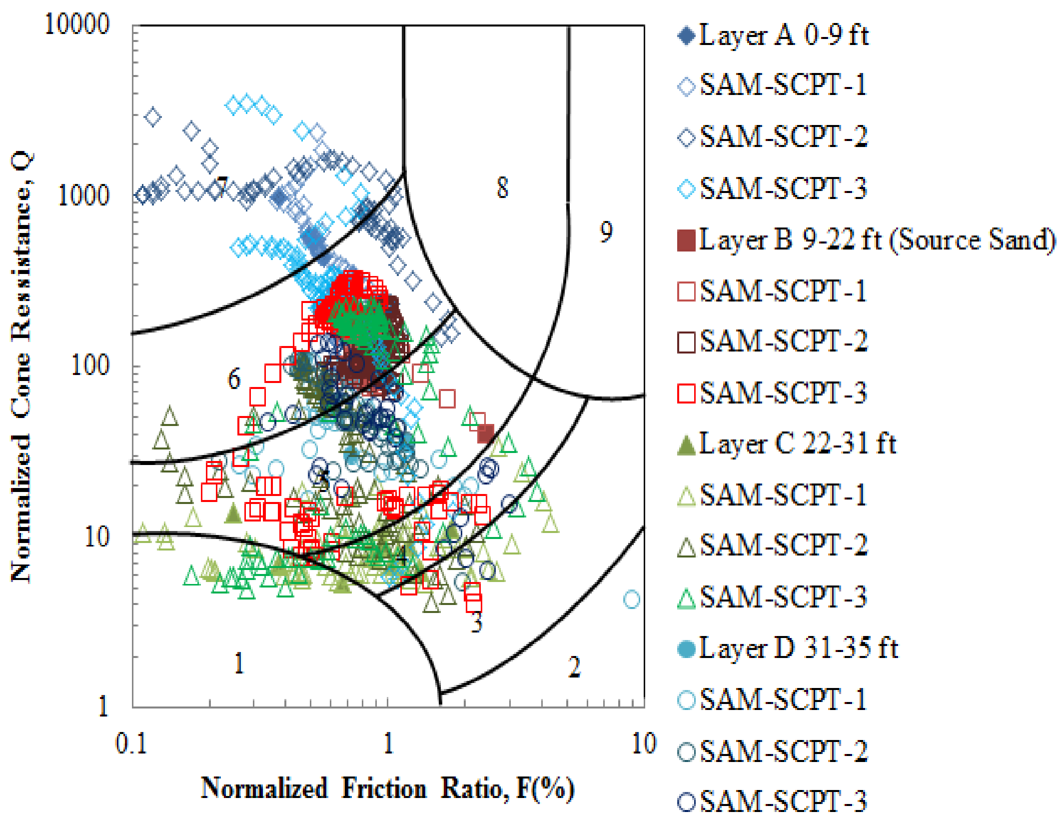


Figure 3.2 CPT Measured and Hydrostatic Pore Pressure at the Sampit Site.

Layer D is located between depths of 31 and 35 ft (9.4 to 10.7 m). The CPT measured pore pressures do not rise above the hydrostatic pressure. The soil identification chart in Figure 3.3 indicates that this layer ranges from silty sand to clean sands (Zone 5 and 6).



Zone	Soil Behavior Type	Zone	Soil Behavior Type
1.	Sensitive, fine grained;	6.	Sands: clean sands to silty sands
2.	Organic soils, peats	7.	Gravelly sand to sand;
3.	Clays: clay to silty clay;	8.	Very stiff sand to clayey sand;
4.	Silt mixtures: clayey silt to silty clay;	9.	Very stiff fine grained
5.	Sand mixtures: silty sand to sandy silt;		

Figure 3.3 Soil behavior type classification chart after Robertson (1990) with data from the Sampit site

3.2.2 Gapway

Using GAP-SCPT-1 a five layer stratigraphy was delineated and labelled as A, B, C, D and E. Layer A begins at the ground surface down to an average depth of 3 ft (0.9 m). From the CPT based soil identification chart, Layer A falls within Zone 5 to 7 and is generally found to vary from silty sand to sand. Some of the data also plots in the stiff sand region (Zone 8) as shown in Figure 3.6. This layer lies above the groundwater water table and no pore pressures were detected in this region, as shown in Figure 3.5.

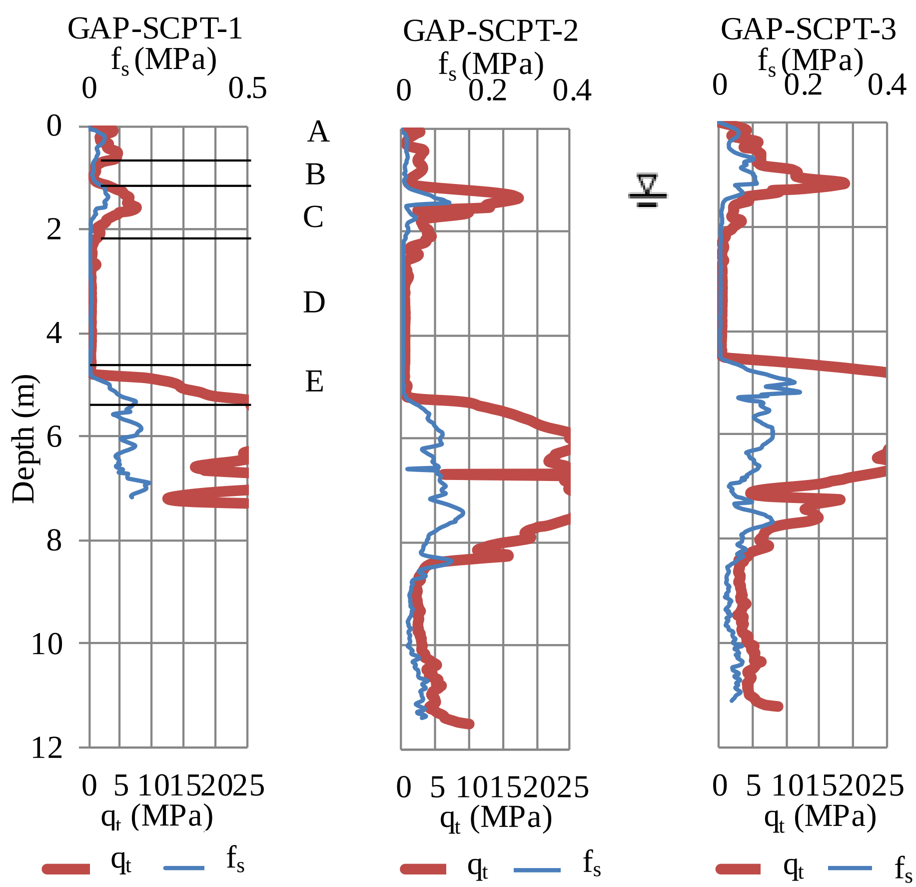


Figure 3.4 Soil Stratigraphy from CPT Data (q_t and f_s) at the Gapway Site.

The underlying 1 ft (0.3 m) layer was noted by Williamson (2013) as a small clay cap layer due to the low tip resistance and pore pressures detected at the site. However, the soil behavior from Figure 3.6 indicates that it has presence of silts and sands. The layer falls within Zone 5 and 6 which suggests that the soil has very small amount of fines. From Figure 3.4, it is clear that GAP-SCPT-3 and GAP-SCPT-2 show a large tip resistance when compared to GAP-SCPT-1 thereby indicating that soils are denser in GAP-SCPT-2 and -3.

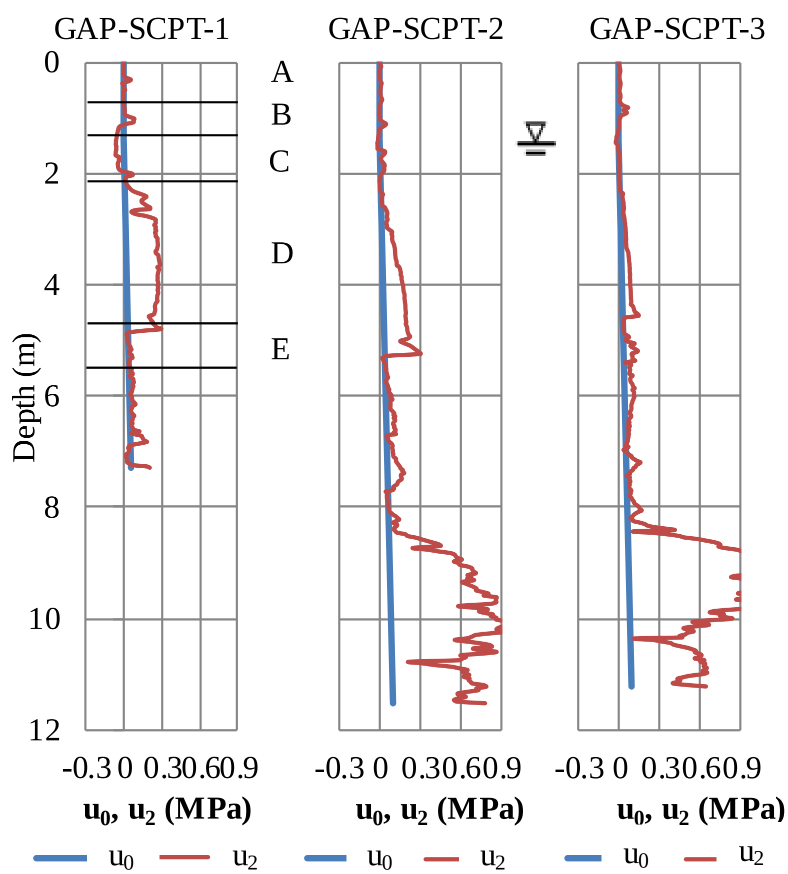
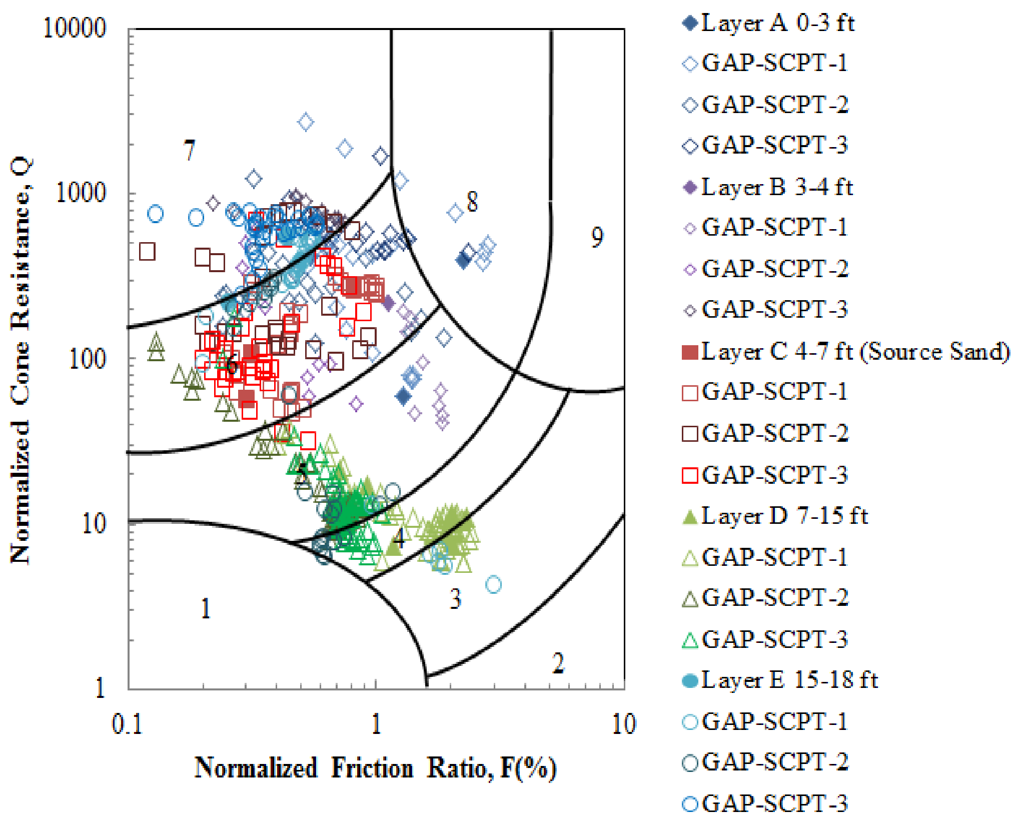


Figure 3.5 CPT Measured and Hydrostatic Pore Pressure at the Gapway Site.

Layer C is located between depths of 4 and 7 ft (1.2 and 2.1 m) and is defined as the source sand layer by Williamson (2013). It is evident from Figure 3.6, that most of the data plots within the region of clean sand to silty sand (Zone 6) because this layer has large tip resistance and negligible pore pressures. The water table is found to be at a depth of 4.5 ft (1.4 m) (see Figure 3.4 and 3.5). Note that $(q_{c1N})_{cs}$ is less than 160 for all the three test locations and hence this layer is considered to be liquefiable.



Zone	Soil Behavior Type	Zone	Soil Behavior Type
1.	Sensitive, fine grained;	6.	Sands: clean sands to silty sands
2.	Organic soils, peats	7.	Gravelly sand to sand;
3.	Clays: clay to silty clay;	8.	Very stiff sand to clayey sand;
4.	Silt mixtures: clayey silt to silty clay;	9.	Very stiff fine grained
5.	Sand mixtures: silty sand to sandy silt;		

Figure 3.6 Soil behavior type classification chart after Robertson (1990) with data from the Gapway site

Layer D extends from a depth of 7 ft (2.1 m) to a depth of approximately 15 ft (4.6 m) deep. Figure 3.6 indicates that soil consists of a mixture of clays, silts and sands as most of the data points fall into Zone 4, 5 and 6. This layer has almost negligible tip resistance and sleeve friction (See Figure 3.4). The CPT measured pore pressure is above the hydrostatic pressure as seen in Figure 3.5 and indicates significant amount of fines in this soil layer.

The next 3 ft (0.9 m) labelled as Layer E primarily consists of sands and a small fraction of silts. The soil identification chart in Figure 3.6 indicates that the data falls primarily in Zone 6 and 7 and a small fraction in Zone 4. Based on the CPT analysis, large tip stress and sleeve friction and significant pore pressures were detected in this layer.

3.2.3 Hollywood

HWD-CPT-4 was used to delineate the soil layers in Hollywood. The top three layers in the soil profile are labelled as A, B and C. The top 9 ft (2.7 m) identified as Layer A lies above the ground water table as presented in Figure 3.7 and has very high tip resistance and sleeve friction. In Figure 3.8, the CPT measured pore pressure slightly rises above the hydrostatic pressure for HWD-CPT-4 but it reflects nearly zero pore pressure measurements for the other two test locations. Layer A is characterized as a sand layer because most of the data falls into Zone 6 and 7 as shown in Figure 3.9. The groundwater table is assumed to be at approximately 9 ft (2.7 m) below the ground surface for all the three test locations.

The source sand explained by Williamson (2013) extends from 9 to 14 ft (2.7 to 4.2 m) deep and is identified as Layer B. From the CPT analysis, it is observed that this layer has high tip resistance but no significant pore pressures (see Figure 3.7 and 3.8). As presented in Figure 3.9, the data plots in Zone 6 indicating that the source sand consists of clean sand to silty sand. For all the three test locations, average $(q_{c1N})_{cs}$<160 and thus the soil layer is susceptible to liquefaction.

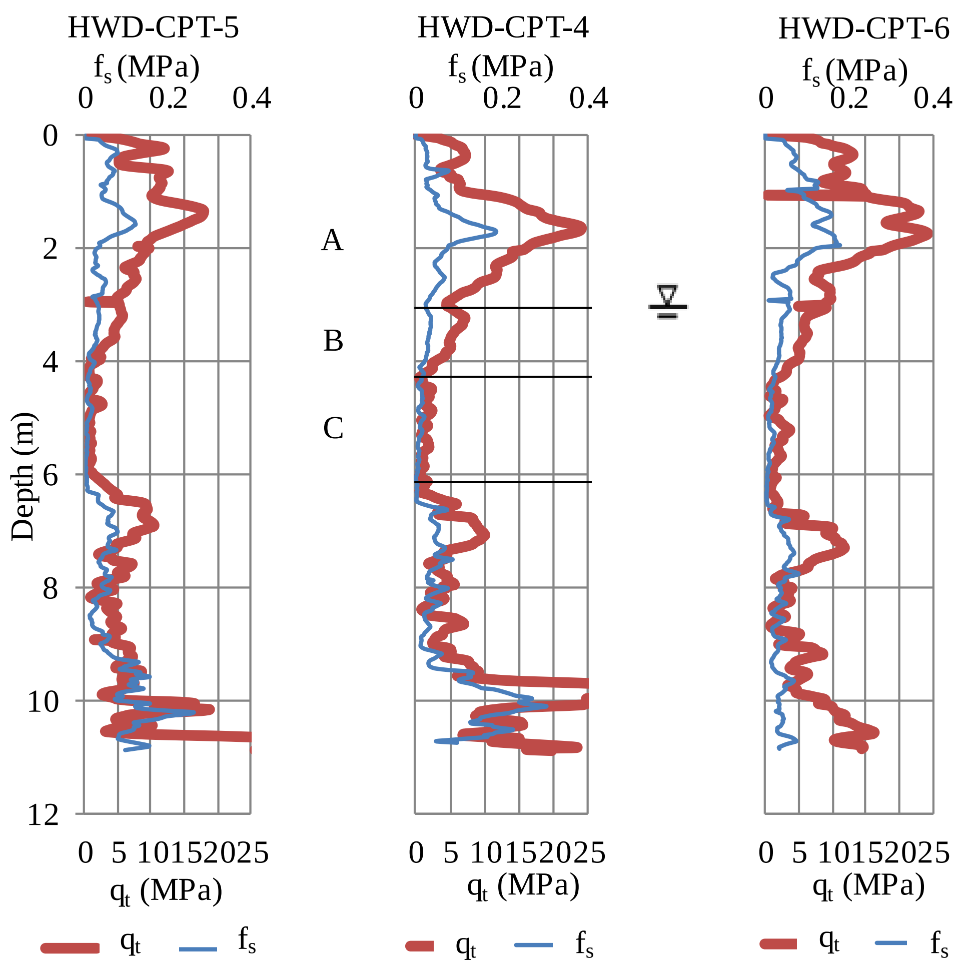


Figure 3.7 Soil Stratigraphy from CPT Data (q_t and f_s) at the Hollywood Site.

The underlying 3 ft (0.9 m) layer is labelled as Layer C and consists of a mixture of clayey silt to sandy silt based on Figure 3.9 that shows most of the data plotting into Zone 4 and 5. The tip resistance and sleeve friction profiles shown in Figure 3.7 are similar for all the three test locations. Excess pore water pressures are observed at HWD-CPT-4 and -5 but no excess pore pressures develop in HWD-CPT-4 site as seen in Figure 3.8 indicating that the soil layers in HWD-CPT-4 and -5 have higher percentage of fines content.

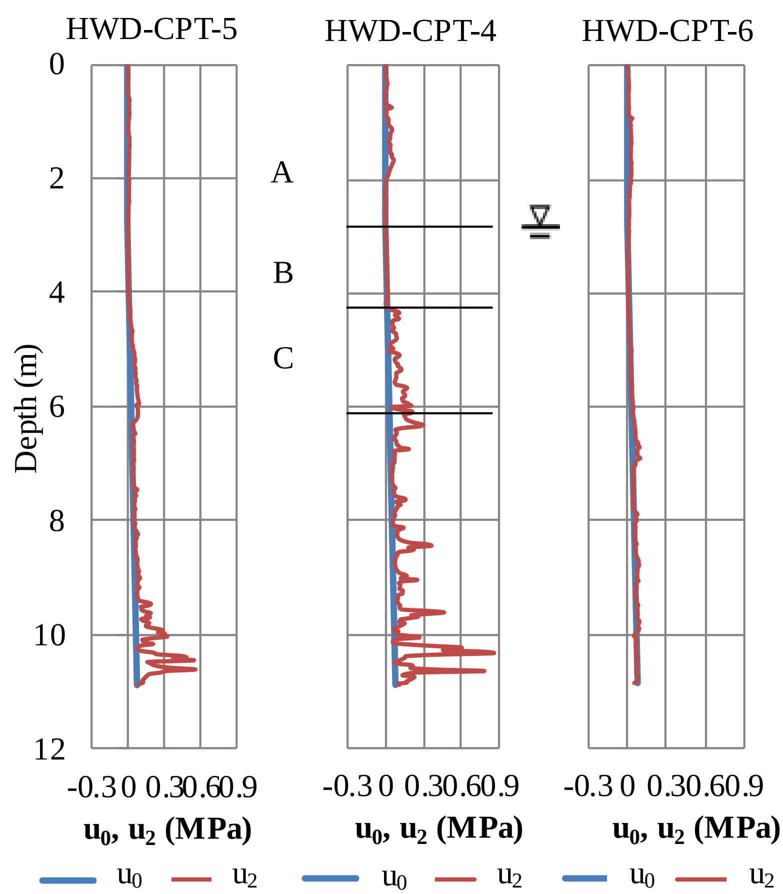
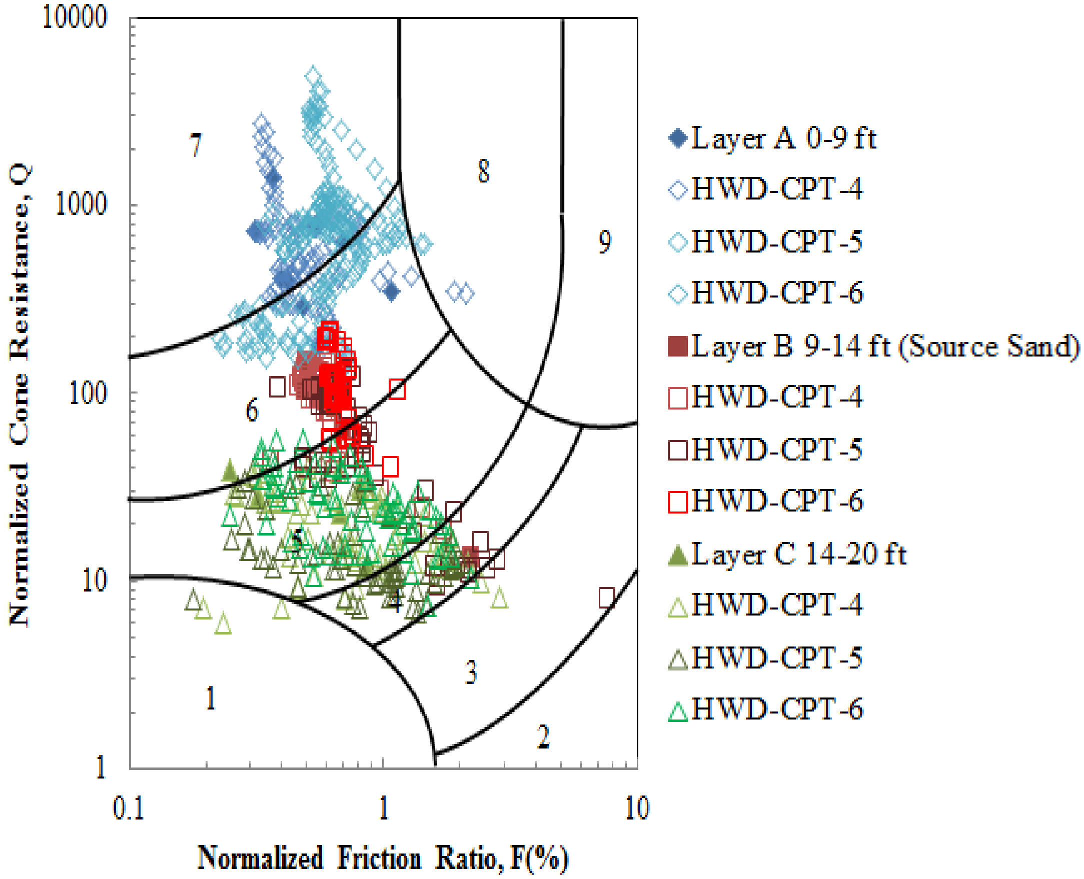


Figure 3.8 CPT Measured and Hydrostatic Pore Pressure at Hollywood Site



Zone	Soil Behavior Type	Zone	Soil Behavior Type
1.	Sensitive, fine grained;	6.	Sands: clean sands to silty sands
2.	Organic soils, peats	7.	Gravelly sand to sand;
3.	Clays: clay to silty clay;	8.	Very stiff sand to clayey sand;
4.	Silt mixtures: clayey silt to silty clay;	9.	Very stiff fine grained
5.	Sand mixtures: silty sand to sandy silt;		

Figure 3.9 Soil behavior type classification chart after Robertson (1990) with data from the Hollywood site

3.2.4 Four Hole Swamp

A three layered stratigraphy was defined from FHS-SCPT-1 and is presented in Figure 3.10 for Four Hole Swamp. Layer A extends from the ground surface down to a depth of 9 ft (2.7 m) and the ground water table starts at the bottom of this layer as shown in Figure 3.10. High tip resistance and sleeve friction are shown with depth for all the three test location. From Figure 3.12, CPT data from layer A lies within Zone 6, 7 and 8, thus the soil varies from clean sand to silty sand to stiff sand. CPT measured pore pressures are seen to rise slightly above the hydrostatic pressure in Figure 3.11 thereby indicating that soil has presence of considerable amount of fines.

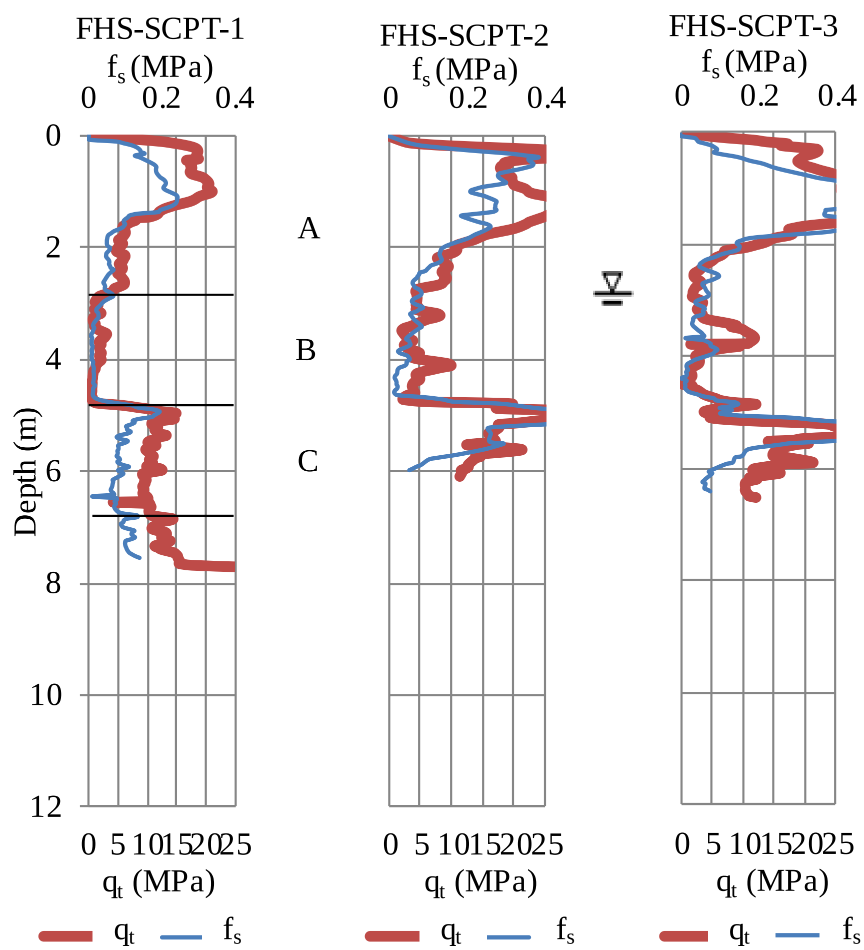


Figure 3.10 Soil Stratigraphy from CPT Data (q_t and f_s) at the Four Hole Swamp Site

The underlying source sand layer extends from 9 to 15 ft (2.7 to 4.6 m). As presented in Figure 3.12, it is observed that soil behavior varies from silty clay to silty sands as the data plots within Zone 4 through 6. As shown in Figure 3.10 and 3.11, FHS-SCPT-1 has low tip resistance and slight fluctuation in CPT measured pore pressures. However, FHS-SCPT-2 and FHS-SCPT-3 show higher tip resistance and no excess pore water pressures. Data from FHS-SCPT-1 fall within Zone 4 through 6 indicating that soil has presence of clays and silts while FHS-SCPT-2 and FHS-SCPT-3 fall into Zone 5 and 6 consisting mostly of sand mixtures (see Figure 3.12). This soil layer is considered to be liquefiable since $(q_{c1N})_{cs}$ is less than 160 for all the three test locations.

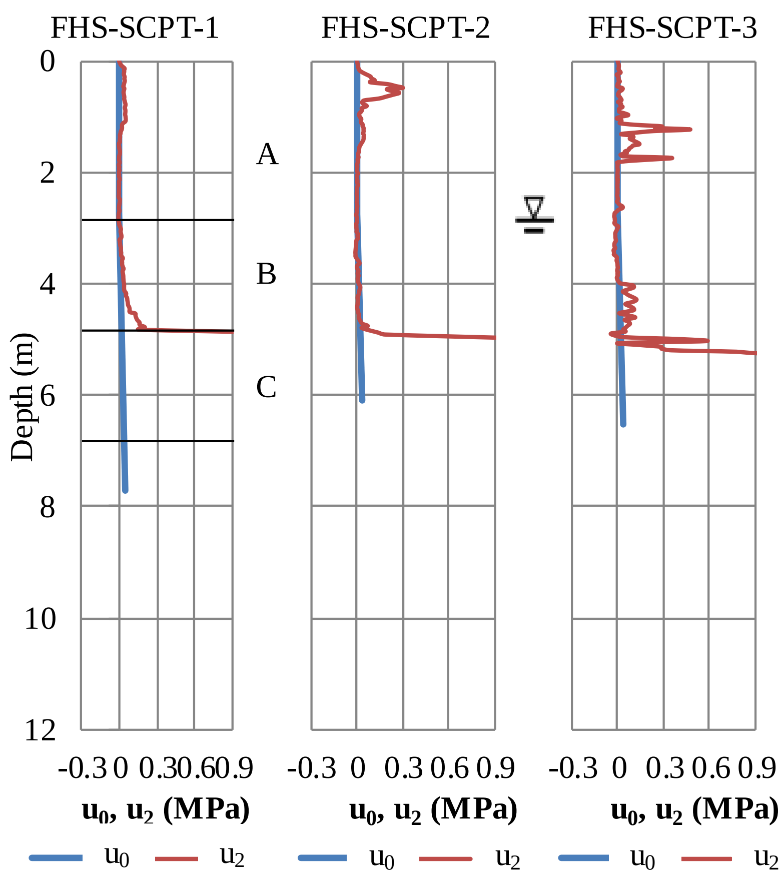
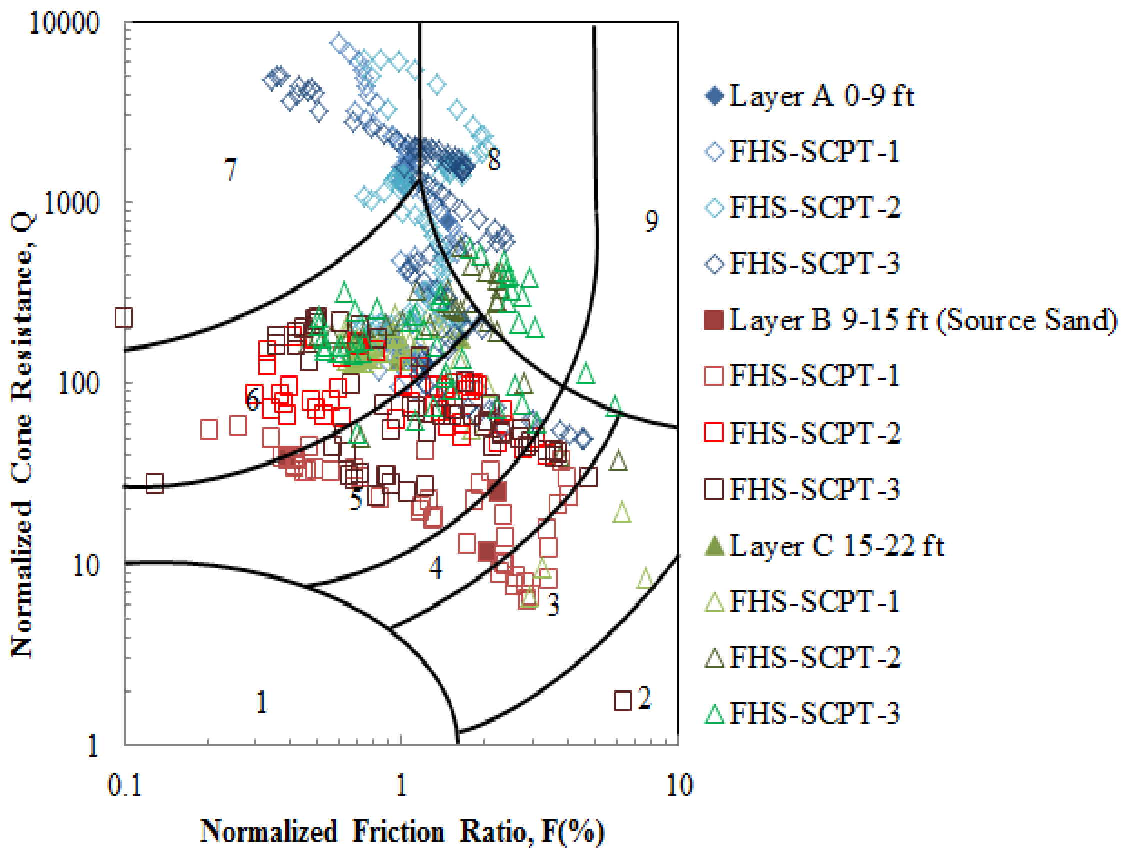


Figure 3.11 CPT Measured and Hydrostatic Pore Pressure at the Four Hole Swamp Site.

Layer C lies between depths of 15 and 22 ft (4.6 to 6.7 m). This layer shown has high tip resistance and sleeve friction. There is an abrupt increase in CPT measured pore pressure (see Figure 3.11) at a depth of 4.6 m which indicates soil beneath this depth has sufficient amount of fines. The CPT based soil identification chart as presented in Figure 3.12 implies that most of the data plots in Zones 5 and 6. Hence, Layer C consists of mixture of sands and silts.



Zone	Soil Behavior Type	Zone	Soil Behavior Type
1.	Sensitive, fine grained;	6.	Sands: clean sands to silty sands
2.	Organic soils, peats	7.	Gravelly sand to sand;
3.	Clays: clay to silty clay;	8.	Very stiff sand to clayey sand;
4.	Silt mixtures: clayey silt to silty clay;	9.	Very stiff fine grained
5.	Sand mixtures: silty sand to sandy silt;		

Figure 3.12 Soil behavior type classification chart after Robertson (1990) with data from the Four Hole Swamp site.

3.2.5 Fort Dorchester

The top 3 layers at the Fort Dorchester Site Stratigraphy were defined using FD-SCPT-1 and SCPT-2 and are labelled as A, B and C as shown in Figure 3.13. The CPT data analyzed for the Fort Dorchester site extends from the ground surface to a depth of 12 ft (3.7 m). The groundwater table is approximately at 17 ft (5.2 m) below the ground surface.

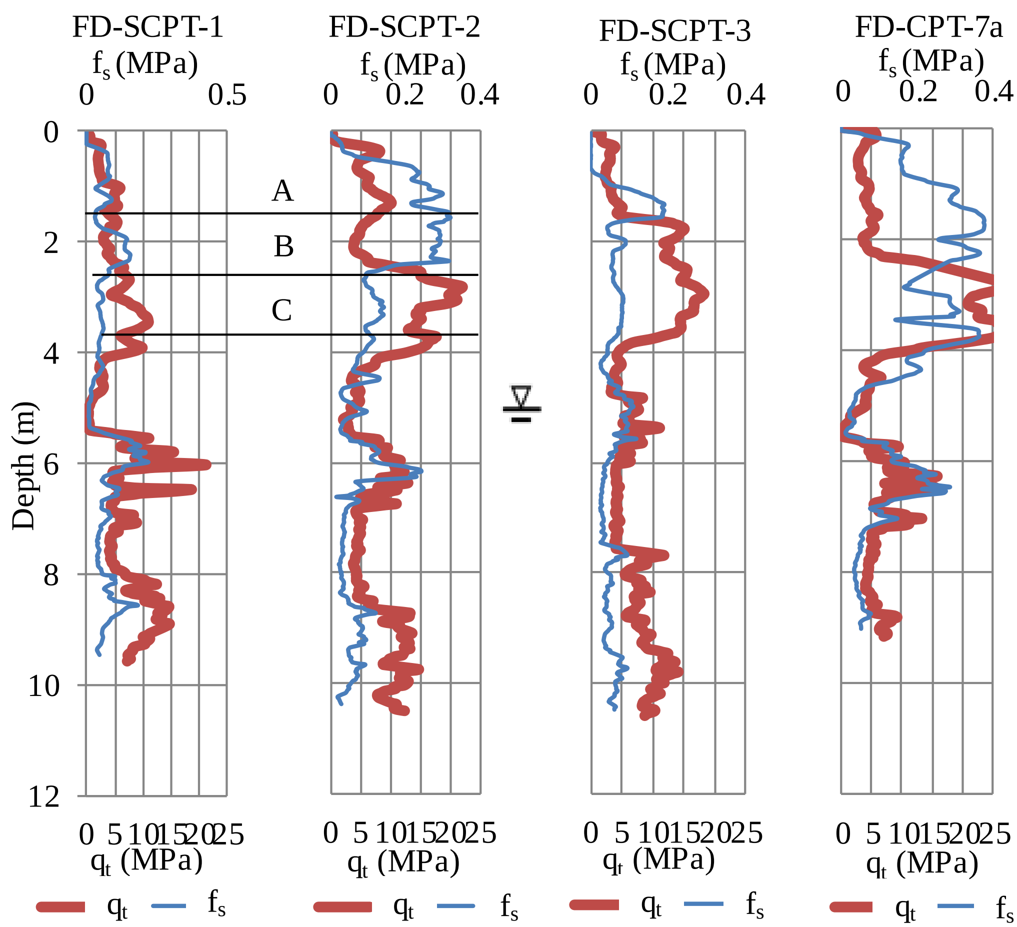


Figure 3.13 Soil Stratigraphy from CPT Data (q_t and f_s) at the Fort Dorchester Site.

Layer A is located beneath the ground surface down to an average depth of 5 ft (1.5 m) and has low tip resistance as presented in Figure 3.13. This figure, however, shows that all test locations apart from FD-SCPT-1 have very high sleeve friction. No pore pressures are detected in this layer (See Figure 3.14). Layer A soil mostly fell into Zone 6 and 8 suggesting that the soil varies from sands to very stiff sands to clayey sand (see Figure 3.15 and 3.16).

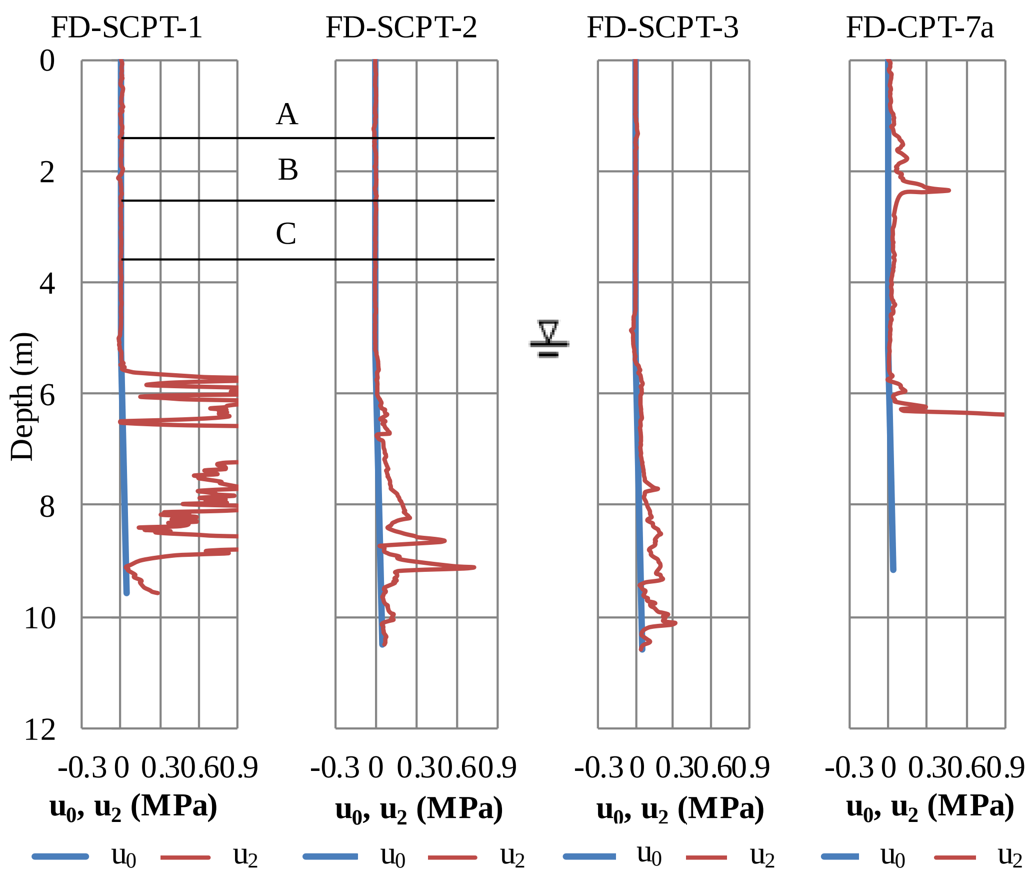
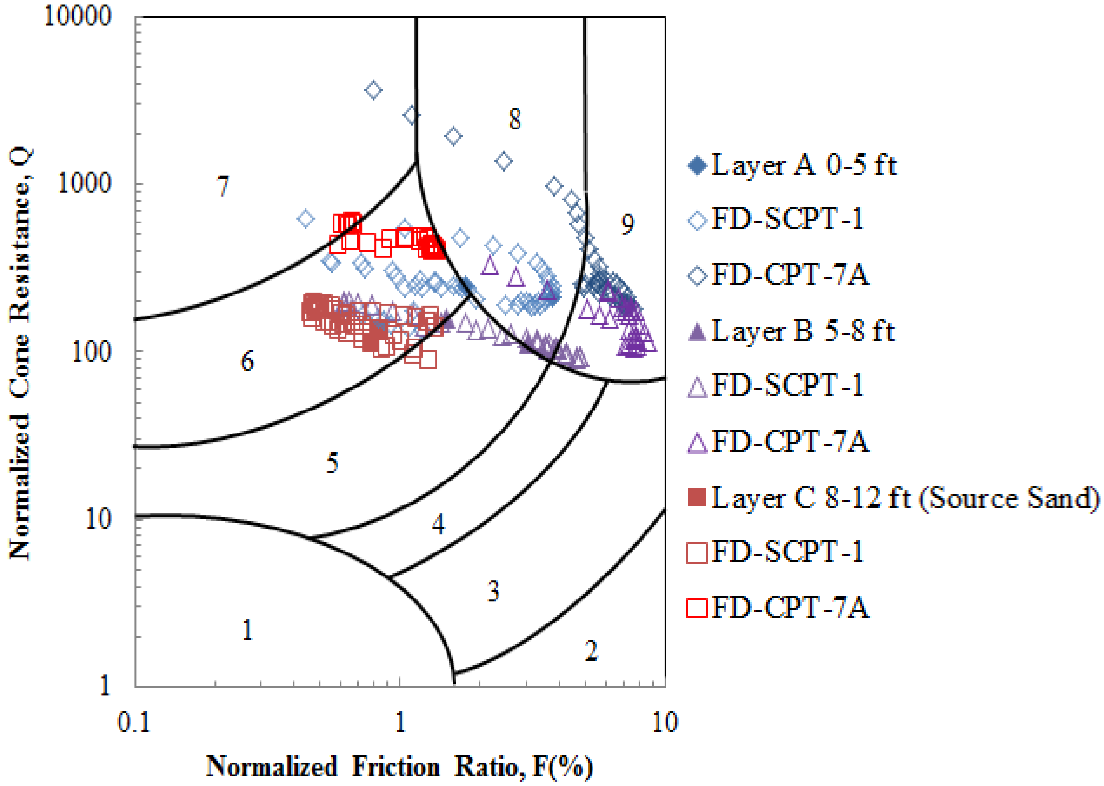


Figure 3.14 CPT Measured and Hydrostatic Pore Pressure at the Fort Dorchester Site

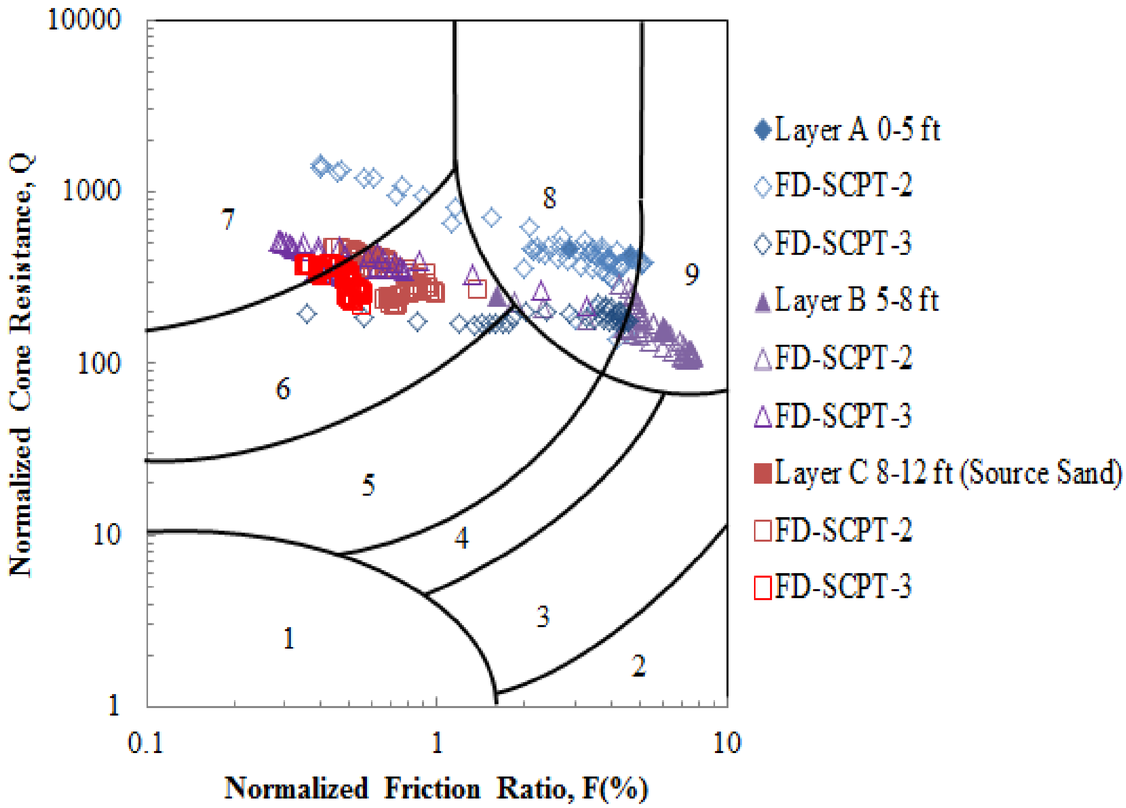
The underlying 3 ft (0.9 m) soil layer is identified as Layer B and variations in tip resistance and sleeve friction are detected from Figure 3.13. On the other hand, only FD-CPT-7a has CPT measured pore pressures which rise above the hydrostatic pore pressure. The other test locations detect almost zero pore pressures (See Figure 3.14). Soil identification chart in Figure 3.15 and 3.16 determines that Layer B lies mainly in Zone 8 and 9 and the soil varies from stiff sands to very stiff fine grained. Some of the data points also fell into Zone 6 indicating presence of silty sands to clean sand.



Zone	Soil Behavior Type	Zone	Soil Behavior Type
1.	Sensitive, fine grained;	6.	Sands: clean sands to silty sands
2.	Organic soils, peats	7.	Gravelly sand to sand;
3.	Clays: clay to silty clay;	8.	Very stiff sand to clayey sand;
4.	Silt mixtures: clayey silt to silty clay;	9.	Very stiff fine grained
5.	Sand mixtures: silty sand to sandy silt;		

Figure 3.15 Soil behavior type classification chart after Robertson (1990) with data from the Fort Dorchester Site oriented at E-W direction.

Layer C extends from 8 ft (2.4 m) to a depth of 12 ft (3.7 m) and represents the source sand layer. Figure 3.13 shows that the soil has high tip resistance and sleeve friction. Also, no CPT measured pore pressures are observed in this layer as seen in Figure 3.14. As shown in Figure 3.15 and 3.16, the source sand layer lies in Zone 6 and the soil behaves as clean sands to silty sands. Even though the soil has high tip resistance $(q_{c1N})_{cs}$ is less than 16 MPa, thereby, indicating that this layer is susceptible to liquefaction if the ground water table were higher than the present day water table.



Zone	Soil Behavior Type	Zone	Soil Behavior Type
1.	Sensitive, fine grained;	6.	Sands: clean sands to silty sands
2.	Organic soils, peats	7.	Gravelly sand to sand;
3.	Clays: clay to silty clay;	8.	Very stiff sand to clayey sand;
4.	Silt mixtures: clayey silt to silty clay;	9.	Very stiff fine grained
5.	Sand mixtures: silty sand to sandy silt;		

Figure 3.16 Soil behavior type classification chart after Robertson (1990) with data from the Fort Dorchester Site oriented at N-S direction.

3.2.6 Soil Behavior Type Index (I_c) profiles with depth

The I_c values are calculated using equation 2.8 to screen out layers susceptible to liquefaction (i.e. I_c>2.6) and also differentiate between clay like and sand like soils as presented in previous studies by Robertson and Wride (1998) and Robertson (2009) (See section 2.3.2 and 2.3.5.2). The following profiles with depth for each of the soil layers at test locations SAM-SCPT-1, GAP-SCPT-1, HWD-CPT-4, FHS-SCPT-1, FD-SCPT-1 and FD-SCPT-2 are shown below. Note that the data points are plotted at corresponding depths where the DMT data was obtained.

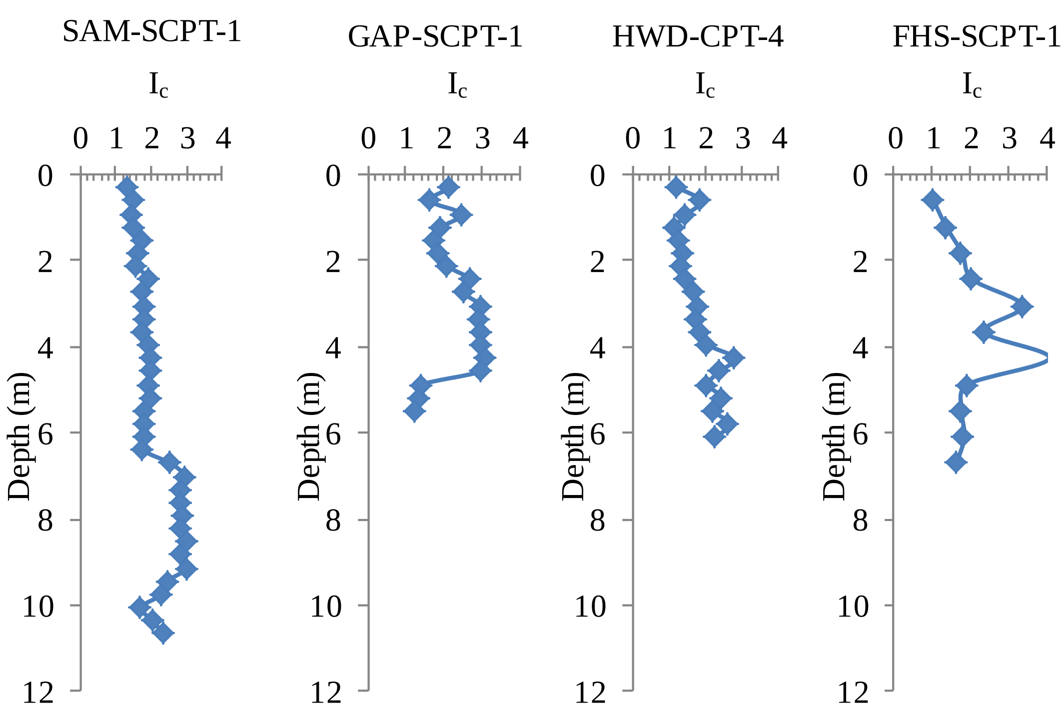


Figure 3.17 I_c vs depth profile at the Sampit, Gapway, Hollywood and Four Hole Swamp Sites.

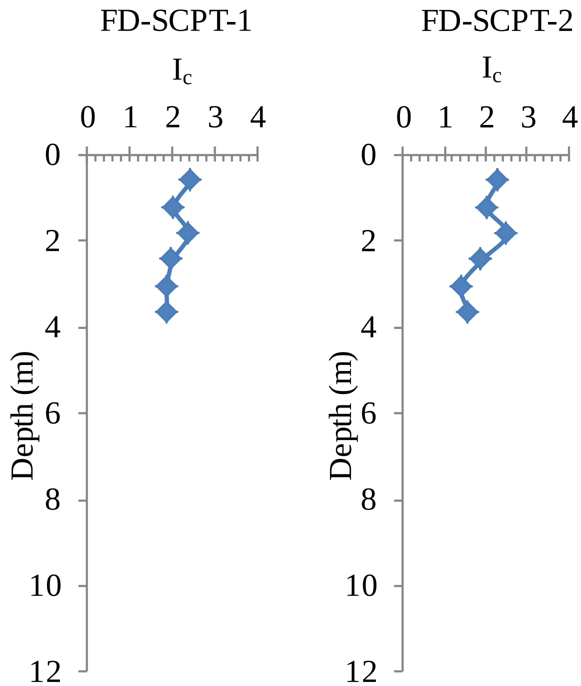


Figure 3.18 I_c vs depth profile at the Fort Dorchester Site

3.3 Soil Behavior from DMT

At the Sampit, Gapway, Hollywood, Four Hole Swamp and Fort Dorchester Sites, the dilatometer test was conducted to obtain I_D, K_D and E_D values which are plotted with depth in Figures 3.19, 3.21, 3.23, 3.25, 3.27 and 3.28. The profiles are shown to compare the results between different soil layers at a particular site. The soil behavior type from DMT is analyzed using the Soil Identification E_D-I_D chart (ASTM D6635) shown in Figure 2.6 in Section 2.3.1.

3.3.1 Sampit

The DMT test was performed in close proximity to the SAM-SCPT-1 test location and the results are shown in Figure 3.19. The soil profile is divided into four layers (0 to 9 ft (0 to 2.7 m), 9 to 22 ft (2.7 to 6.7 m), 22 to 31 ft (6.7 to 9.4 m), 31 to 35 ft (9.4 to 10.7 m) where the source sand layer varies from approximately 9 to 22 ft (2.7 to 6.7 m) (Williamson, 2013).

Figure 3.20 presents a soil type identification chart with data from DMT test conducted at the Sampit site. I_D and K_D values are plotted to a depth of 35 ft (10.7 m). The layer from 0 to 9 ft (0 to 2.7 m) is a dense sandy silt to silty sand. The source sand layer appears to be a medium dense to high density sandy silt. The layer from 22 to 31 ft (6.7 to 9.4 m) is a soft silty clay to clay. Layer 31 to 35 ft (9.4 to 10.7 m) is indicated as being clayey silt to clay.

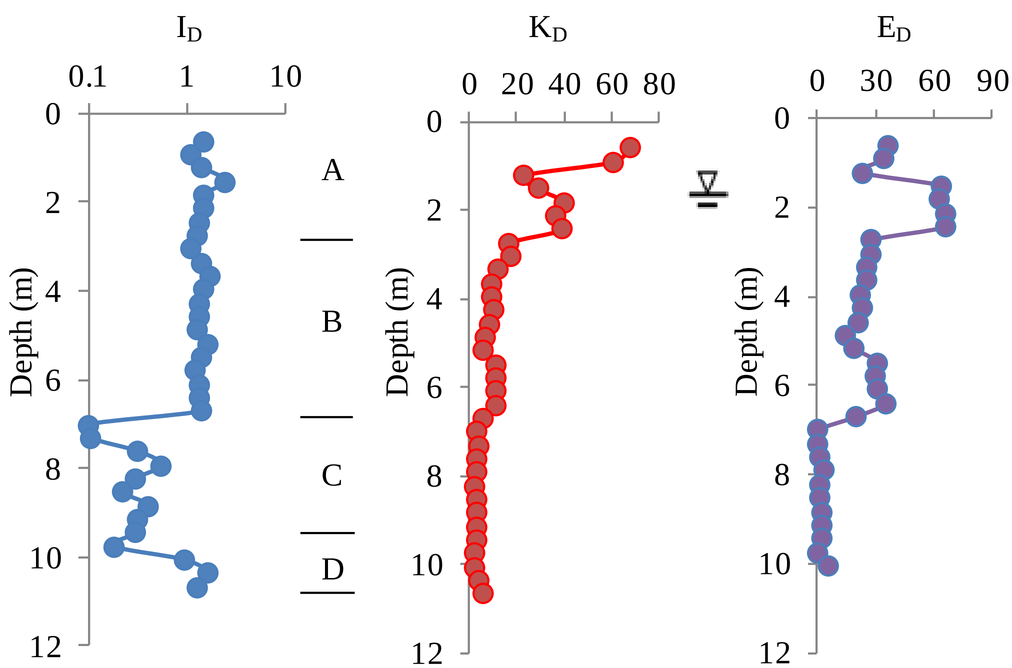


Figure 3.19 I_D, K_D, E_D profiles with depth at the Sampit Site.

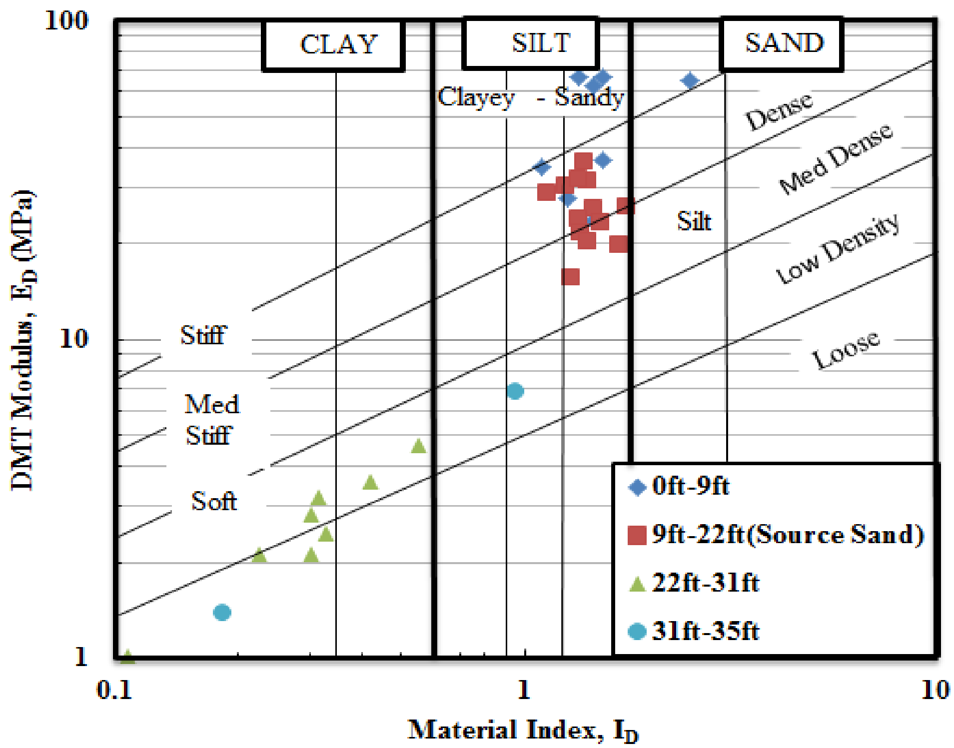


Figure 3.20 DMT modulus and material index chart (ASTM D 6635) with DMT results at the Sampit Site

3.3.2 Gapway

The DMT test was performed closest to the GAP-SCPT-1 test location and was previously analyzed by Williamson (2013). As shown in Figure 3.21, the soil profile is divided into five layers (0 to 3 ft (0 to 0.9 m), 3 to 4 ft (0.9 to 1.2 m), 4 to 7 ft (0.9 to 2.1 m), 7 to 15 ft (2.1 to 4.6 m), 15 to 18 ft (4.6 to 5.5 m) where the source sand layer was identified to range from 4 to 7 ft (0.9 to 2.1 m).

Figure 3.22 presents the soil type identification chart with data from DMT test conducted at the Gapway site. I_D and K_D values are plotted to a depth of 18 ft (5.5 m). It is seen from the figure that layer 0 to 3 ft (0 to 0.9 m) ranges from a medium to dense sandy silt to sand. The layer from 3 to 4 ft (0.9 to 1.2 m) has only one data point which shows that this layer behaves as a low density sandy silt. The source sand layer materials behave as a medium dense clayey silt to silty sand. The layer from 7 to 15 ft (2.1 to 4.6 m) has a wide range of soil types varying from soft silty clay to clay to clayey silt. The layer 15 to 18 ft (4.6 to 5.5 m) consists of high density silty sand with a small fraction of clay content.

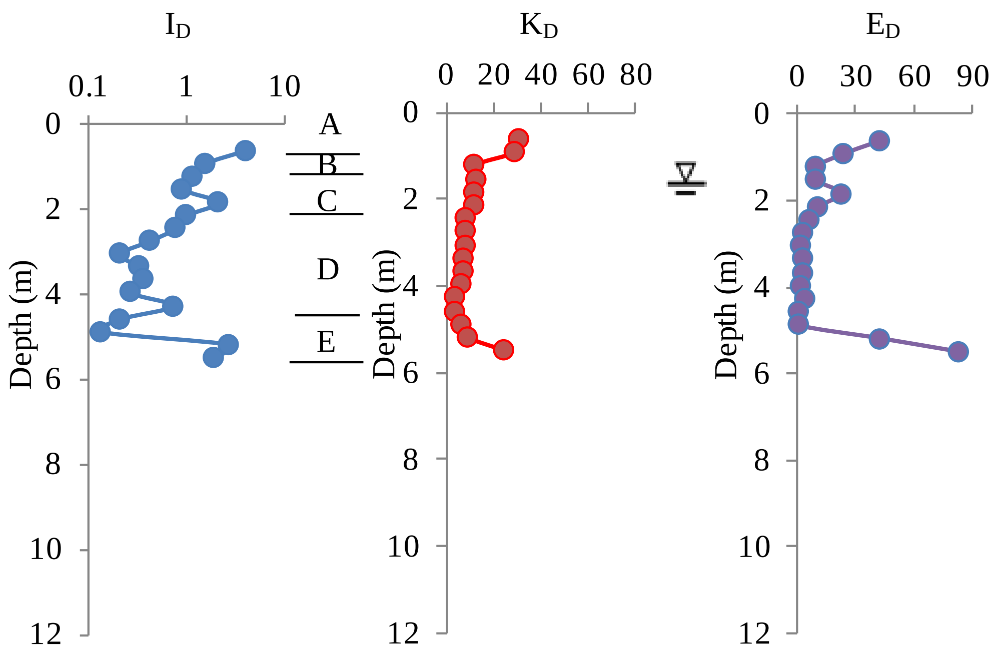


Figure 3.21 I_D, K_D, E_D profiles with depth at the Gapway Site.

3.3.3 Hollywood

The DMT test was conducted next to the HWD-CPT-4 sounding and the results are presented in Figure 3.23. The soil profile is divided into three layers (0 to 9 ft (0 to 2.7 m), 9 to 14 ft (2.7 to 4.2 m), 14 to 20 ft (4.2 to 6.1 m) and the source sand layer extends from 9 to14 ft (2.7 to 4.2 m) (Williamson, 2013).

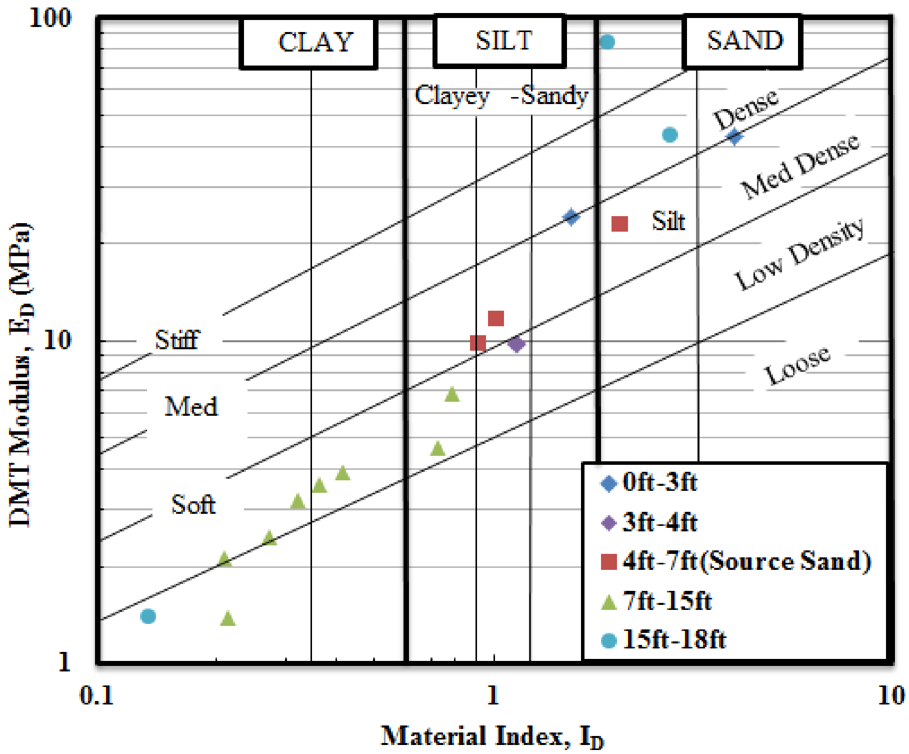


Figure 3.22 DMT modulus and material index chart (ASTM D 6635) with DMT results at the Gapway Site.

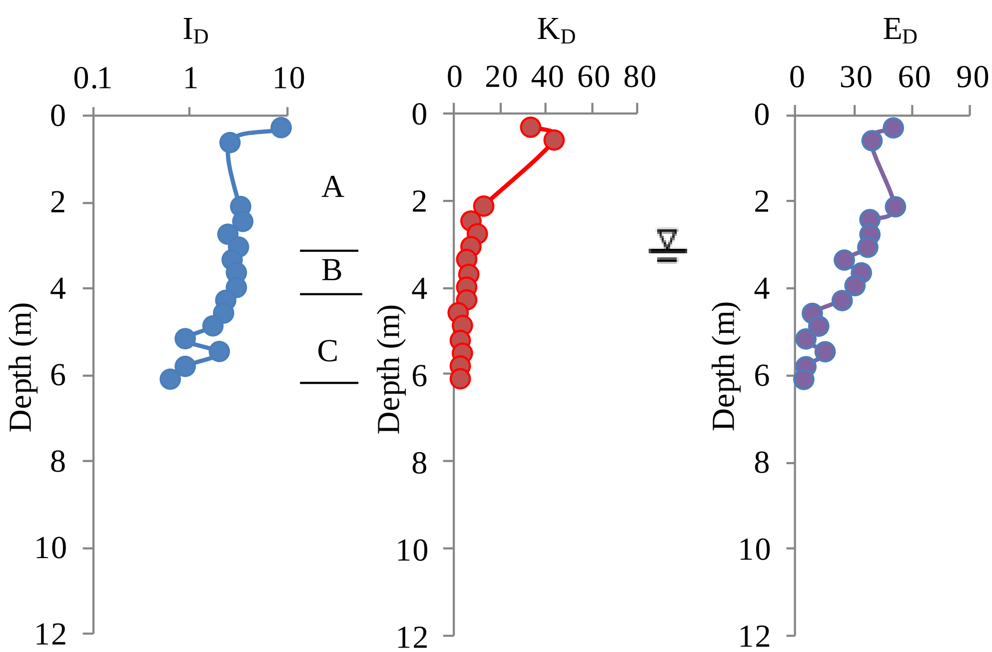


Figure 3.23 I_D, K_D, E_D profiles with depth at the Hollywood Site.

Figure 3.24 shows the soil type identification chart with data from DMT test performed at the Hollywood site. The soil behavior type for the layer from 0 to 9 ft (0 to 2.7 m) is shown to vary from a medium dense sand to a dense silty sand. The source sand layer from 9 to 14 ft (2.7 to 4.2 m) is a silty sand of medium density. The layer from 14 to 20 ft (4.2 to 6.1 m) below the source sand has a wide range of soil types from low density clayey silt to sandy silt to silty sand.

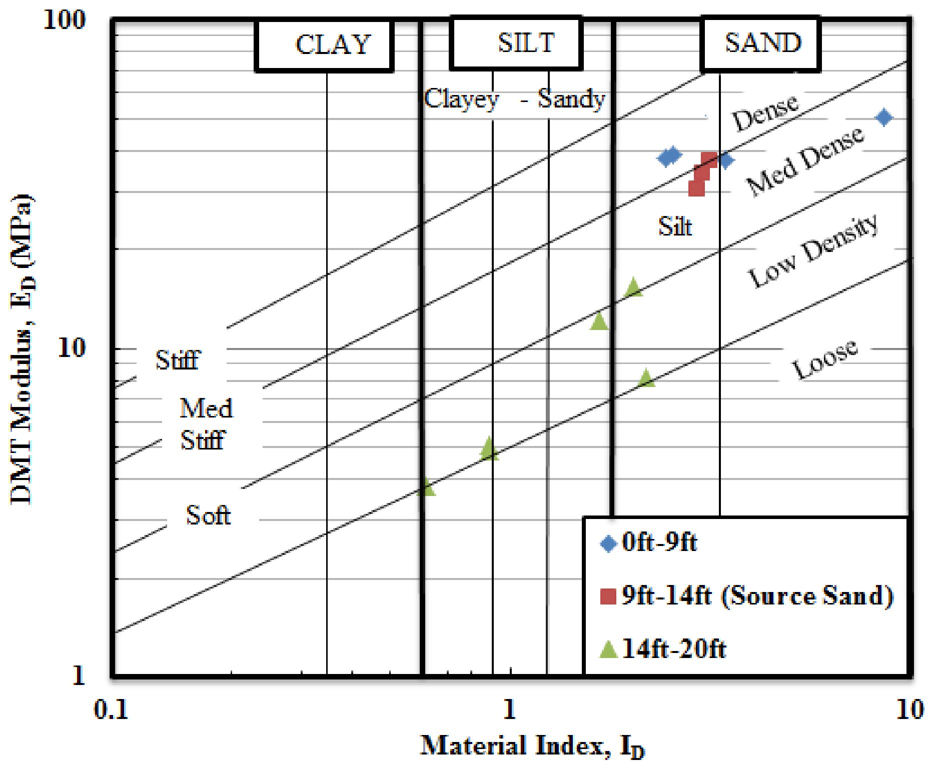


Figure 3.24 DMT modulus and material index chart (ASTM D 6635) with DMT results at the Hollywood Site.

3.3.4 Four Hole Swamp

The results from FHS-DMT, performed nearest to the FHS-SCPT-1 test location are shown in Figure 3.25. The soil profile is divided into three layers (0 to 9 ft (0 to 2.7 m), 9 to 15 ft (2.7 to 4.6 m) and 15 to 22 ft (4.6 to 6.7 m)) where the source sand layer is located between 9 and 15 ft (2.7 and 4.6 m) (Williamson, 2013).

Figure 3.26 shows the soil type identification chart with data from DMT test performed at Four Hole Swamp. The soil behavior type for the layer from 0 to 9 ft (0 to 2.7 m) behaves as a dense silty sand to sand. The source sand layer from 9 to 15 ft (2.7 to 4.6 m) varies from sandy silt of low density to dense silty sand. The layer from 15 to 22 ft (4.6 to 6.7 m) has only one data point in the figure which shows the layer is a very soft clay.

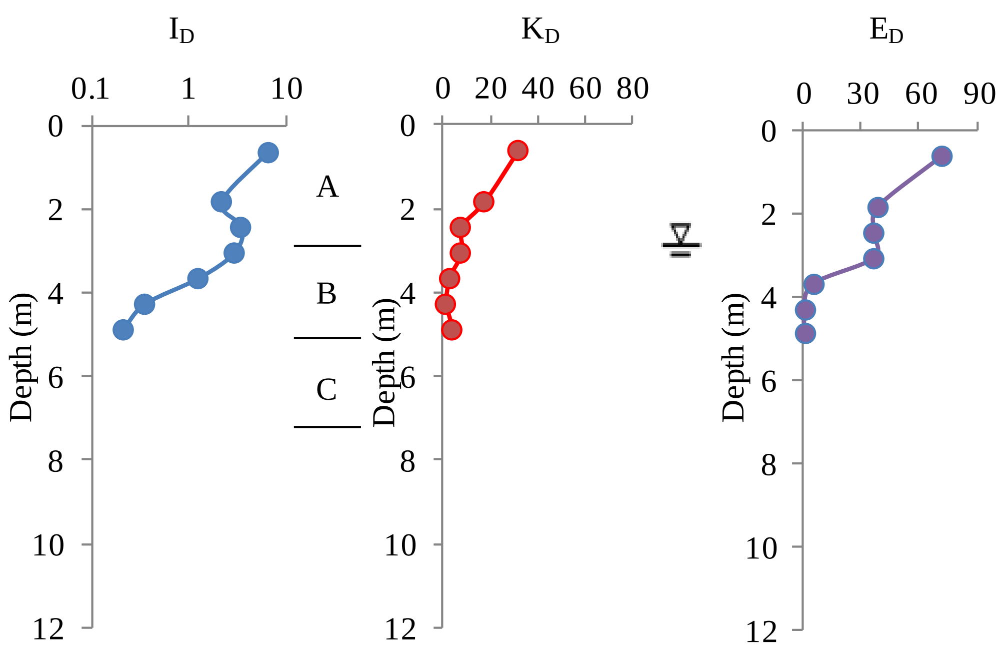


Figure 3.25 I_D, K_D, E_D profiles with depth at the Four Hole Swamp Site.

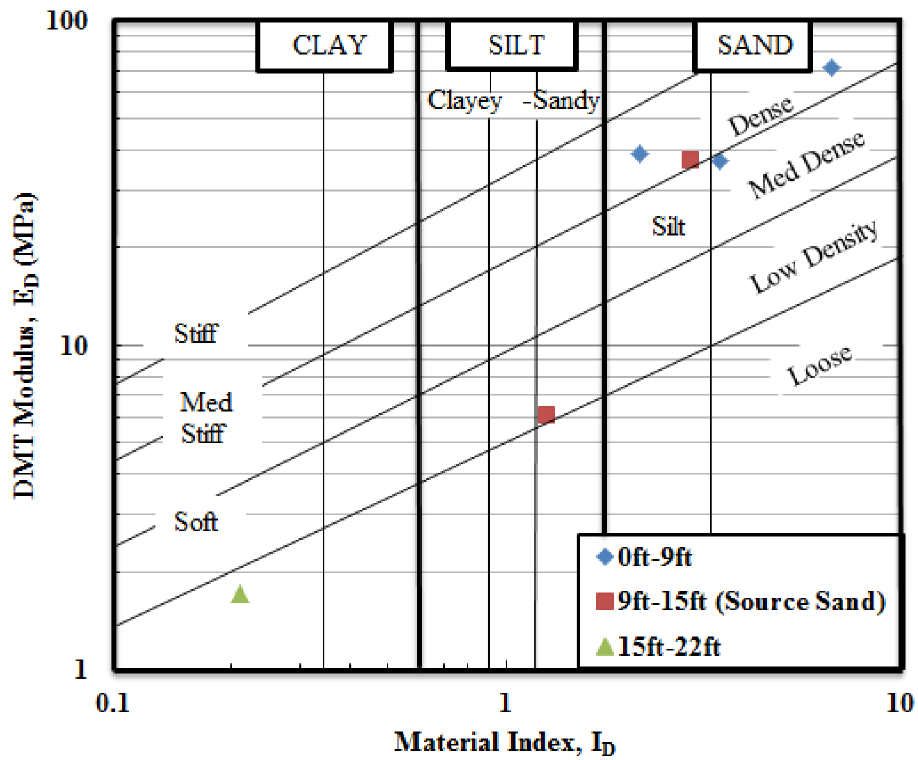


Figure 3.26 DMT modulus and material index chart (ASTM D 6635) with DMT results at the Four Hole Swamp Site.

3.3.5 Fort Dorchester

The results for DMT tests FD-EW and FD-NS, closest to FD-SCPT-1 and FD-SCPT-2 respectively are presented in Figures 3.27 and 3.28. For both DMT test locations, the soil profile is divided into three layers (0 to 5 ft (0 to 1.5 m), 5 to 8 ft (1.5 to 2.4 m), and 8 to 16 ft (2.4 to 4.9 m) where the source sand layer lies within 8 to 16 ft (2.4 to 4.9 m) (Williamson, 2013).

The soil type identification charts for FD-DMT-EW and FD-DMT-NS are shown in Figures 3.29 and 3.30 respectively. DMT data is only available down to a depth of 12 ft (3.7 m), thus data from 8 to 12 ft (2.4 to 3.7 m) is used to characterize the source sand in this case. For the FD-NS test location, the soil behavior type for the layer from 0 to 5 ft

(0 to 1.5 m) is a dense silty sand. The layer from 5 to 8 ft (1.5 to 2.4 m) ranges from dense sandy silt to sand. The source sand layer from 8 to 12 ft (2.4 to 3.7 m) has one data point which describes it to be a dense silty sand. The soil behavior type for the layer from 0 to 5 ft (0 to 1.5 m) at the FD-EW test location varies from medium to dense silty sand. Layer 5 to 8 ft (1.5 to 2.4 m) and Layer 8 to 12 ft (2.4 to 3.7 m) in FD-EW have similar soil behavior type as in FD-NS.

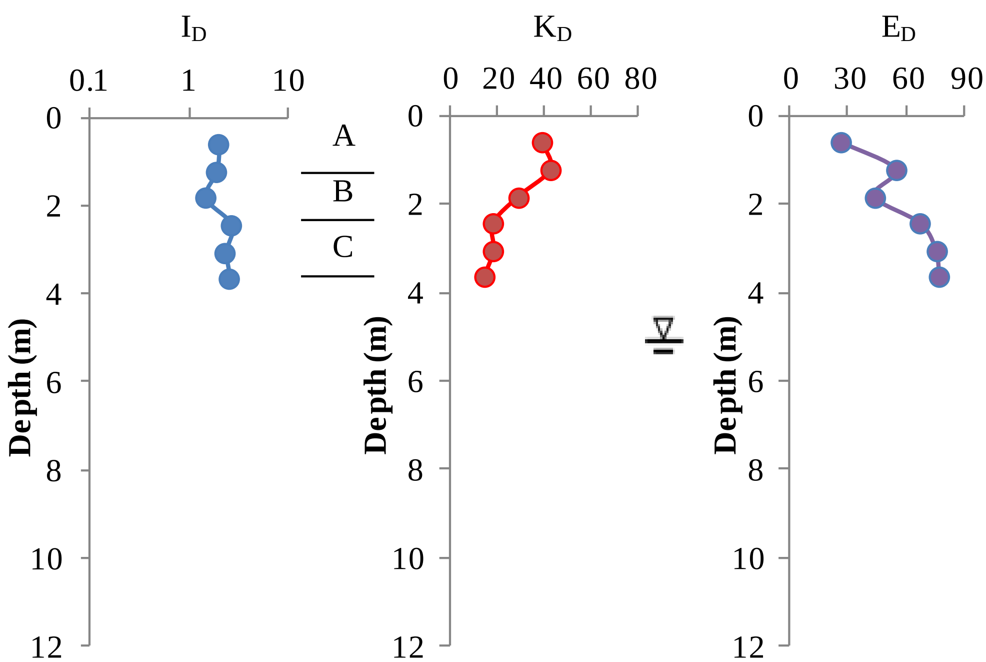


Figure 3.27 I_D, K_D, E_D profiles with depth at the Fort Dorchester-EW site.

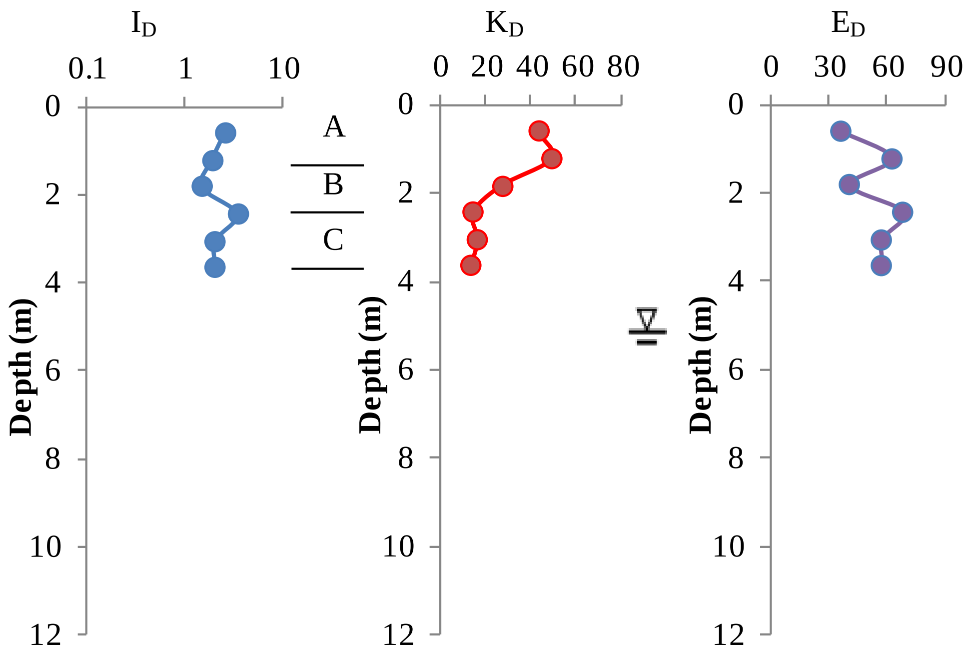


Figure 3.28 I_D, K_D, E_D profiles with depth at the Fort Dorchester-NS site.

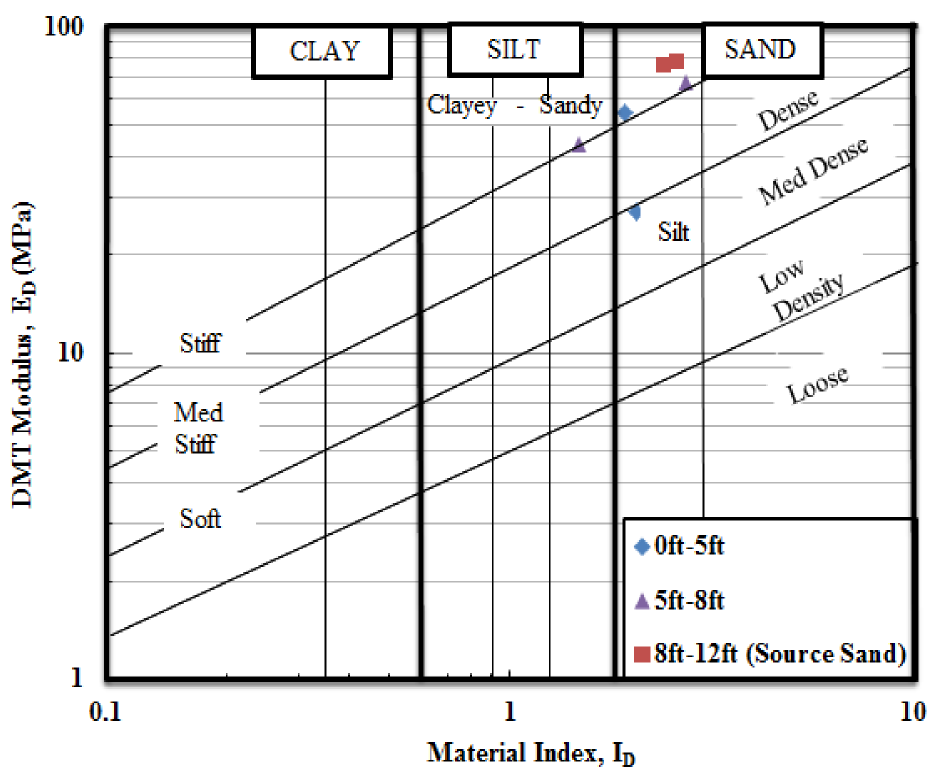


Figure 3.29 DMT modulus and material index chart (ASTM D 6635) with DMT results at the Fort Dorchester Site oriented at E-W direction.

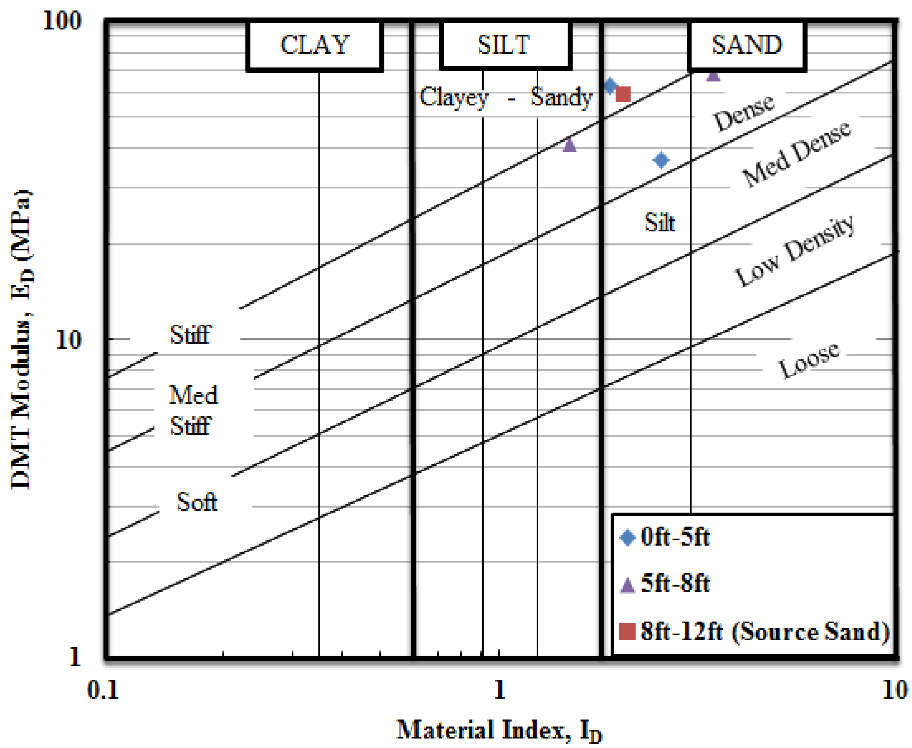


Figure 3.30 DMT modulus and material index chart (ASTM D 6635) with DMT results at the Fort Dorchester Site oriented at N-S direction.

3.4 Discussion

A comparison is made from the results obtained from both CPT based Soil behavior Classification Chart by Robertson (1990) and DMT based soil identification chart (ASTM D6635). As summarized in Table 3.2, CPT test data from Sampit show similar soil behavior in Layer A, B and C when compared to the DMT test data. The source sand layer B, comprises mostly of sand and silt mixtures throughout the site. Most of the data lies within Zones 5 and 6 which are potentially liquefiable as shown in Figure 3.3. However, it can be inferred from the CPT based soil behavior chart, the assumed source sand layer at test location SCPT-3 has considerable amount of fines at a depth of 9 ft to 13 ft (2.7 to 4.3 m) since the CPT data within this layer fall into Zone 3, 4 and 5. The soil layer in this zone may be too clay rich to liquefy and hence the top boundary of the source sand layer at this this test location may need to be shifted to a depth below 13 ft (4.3 m). The soil behavior in Layer D consists of coarse sands and silts in the CPT based chart whereas the DMT recognized the soil behavior type as mostly clays.

The CPT based SBT chart and I_D-E_D chart analyzed for Gapway both show that Layer A has presence of mixed sands. It is, however, evident from both charts that Layer B contains mostly sand and silt mixtures which undermine the clay cap layer defined by Hu (2001). The source sand layer behaves differently when a comparison is made between the two methods. The DMT test data suggests that the source sand layer has presence of medium dense clays and silty sands while CPT data shows that it has only sand mixtures. It can be inferred from the CPT data, that soils in the source sand layer are granular with less amount of fines and can be considered to be potentially liquefiable. The data invariably falls into the liquefiable zone as presented in Figure 3.6. However, the results from DMT are closer to the USCS classification of soils provided earlier by Williamson (2013) and can be considered to further validate the boundary of the source sand layer. It is observed from the CPT based chart that the test location SCPT-1 which is closest to the DMT exhibit clayey soil behavior in Layer D as obtained from the I_D-E_D chart. The other two CPT test locations SCPT-1 and -3 which are located further away from the DMT consist of silt and sand mixtures respectively. This indicates the soil variability in Layer D for the three test locations across the site. Both DMT and CPT charts indicate the presence of sand mixtures with a very small fraction of clays in Layer E.

At Hollywood, both CPT and DMT methodologies show the best agreement for all soil layers in comparison to the rest of the sites. As shown in the CPT based soil identification chart, Layer A, B and C show the same soil behavior type for the three test locations across the site and are also similar to the soil behavior classification presented in the DMT I_D-E_D chart (See summary Table 3.2). The soil behavior for the source sand layer from both these charts also compares well with the USCS Soil classification chart used by Williamson (2013). As shown in Figure 3.9, the source sand layer fell into Zone 6 which is considered to be a potentially liquefiable zone. Hence, the source sand layer interface for the three CPT test locations is considered to be a good assumption and soils within this region can be considered as susceptible to liquefaction.The CPT and DMT results obtained from Four Hole Swamp show similar soil behavior in Layer A. Layer A produces the highest tip resistance and sleeve friction when compared to rest of the sites and therefore is considered to have very dense and stiff sands in this region. The source sand layer, B, from the CPT data shows that it consists of a wide range of soils and has a high percentage of fines. I_D-E_D chart shows similar behavior characteristics since it comprises of low density silt mixtures. Figure 3.12 indicates that the source sand layer falls within Zone 4, 5 and 6, hence, it may be considered unliquefiable due to the presence of large amount of fines. Further analysis on liquefaction susceptibility is presented in Chapter 5. The CPT based SBT chart indicates that Layer C lies within Zone 5, 6 and consists of sand mixtures while I_D-E_D chart indicates that soil comprises of very soft clay. Hence, there is a clear discrepancy between both the charts. While analyzing the DMT data only one data point at a depth of 16 ft (4.9 m) was used to represent layer C therefore I_D-E_D chart may not be considered to classify soils in this case even though this layer was classified as a clay layer from the USCS Soil Classification chart used by Williamson (2013).

At the Fort Dorchester site, soil behavior in SCPT-1 and CPT-7a test locations is compared to the E-W oriented DMT while soil behavior in SCPT-2 and SCPT-3 test locations is compared to the N-S oriented DMT. From the CPT and DMT based charts, Layer A for all the CPT test locations was considered to have very stiff sands to clayey sands whereas both DMT-NS and DMT-EW consists of high density silty sands. The CPT based method was analogous to the USCS soil classification unlike the DMT. Layer B showed similar CPT soil behavior type to that of Layer A and compared well with the DMT test results in a similar manner. However, in this case, the USCS soil classification used by Williamson (2013) indicated that this layer has presence of high plasticity clays. The source sand layer, C, comprised of silty sands as indicated by both the CPT and DMT charts. As shown in Figures 3.15 and 3.16, the source sand layer plotted in Zone 6 indicating that the layer is susceptible to liquefaction. Both the DMT and CPT charts confirmed the soil behavior type obtained from USCS soil classification by Williamson (2013).

Table 3.2 Summary of Soil Behavior Type from Different Methods

Site	Depth	Layer	USCS Soil Classification (Williamson, 2013)	E_D-I_D Soil Identification Chart (ASTM D 6635)	CPT SBT Chart (Robertson, 1990)
Sampit	0-9ft	A	SP-SM	High Density Sandy Silt to Silty Sand	Clean Sands to Silty Sand; Zone 6, Zone 7 (above WT)
	9ft-22ft (Source Sand)	B	SP, SP-SC	Medium Dense to High Density Sandy Silt	Clean Sands to Silty Sand; Zone 6
	22ft-31ft	C	CL	Soft Silty Clay to Clay	Mixture of clay, silt and Sand; Zones 4, 5, 6
	31ft-35ft	D	SP-SM	Soft Clay to Clayey Silt	Clean Sands to Silty Sand to Sandy Silt; Zone 5, 6
Gapway	0-3ft	A	Mixed Sands	Medium Density to High Density Sandy Silt to Sand	Clean Sands to Silty Sand; Stiff sand; Zones 5, 6; Zone 7(above WT)
	3ft-4ft	B	Clay Cap	Low Density Sandy Silt	Clean Sands to Silty Sand to Sandy Silt; Zones 5, 6
	4ft-7ft (Source Sand)	C	SP-SC/SM	Medium dense Clayey Silt to Silty Sand	Clean Sands to Silty Sands; Zone 6
	7ft-15ft	D	Clay	Soft Clay to Clayey Silt	Mixed clays, silts and sands; Zones 4, 5, 6
	15ft-18ft	E	Coarse Sand	High Density Silty Sand; Soft Clay	Gravelly Sand to Sand; Clean sand to silty sand; Zones 6, 7

Hollywood	0-9ft	A	SM	Medium Dense Sand to High Density Silty Sand	Clean Sands to Silty Sand; Gravelly Sand Zones 6; Zone 7 (above WT)
	9ft-14ft (Source Sand)	B	SP-SM	Medium Density Silty Sand	Clean sands to silty sands; Zone 6
	14ft-20ft	C	SC-SM	Low Density Clayey silt to Sandy Silt to Silty Sand	Clayey silt to sandy silt; Zones 4, 5
Four Hole Swamp	0-9ft	A	SC-SM	Dense Silty Sand to Sand	Clean Sands to Silty Sand to Stiff Sand; Zones 6; Zone 7, 8 (above WT)
	9ft-15ft (Source Sand)	B	SP-SC	Low Density to High Density Sand Silt to Silty Sand	Silty Clay to silty sands; Zones 4, 5, 6
	15ft-22ft	C	SC	Very Soft Clay	Clean Sands to Silty Sand to Sandy Silt; Zones 5, 6
Fort Dorchester	0-5ft	A	SC	High Density Silty sand	Sands to Very Stiff Sand to clayey sand; Zones 6,8
	5ft-8ft	B	CH	High Density Sandy Silt to Sand	Sands to Very Stiff Sand to stiff fine grained; Zones 6, 8,9
	8ft-12ft (Source Sand)	C	SC-SM	High Density Silty Sand	Clean Sands to Silty sands; Zone 6

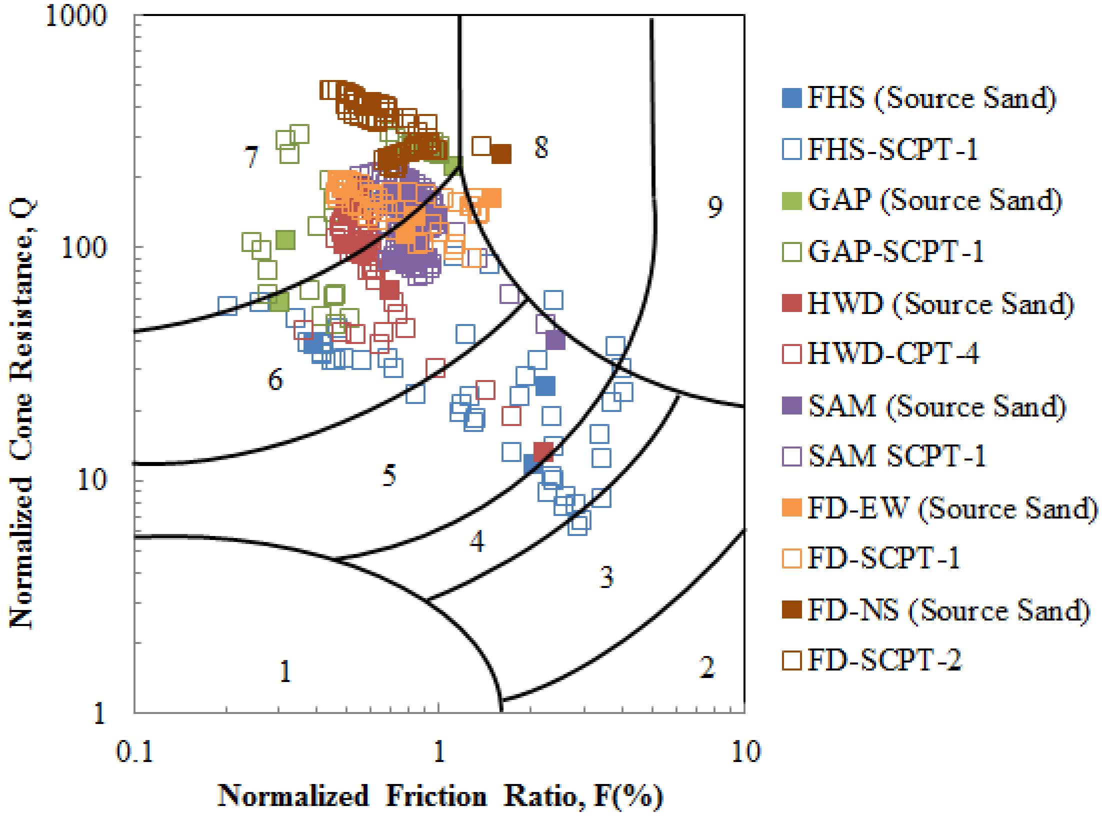
3.5 All Source Sands

3.5.1 Soil Behavior Type from CPT

As shown in Figure 3.31, the source sand data for all the sites at test locations closest to the DMT are plotted on the CPT Soil Behavior Chart by Robertson and Wride (1990). As per earlier discussion in Section 3.2, the majority of the source sand data for GAP, HWD, SAM plot within Zones 6 and 7 indicating presence of clean sands to silty sands. The source sand data at FD fall mostly within Zones 7 and 8 and thus indicates gravelly sands to very stiff sands. FHS site has a wide range of soils from clayey silts to silty sands since it plots within Zones 4, 5 and 6. The closed square symbols falling into Zone 5 for Hollywood and Sampit represent depths at 14 ft (4.3 m) and 22 ft (6.7 m) respectively and both lie on the boundary of the source sand layer and can be neglected for this analyses. The source sand data at SAM, GAP, HWD and FD sites are potentially liquefiable according to Robertson and Wride's (1998) liquefaction criteria F<1% (See section 2.3.2). However, there is an anomaly at the FHS site and may not be considered susceptible to liquefaction since it contains considerable amount of fines.

3.5.2 Consideration of Relative Density Measurements

The maximum, minimum and average relative densities for the source sands as summarized in Table 3.4 are calculated using Equation 2.10 suggested by Kulhawy and Mayne (1990). The relative densities obtained from the CPT data for source sands is found to be in the range 9-39% for SAM, 27-65% for GAP, 3-32% for HWD and 2-17% for FHS, 17-41% for FD-SCPT-1 and 40-90% for FD-SCPT-2.



Zone	Soil Behavior Type	Zone	Soil Behavior Type
1.	Sensitive, fine grained;	6.	Sands: clean sands to silty sands
2.	Organic soils, peats	7.	Gravelly sand to sand;
3.	Clays: clay to silty clay;	8.	Very stiff sand to clayey sand;
4.	Silt mixtures: clayey silt to silty clay;	9.	Very stiff fine grained
5.	Sand mixtures: silty sand to sandy silt;		

Figure 3.31 Soil behavior type classification chart after Robertson (1990) with Source Sand data at all sites.

The results of DMT soil behavior classification summarized in Table 3.2 are related to Table 3.3 to predict the range of relative densities for all source sands. According to Table 3.4, the source sands at all sites show higher relative densities using DMT data in comparison to the CPT. As per Table 3.3, the CPT test results indicate that Sampit, Hollywood and Four Hole Swamp consists of very loose to loose soil deposits. However, the DMT test results show that the source sands consist of medium to dense soil deposits. For Gapway and Fort Dorchester site, CPT test results show that the source sands have medium and medium to dense soil deposits respectively while the corresponding DMT results indicate presence of medium to dense and dense to very dense soil deposits. Hence, there is a clear discrepancy between the relative densities obtained from both these methods.

Furthermore, as shown in Table 3.4, the relative density obtained from laboratory tests (ASTM D 4254) performed on high quality samples collected at SAM, HWD and FHS sites (Hasek, 2014). As shown in Table 3.2, the relative densities obtained for the source sands is found to be in the range 40 to 75% for SAM, 16 to 61% for HWD and 24 to 52% for FHS. The average relative densities calculated for the source sands at SAM, HWD and FHS are 63, 46 and 41 respectively. Therefore, based on physical measurements, it is indicated from Table 3.3 that the source sands have presence of loose to medium density sands. Note that the source sands were previously classified as medium dense to high density sands as shown in Table 3.2 and 3.3.

Table 3.3 Qualitative Description of Granular Soil Deposits (Das, 1990)

Relative Density D_r (%)	Description of soil deposit
0-15	Very loose
15-50	Loose
50-70	Medium
70-85	Dense
85-100	Very dense

Table 3.4 Summary of Relative Densities, D_r (calculated in %) for Source Sands

Site		CPT			DMT	Laboratory Measurements		
		Min	Avg	Max		Min	Avg	Max
Sampit		9	27	39	50-85	40	63	75
Gapway		27	48	65	50-70	-	-	-
Hollywood		3	20	32	50-70	16	46	61
Four Hole Swamp		2	6	17	15-85	24	41	52
Fort Dorchester	FD-SCPT-1	17	30	41	85-100	-	-	-
	FD-SCPT-2	40	70	90	85-100	-	-	-

[1] D_r obtained from CPT data using Kulhawy and Mayne (1990) relation.
[2] D_r obtained from DMT data using Table 3.2 and 3.3

3.5.3 Soil Behavior from DMT

Based on the discrepancy between the relative densities calculated from the CPT data, the DMT data and the physical measurements, a new DMT soil behavior chart is proposed and shown in Figure 3.32. The figure contains the DMT data for the source sand layers at SAM, GAP, HWD, FHS and FD sites and the chart is modified by shifting the degree of density (e.g. Loose in place of Low density, Low in place of Medium density, etc…) using the laboratory measurements of relative density. Note that the modified DMT chart is now in good agreement with the CPT Soil Behavior Chart.

Based on the modified DMT Soil Behavior Chart shown in Figure 3.32, the source sand layer for SAM consists of low density to medium density sandy silt. For GAP, it appears to have low density silts to silty sands. The source sand layer at HWD is a low density to medium density silty sand. This layer at FHS represents a wide range of soils from soft silty clays to loose sandy silts to medium density silty sands. Source sand layer at FD is composed of dense silty sands. As previously discussed in Chapter 2, the water table at the FD site was predicted to be closer to the ground surface during Paleoliquefaction events. According to the current prediction of the water table at FD, it is evident that the soil layers above the water table have densified over the years. Hence, the source sand layer for both the test locations at FD plots in the dense region.

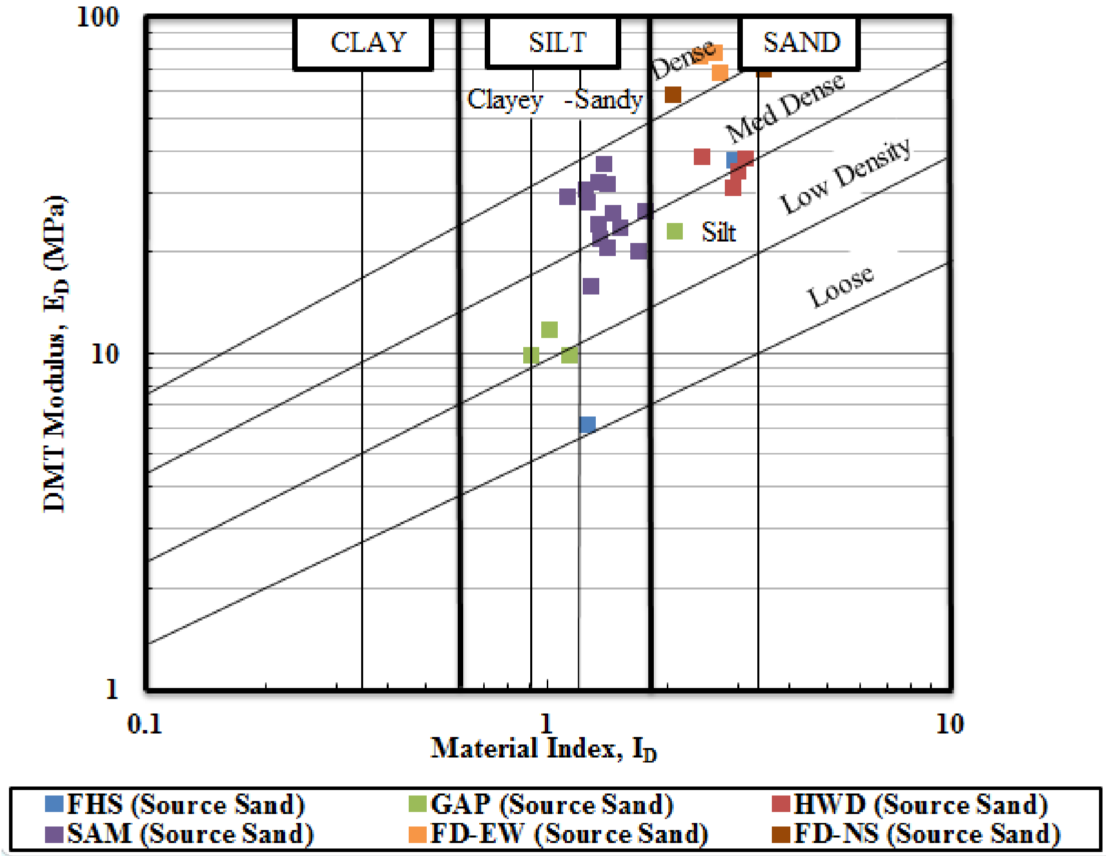
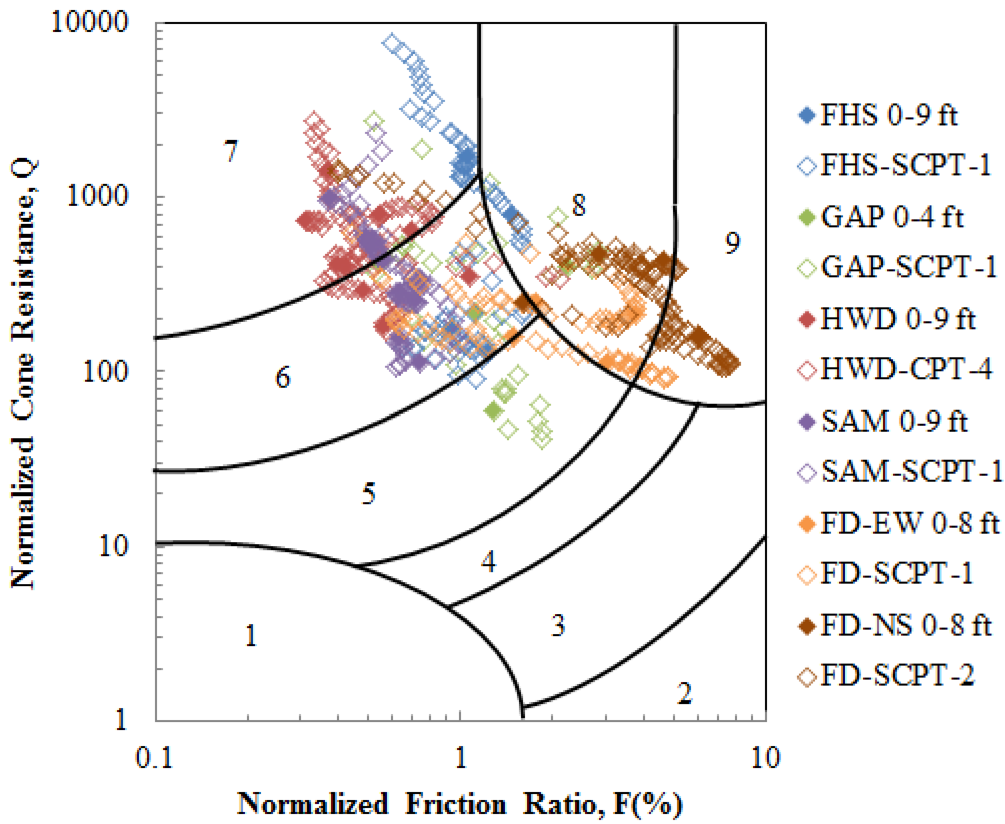


Figure 3.32 DMT modulus and material index chart (ASTM D 6635) with Source Sand data at all sites.

3.6 Overburden Layer

The soil layers above the source sand layer are plotted on the CPT soil behavior chart for all test locations closest to the DMT for all the sites as presented in Figure 3.33.

It is indicated from the figure that the overburden soil for SAM, GAP, HWD and FHS mostly fall within Zones 6 and 7 and has presence of clean sands to silty sands to gravelly sands. If the source sand layer liquefies during a future earthquake, sandblows would form since the ejection of liquefied sand will occur onto the surface easily due to the freely draining sands present in the overburden layer.



Zone	Soil Behavior Type	Zone	Soil Behavior Type
1.	Sensitive, fine grained;	6.	Sands: clean sands to silty sands
2.	Organic soils, peats	7.	Gravelly sand to sand;
3.	Clays: clay to silty clay;	8.	Very stiff sand to clayey sand;
4.	Silt mixtures: clayey silt to silty clay;	9.	Very stiff fine grained
5.	Sand mixtures: silty sand to sandy silt;		

Figure 3.33 Soil behavior type classification chart after Robertson (1990) with Overburden Layer data at all sites.

As shown in Figure 3.33, the overburden layer at FD site lies within Zones 8 and 9. Note that the water table depth at FD site is currently found at 17 ft (5.2 m) and hence the source sand is not susceptible to liquefaction due to its unsaturated state. According to the topography at this site, it is unlikely that the water table would rise above the source sand layer. If the water table rises, it would require a large magnitude earthquake and high peak ground acceleration for the liquefied sand to break through the thick overlying dense clayey sand and stiff fine grained layer.

3.7 Summary

This chapter included a summary of the DMT and CPT methodologies used to identify the soil behavior type of soils at five sites in the SCCP. A summary of q_s, f_s, u_0, u_2, I_c, I_D, K_D and E_D profiles with depth were presented to show how these parameters vary with depth and illustrate the soil stratigraphy for each of the sites. As shown in Table 3.2, in general, the soil behavior type found from both the CPT Soil Behavior chart of Robertson (1990) and the DMT Soil Identification Chart (ASTM D6635) were in good agreement with the USCS Soil classification provided by Williamson (2013). However, several discrepancies including soil behavior type for soils above the groundwater table and relative densities between CPT and DMT test results were also observed.

The source sands for all the sites provided higher relative densities using DMT data when compared to relative densities obtained from CPT test results. The DMT based soil behavior chart for source sands was modified based on physical measurements of relative densities obtained from laboratory tests. This modified chart was observed to be in good agreement with the soil classification presented in the CPT Soil Behavior chart for source sands.

Of interest to the study of liquefaction susceptibility it is important to note that the data from the source sand layers at the SAM, GAP, HWD and FD sites plotted within Zones 5 and 6 on the CPT Soil Behavior Charts which indicated clean sands to silty sands to sandy silts which are potentially liquefiable soils. The source sand layer at FHS data, however, plotted within Zones 4, 5 and 6 indicating the presence of a large amount of fines which are non-susceptible to liquefaction. Since, the overburden soil layer at SAM, GAP, HWD and FHS consists of mostly free draining clean sands to gravelly sands, formation of sandblows would be a common phenomenon in future seismic events. However, such a phenomenon would be less likely possible at the FD site due to the densification and unsaturated state of the source sand layer. Further analyses on the liquefaction susceptibility of the source sand layers will be presented in Chapter 5.

CHAPTER 4

SITE SPECIFIC CORRELATIONS

4.1 Introduction

In this chapter, DMT, SPT and CPT tests that were conducted in close proximity to each other provide in situ data which have been used to classify soils and identify possible correlations between normalized in situ test parameters specific to SCCP. The CPT and DMT data specific to SCCP is used to compare with previously published correlations provided for coarse grained and fine grained soils. New SPT-DMT correlations specific to SCCP are also developed from existing published correlations presented for a wide range of soils. In this study, the data from CPT and DMT test performed in close proximity to each other is used to develop site specific relations between K_D and Q and E_D and Q for the 5 sites in the SCCP.

4.2 DMT and CPT Correlation

4.2.1 K_D-Q Relation

The values of K_D and Q are calculated for each site using equation 2.4 and 2.6 respectively (See section 2.3.1 and 2.3.2). Certain values have been neglected due to insufficient data at the DMT site. Relations between log K_D versus log Q were developed based on the Q-K_D chart recommended by Robertson (2009). This chart is generally used to characterize fine grained soils for $I_C > 2.6$ and $I_D < 1.0$ and can also be used to screen out soil layers that are too clay rich to liquefy. A best overall fit is drawn over the range of values to compare the data with published average values derived from Equations 2.21, 2.22, 2.25 and 2.26 (See Section 2.3.5.1). Equations 2.21 and 2.22 were derived by Robertson (2009) from previous studies for fine grained soils by Marchetti (1980) and Kulhawy and Maine (1990); and Marchetti (1980) and Wroth (1984) and Ladd(1991) respectively. Schneider et al. (2008) provided correlations for insensitive or soft clays and insensitive clays given by Equation 2.25 and 2.26 respectively. Equations 2.21, 2.22 and 2.25 gave similar K_D and Q values and hence can be used to represent soft clays while the upper bound correlation 2.26 is used to represent insensitive clays for $Q<10$.

The K_D and Q values for SAM-DMT and SAM-SCPT-1 respectively are plotted in the Q-K_D chart recommended by Robertson (2009) as shown in Figure 3.23. The values plotted on the chart based on $I_c>2.6$ represent the soil layer which extends from 22 to 31 ft (6.7 m to 9.4 m). This layer is located beneath the source sand layer. The trend line included in Figure 4.1 appears to be similar to the linear trends from the relationships represented by Equations 2.21, 2.22 and 2.25. According to the chart, this layer shows presence of very soft clays.

The Q-K_D values from GAP-DMT and GAP-SCPT-1 for the soil layer located at a depth of 7 ft to a depth of 15 ft are shown in Figure 4.2. The trend line drawn in Figure 3.24 is closer to the upper bound correlations from Equation 2.26 and 2.22. Hence, the soil layer has a mixture of sensitive and insensitive clays. It is predicted that this layer generates higher excess pore pressures around the DMT probe (See Section 2.3.5.1).

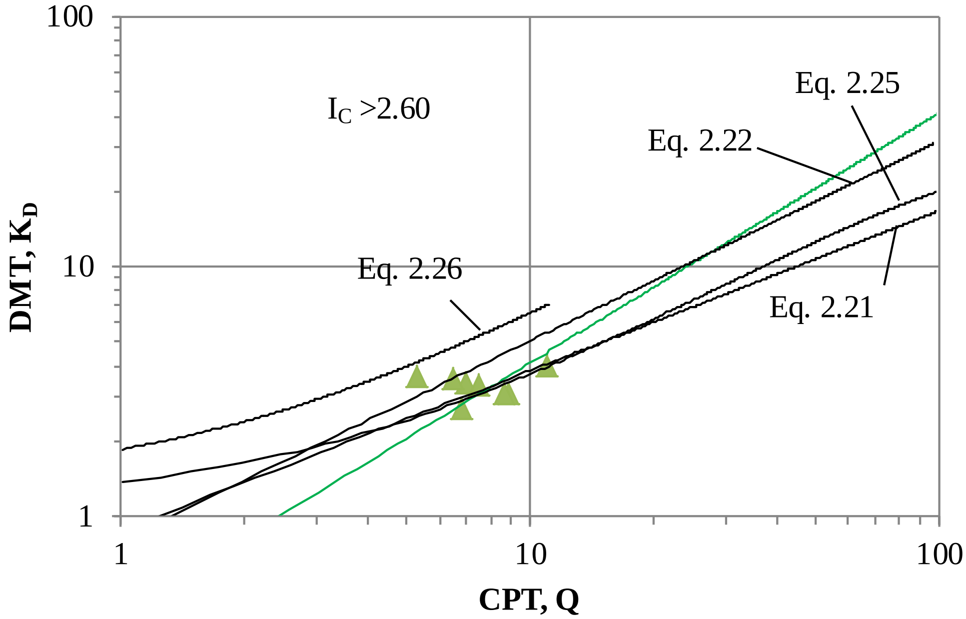


Figure 4.1 Correlations between K_D and Q in fine grained soils where I_c >2.6 and I_D<1using data from Sampit Site.

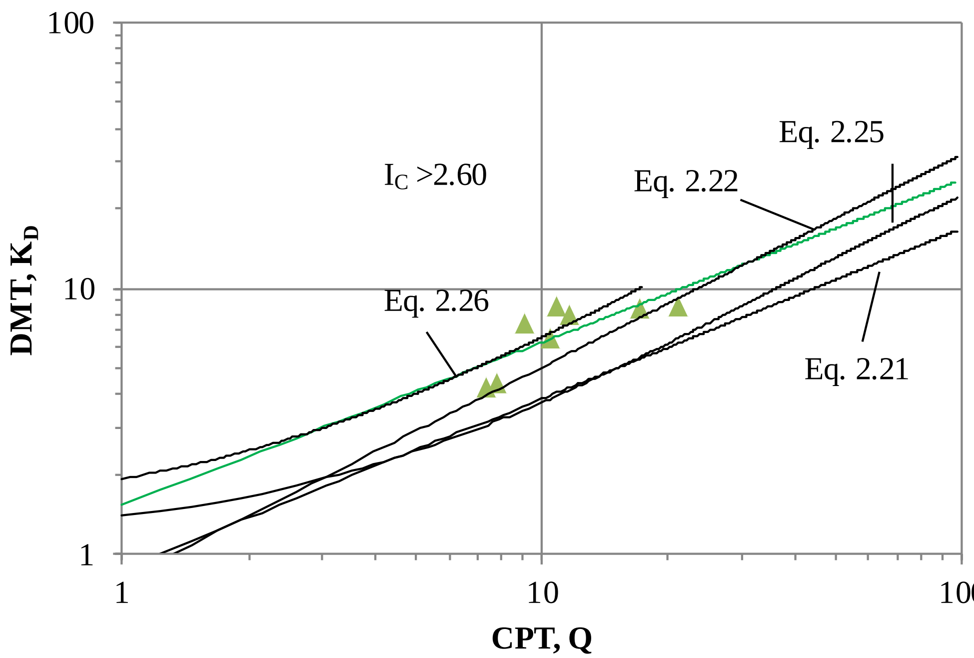


Figure 4.2 Correlations between K_D and Q in fine grained soils where I_c >2.6 and I_D<1using data from Gapway Site.

For HWD-DMT and HWD-CPT-4, only one data point at a depth of 19 ft (5.8 m) is used to represent the soil layer which extends from 14 ft (4.3 m) down to a depth of 20 ft (6.1 m). As shown in Figure 4.3, the data point plots below the existing regression lines and is considered as an outlier. Thus, it can be predicted that this site mostly consist of coarse grained soils where $I_c \leq 2.6$ and $I_D>1$ (See Figure 3.17 and 3.23 in Sections 3.2.6 and 3.3.3 respectively).

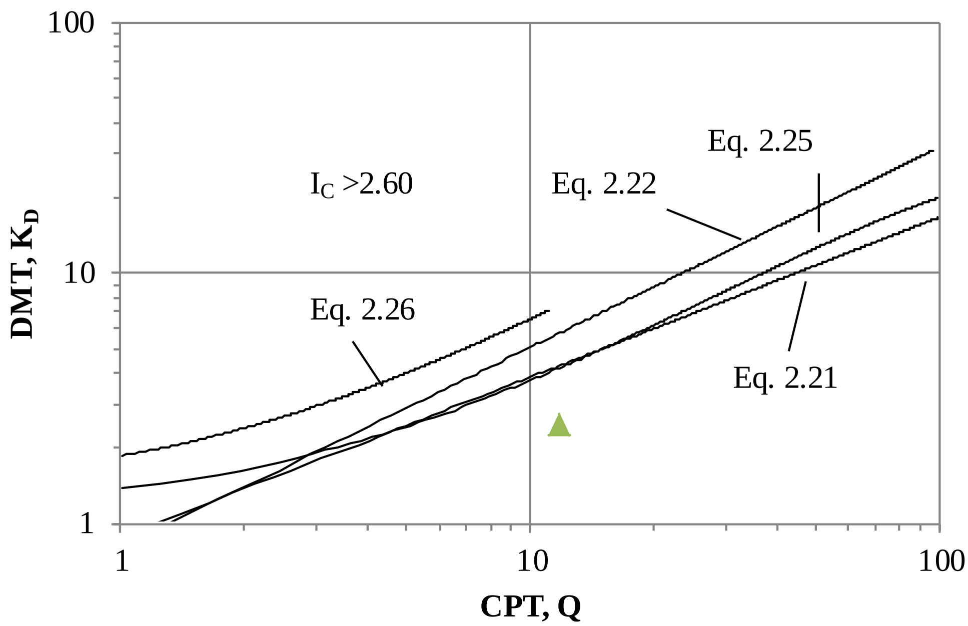


Figure 4.3 Correlations between K_D and Q in fine grained soils where I_c >2.6 and I_D<1 using data from Hollywood Site.

The K_D and Q values are calculated for FHS-DMT and FHS-SCPT-1 and are shown in Figure 4.4. According to K_D-Q chart, the data plots within the source sand layer which is located at approximately 9 ft (2.7 m) to a depth of 15 ft (4.6 m) deep. The regression line included in the Figure 4.4 plots well below the lower bound trend represented by equation 2.21. Hence, these two data points shown in Figure 3.26 are considered as outliers. It is noted that only two data points meet the criteria for fine grained soils (I_c>2.6 and I_D<1) but these fall within the source sand layer (See Figures 3.17 and 3.25). Therefore, future study is needed to understand this contradictory behavior at Four Hole Swamp. At the Fort Dorchester site, all I_c values are less than 2.6 and I_D values are greater than 1 (See Figure 3.18, 3.27, 3.28), hence, the Q-K_D chart for fine grained soils by Robertson (2009) was not applicable for this site.

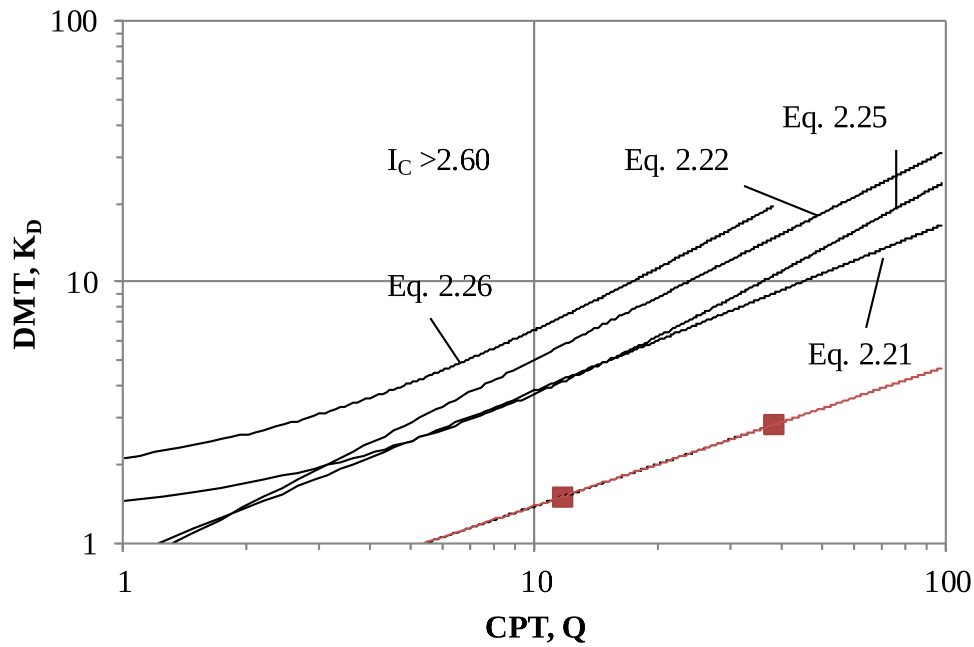


Figure 4.4 Correlations between K_D and Q in fine grained soils where I_c >2.6 and I_D<1 using data from Four Hole Swamp Site.

4.2.2 Q - E_D / σ'_{vo} Relation

Robertson (2009) suggested a log Q versus log E_D / σ_{v0} versus chart to represent normally consolidated soils for adjacent DMT and CPT tests conducted on site. The chart is used to characterize a wide range of soils that range from free draining course-grained soils to undrained fine grained soils. E_D / σ_{v0} and Q values are calculated for each of the sites and are plotted on the E_D / σ_{v0} -Q chart recommended by Robertson (2009). A best fit trend line was drawn for each of the soil layers for each site with the purpose of comparing the data with average published values from Equation 2.29 and 2.30 (See section 2.3.5.1).

The Q - E_D / σ'_{vo} chart proposed by Robertson (2009) is used in this study to determine the correlation for each soil layer and compare them to previously published data. The trend line drawn for each of the soil layers at each site is compared to the overall best fit for a wide range of soils represented by Equation 2.29 (Maine and Liao (2004)). The chart indicated that α lies within the range from 2 to 10 (See Section 2.3.5.1). The correlations from the plot were compared to α value from Equation 2.30 provided by Robertson (2009).

At the Sampit site, the trend lines drawn for each soil layer are compared to the existing correlation. As shown in Figure 4.5, it is seen that the bottom layer which is located between 31 and 35 ft (9.4 and 10.7 m) gives α value equal to 1.9 which does not fall within the specified range. The topmost layer which lies between 0 and 9 ft (0 and 2.7 m(gives α value of 5.5 which is nearest to the existing correlation (where α = 5) and hence the layer may vary from free draining coarse grained soils to undrained fine grained soils.

The trend lines for each of the soil layers at Gapway are shown in Figure 4.6. It is observed that α value for the topmost layer which extends from 0 to 3 ft (0 to 0.9 m) does not fall within the specified range. The source sand data plots closer to the existing regression line but has α value of 2.5 which tends to be very close to lower limit of the specified range.

The trend lines drawn for each of the soil layers at Hollywood nearly merges with the existing regression line. In Figure 4.7, it is indicated that α value for all the soil layers fall within the given range. The layer from 14 to 20 ft (4.3 to 6.1 m) gives α value equal to 5.4 and can be considered to represent a wide range of soils.

The regression line drawn for each of the soil layers at Four Hole Swamp is shown in Figure 4.8. The source sand layer is located between 9 ft and 15 ft (2.7 and 4.6 m) and gives α value equal to 11.6 which does not fall within specified limits. The top 9 ft (2.7 m) layer gives α value equal to 4.5 and can be considered as a reasonable average for a wide range of soils.

Figures 4.9 and 4.10 present the trend line drawn for each of the soil layers at the Fort Dorchester Site. According to the data in FD-SCPT-1 it is observed from Figure 4.9 that the α value for all the soil layer which extends from the ground surface to 12 ft (3.7 m) does not fall within the specified range. However, it is evident from the data in FD-SCPT-2 as shown in Figure 4.10 that α value for the entire soil layer falls within the specified range. The correlation is not well established due to insufficient data points at this site.

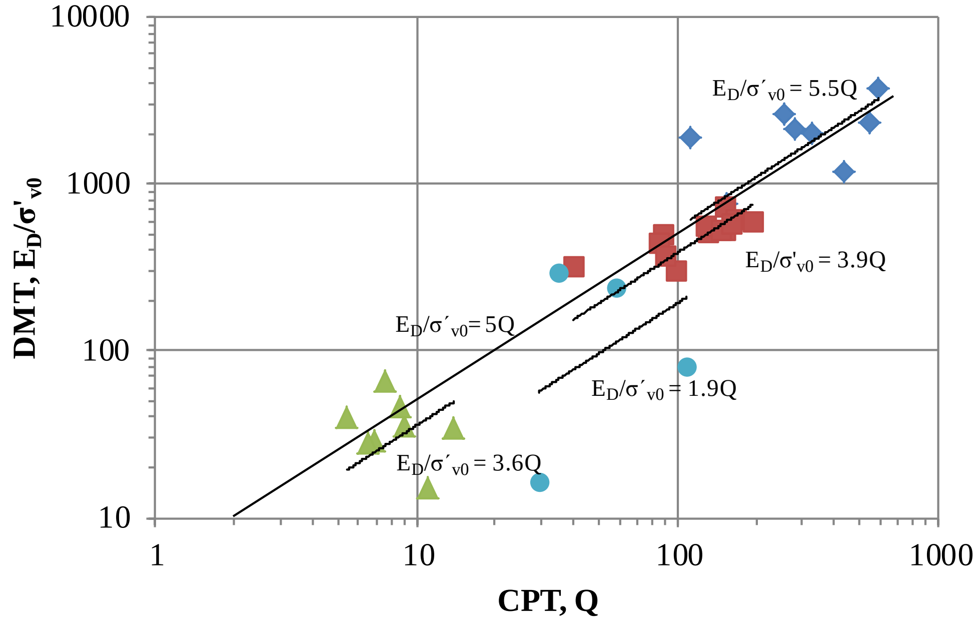


Figure 4.5 Correlations between E_D/σ'_{v0} and Q for all soil types using data from Sampit Site.

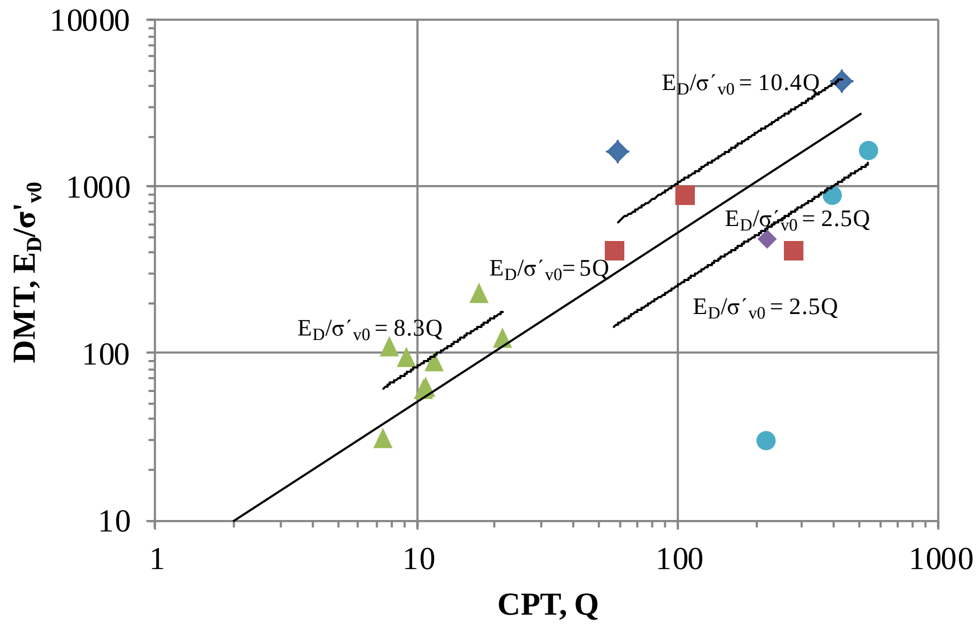


Figure 4.6 Correlations between E_D/σ'_{v0} and Q for all soil types using data from Gapway Site.

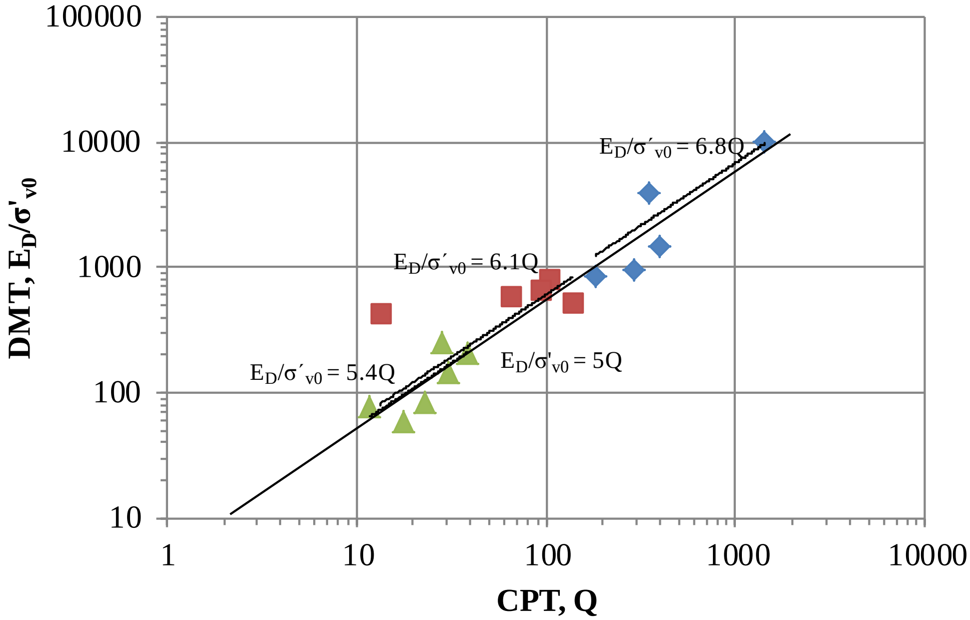


Figure 4.7 Correlations between E_D/σ'_{v0} and Q for all soil types using data from Hollywood Site.

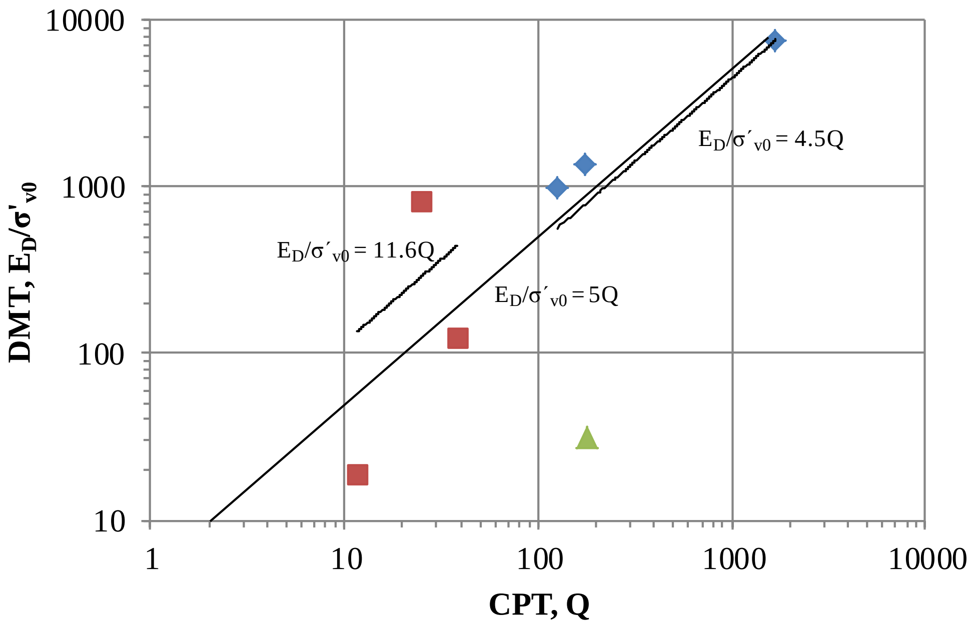


Figure 4.8 Correlations between E_D/σ'_{v0} and Q for all soil types using data from Four Hole Swamp Site.

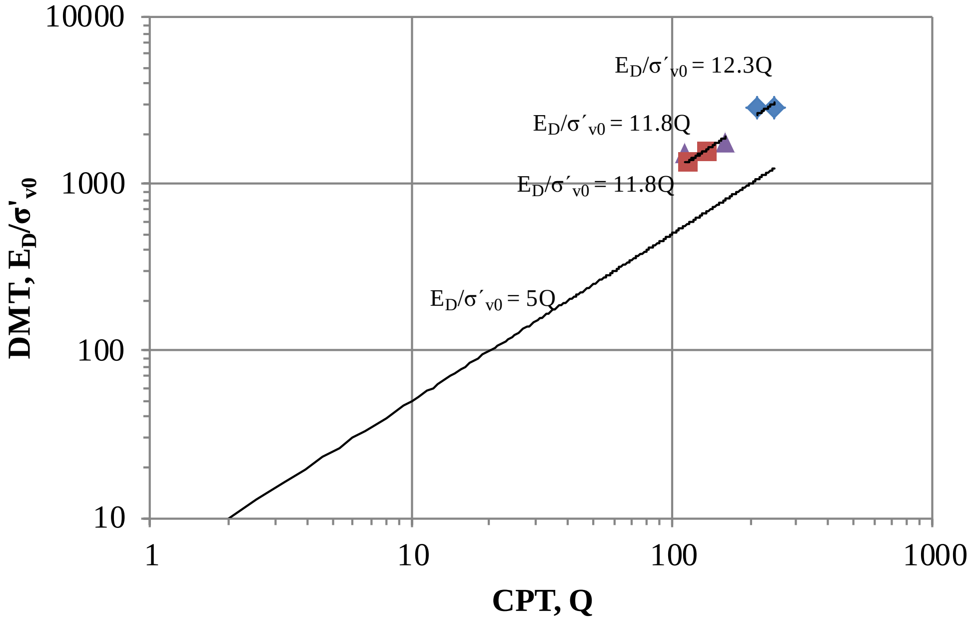


Figure 4.9 Correlations between E_D/σ'_{v0} and Q for all soil types using DMT data from Fort Dorchester Site oriented in E-W direction.

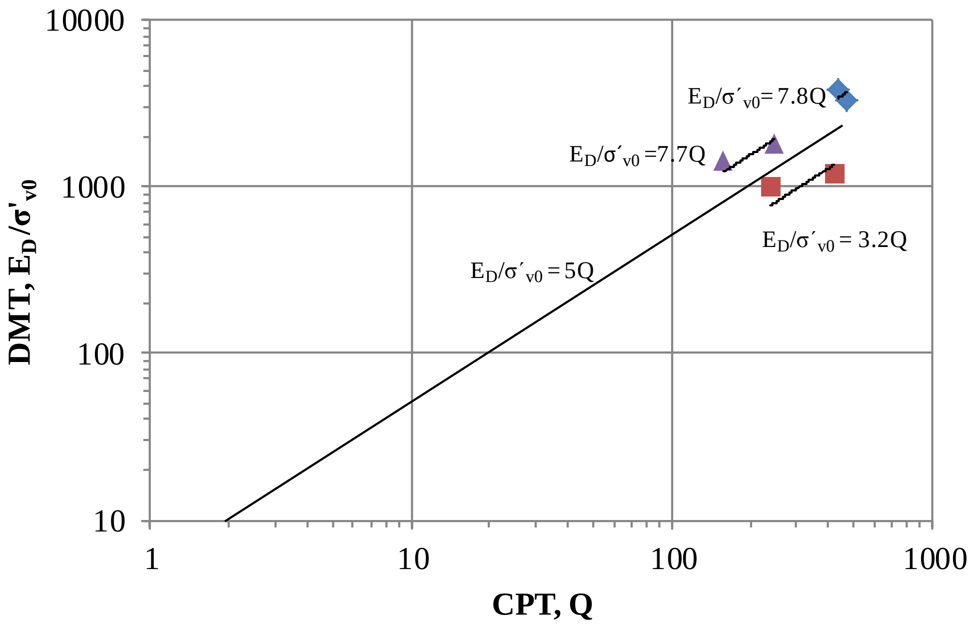


Figure 4.10 Correlations between E_D/σ'_{v0} and Q for all soil types using DMT data from Fort Dorchester Site oriented in NS direction.

Table 4.1 Summary of α values for each site

Site	Test Location	Depth	α from E_D-Q Relation
Sampit	SAM-SCPT-1, SAM-DMT	0-9ft	5.5
Sampit	SAM-SCPT-1, SAM-DMT	9ft-22ft (Source Sand)	3.9
Sampit	SAM-SCPT-1, SAM-DMT	22ft-31ft	3.6
Sampit	SAM-SCPT-1, SAM-DMT	31ft-35ft	1.9
Gapway	GAP-SCPT-1, GAP-DMT	0-3ft	10.4
Gapway	GAP-SCPT-1, GAP-DMT	3ft-4ft	NA
Gapway	GAP-SCPT-1, GAP-DMT	4ft-7ft (Source Sand)	2.5
Gapway	GAP-SCPT-1, GAP-DMT	7ft-15ft	8.3
Gapway	GAP-SCPT-1, GAP-DMT	15ft-18ft	2.5
Hollywood	HWD-CPT-4, HWD-DMT	0-9ft	6.8
Hollywood	HWD-CPT-4, HWD-DMT	9ft-14ft (Source Sand)	6.1
Hollywood	HWD-CPT-4, HWD-DMT	14ft-20ft	5.4
Four Hole Swamp	FHS-SCPT-1, FHS-DMT	0-9ft	4.5
Four Hole Swamp	FHS-SCPT-1, FHS-DMT	9ft-15ft (Source Sand)	11.5
Four Hole Swamp	FHS-SCPT-1, FHS-DMT	15ft-22ft	NA
Fort Dorchester	FD-SCPT-1, FD-DMT-EW	0-5 ft	12.3
Fort Dorchester	FD-SCPT-1, FD-DMT-EW	5ft-8ft	11.8
Fort Dorchester	FD-SCPT-1, FD-DMT-EW	8ft-12ft (Source Sand)	11.8
Fort Dorchester	FD-SCPT-2, FD-DMT-NS	0-5ft	7.8
Fort Dorchester	FD-SCPT-2, FD-DMT-NS	5ft-8ft	7.7
Fort Dorchester	FD-SCPT-2, FD-DMT-NS	8ft-12ft (Source Sand)	3.2

Table 4.2 Site Specific K_D-Q correlations

Site	Layer	K_D-Q relations
Sampit	22-31 ft (6.7-9.4 m)	$K_D = 0.88\ (Q)^{0.64}$ $K_D = 0.8\ (Q)^{0.80}$ $K_D = 0.3\ (Q)^{0.95} + 1.05$
Gapway	7-15 ft (2.6-4.6 m)	$K_D = 0.8\ (Q)^{0.80}$ $K_D = 0.67\ (Q)^{0.91} + 1.1$
Hollywood	14-20ft (4.3-6.3 m)	NA
Four Hole Swamp	9-15ft (2.7-4.6 m)	$K_D = 0.4Q$
Fort Dorchester	NA	NA

[1]No correlation at Hollywood since only one data point plots below the existing regression lines and is considered to be an outlier

[2] No correlation at Dort Dorchester since ID and IC values are out of range

4.3 DMT and SPT Correlations

In this study, the procedure outlined by Hajduk (2006) (See Section 2.3.5.2) was followed for the SCCP sites to establish new correlations between DMT and SPT test data specific to SCCP soils. First, the N and E_D values were selected according to I_D values showing the three different soil behavior types. Some of the data was neglected due to insufficient N values corresponding to specific depths where DMT data was obtained. Since the SPT N values were corrected for overburden, N_{60}, $(N1)_{60}$ and $(N1)_{60cs}$ values were also plotted with E_D to develop new correlations specific to SCCP soils. This data was then compared to existing N_{60}-E_D relation for all soil types by Hajduk (2006) and N-E_D relation for sands by Tanaka and Tanaka (1990) (See Section 2.3.5.2). The corrected blow count $(N_1)_{60}$ and $(N_1)_{60cs}$ values were assumed to be similar to N_{60} values and hence can be used to compare the data with N_{60} values provided by Hajduk (2006). The analysis is restricted to four sites (Gapway, Sampit, Four Hole Swamp and Hollywood) because SPT tests were not performed at the Fort Dorchester site.

4.3.1 Sampit

The results for SAM-SPTE-1 and SAM-DMT sites include data from the entire soil profile to obtain regression correlations are shown in Figures 4.11 through Figures 4.13. N, N_{60} and $(N_1)_{60}$ are plotted with E_D at depths 28, 29, and 32 ft (8.5, 8.8 and 9.8 m) on the chart based on $I_D < 0.6$ i.e. clays is presented in Figures 3.33 (a), (b) and (c) respectively. It is observed from (a) and (b) subfigures that the new correlations in general are in good agreement with the existing relationship recommended by Hajduk (2006) (see Equation 2.36). However, the new correlation obtained from (c) subfigure is relatively weak as the trend line plots above the existing N_{60}-E_D regression line. From the new correlations for clays presented in this work, the ratio of E_D/N is equal to 1.14 which is higher than 1.08. However, the ratios of E_D/N_{60} equal to 0.98 and E_D / $(N_1)_{60}$ equal to 0.68 are lower than 1.08.

For silts, uncorrected and corrected N values are plotted with E_D for depths 2 to 21 ft (0.6 to 6.4 m) and at 33 ft (10.1 m) and are denoted by diamond symbols in Figure 4.12. The data plots reasonably well along the regression line provided by Hajduk (2006). The source sand layer falls within this zone and is denoted by square symbols. The R^2 values of 0.43 and 0.45 obtained from N-E_D and N_{60}-E_D plot respectively is lower than that of Hajduk (2006). However, $(N_1)_{60}$-E_D correlation exhibits a greater R^2 value equal to 0.70 and is considered to associate well with existing correlation (See Equation 2.37). Two data points at a depth of 4 ft (1.2 m) and 8 ft (2.4 m) were considered as outliers and were excluded from the analysis. The excluded point at 4 ft (1.2 m) had a lower E_D value with relatively higher blow counts and vice versa for the point at a depth of 8 ft (2.4 m). This type of soil behavior was not observed in the rest of the data. Including these two points would reduce the R^2 values and therefore is exempt from the regression analysis. The ratios E_D/N and E_D/N_{60} obtained from the new correlations is equal to 4.1 and 3.2 respectively which is higher than 2.65 while $E_D / (N_1)_{60}$ gives a lower value equal to 2.07.

Figure 3.35 presents N values plotted with E_D based on I_D>1.8 for sands. There is only one data point available at a depth of 5 ft shown in Figure 4.13 (a), (b), (c) and (d). Even though the data point plots very close to the regression lines for sands recommended by Tanaka and Tanaka (1999) and Hajduk (2006) (See Equation 2.35 and 2.38), the relationship is very weak and no new correlations can be obtained from it.

4.3.2 Gapway

Hu et al. (2002) presented the $(N_1)_{60}$ values but not the raw N data for GAP-03 in his work (Refer to Williamson (2013)). Therefore, only the $(N_1)_{60}$ data has been used herein. Figure 3.36 (a), (b) and (c) show $(N_1)_{60}$-E_D plots for clays, silts and sands respectively. It can be inferred from subfigure (a) that the data point at 16 ft (4.9 m) has a very high blow count with a very low E_D value and it plots above Hajduk (2006)'s relation. The source sand denoted by square symbols is shown in subfigure (b). The new correlations exhibits a low R^2 value of 0.36 which suggests that the relationship is weak when compared to existing relations proposed by Hajduk (2006). The correlation for sands obtained at depths 2 and 17 ft (0.6 and 5.2 m) shown in subfigure (c) is almost the same as presented by Hajduk (2006). The ratio of E_D/N_{60} obtained for silts is equal to 0.98 which is lower than 2.65. For sands, the new correlation gives the ratio of ED/ N60 equal to 2.4 and is in good agreement with Hajduk (2006)'s E_D/N_{60} value of 2.43 and Tanaka and Tanaka (1999)'s E_D/N value of 2.5.

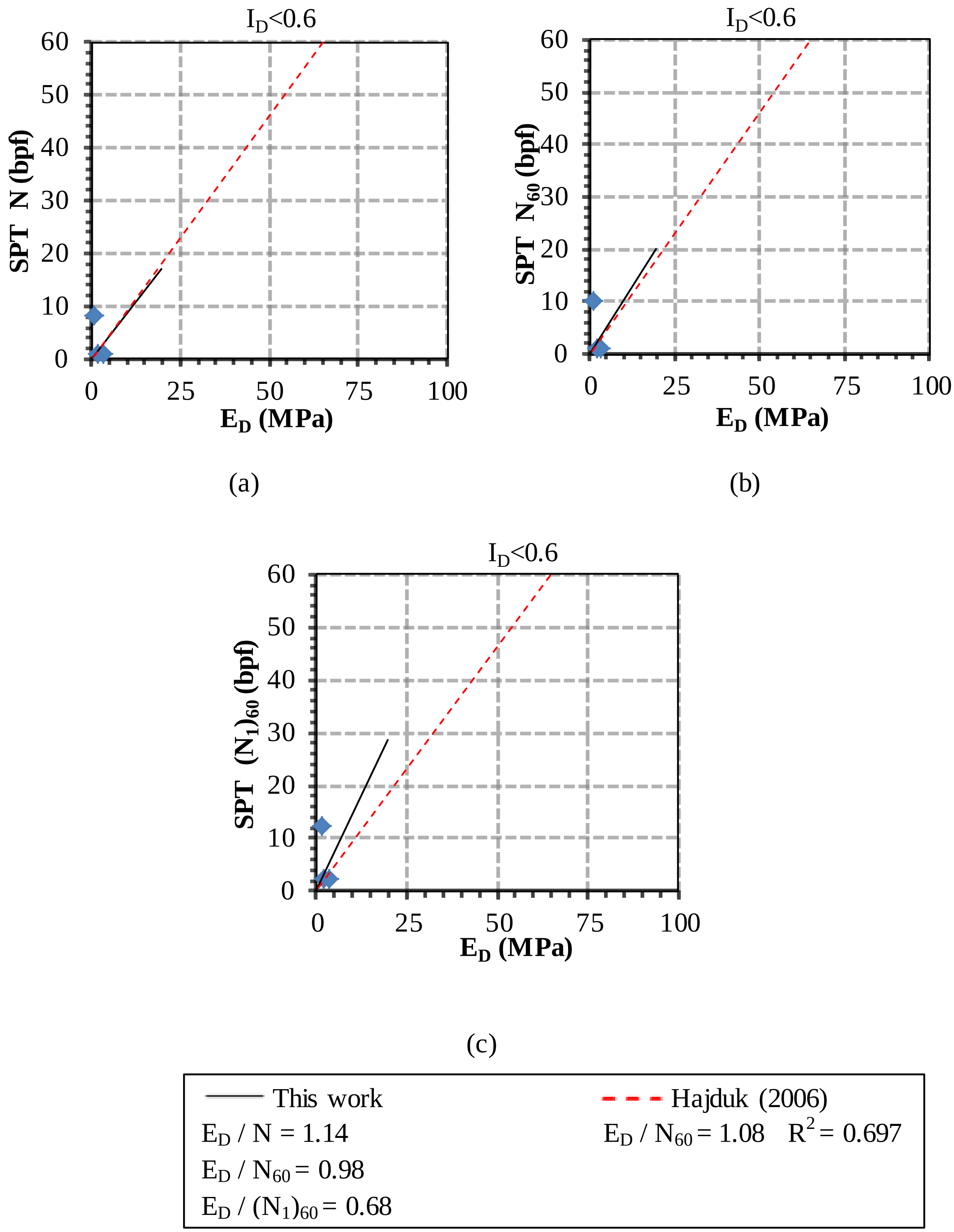


Figure 4.11 SPT-DMT Correlations for Clays at Sampit Site: a) N vs E_D, b) N_{60} vs E_D and c) $(N_1)_{60}$ vs E_D

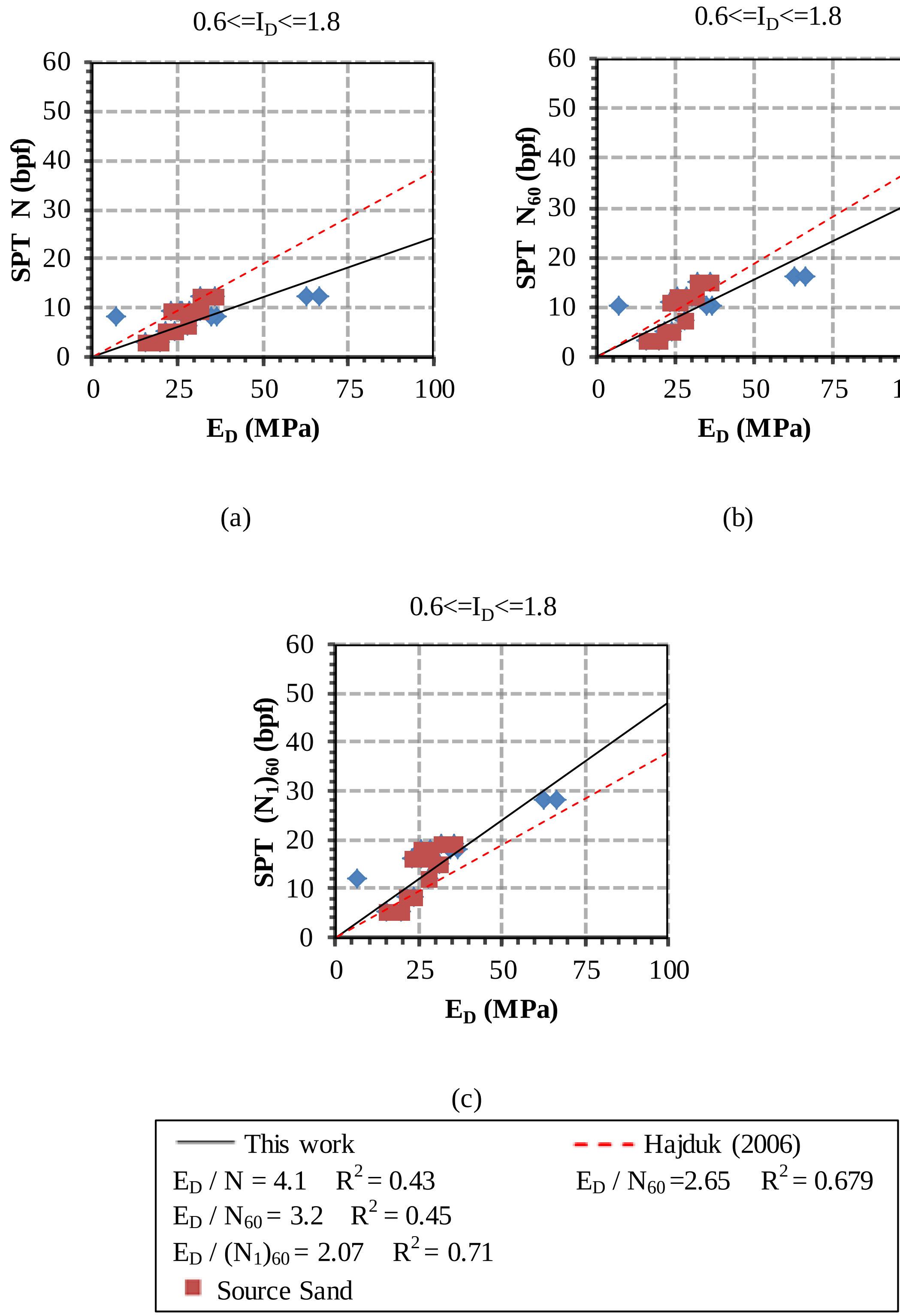


Figure 4.12 SPT-DMT Correlations for Silts at Sampit Site: a) N vs E_D, b) N_{60} vs E_D and c) $(N_1)_{60}$ vs E_D

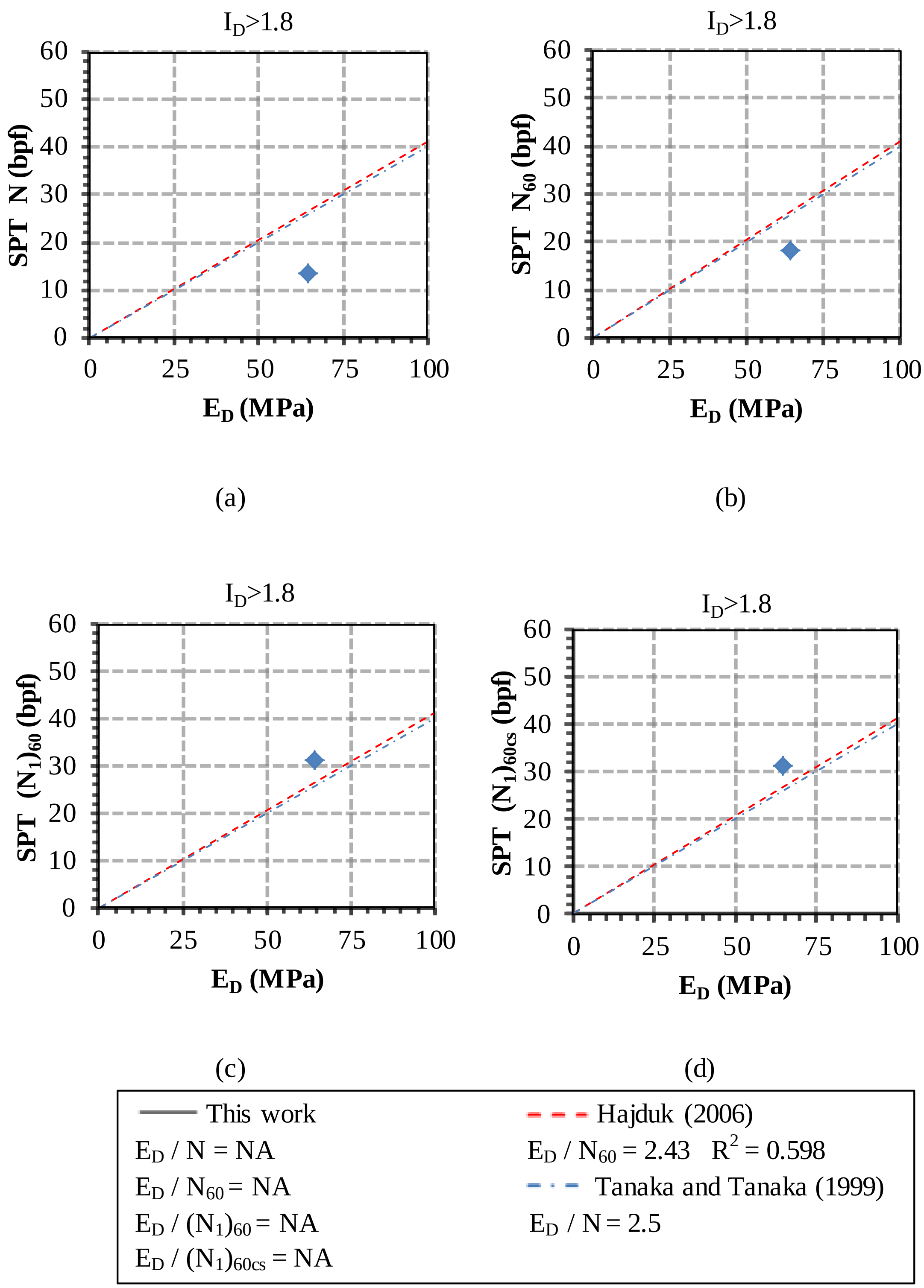
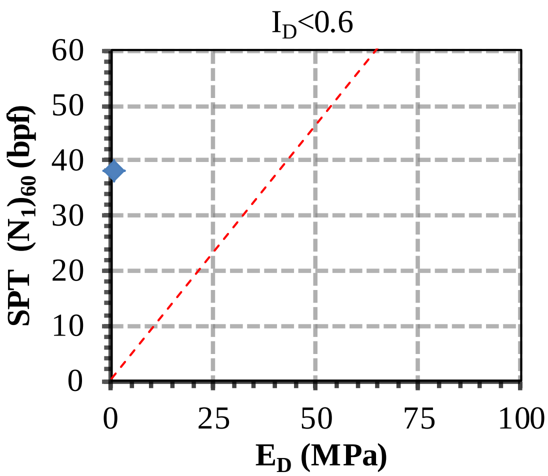
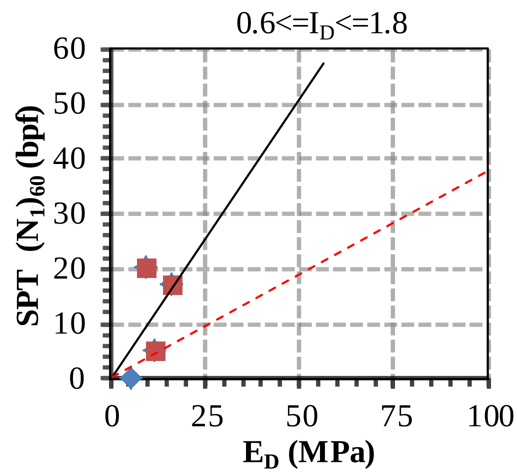


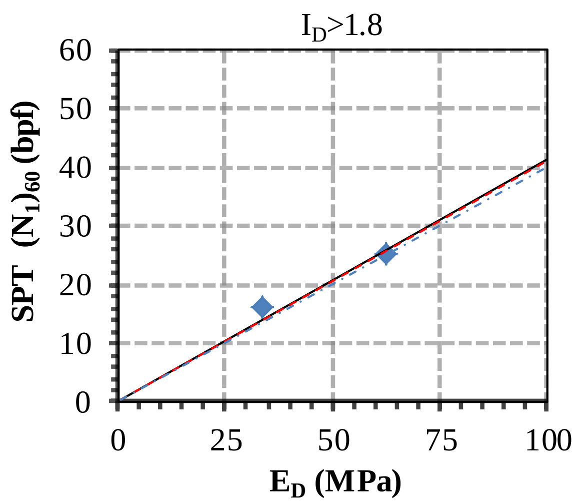
Figure 4.13 SPT-DMT Correlations for Sands at Sampit Site: a) N vs E_D, b) N_{60} vs E_D, c) $(N_1)_{60}$ vs E_D and d) $(N_1)_{60cs}$ vs E_D



(a)



(b)



(c)

This work	Hajduk (2006)
$E_D / (N_1)_{60}$ = NA (Clays)	E_D / N_{60} = 1.08 R^2 = 0.697 (Clays)
$E_D / (N_1)_{60}$ = 0.98(Silts)	E_D / N_{60} = 2.65 R^2 = 0.679 (Silts)
R^2 = 0.36 (Silts)	E_D / N_{60} = 2.43 R^2 = 0.598 (Sands)
$E_D / (N_1)_{60}$ = 2.4 (Sands)	Tanaka and Tanaka (1999)
Source Sand	E_D / N = 2.5 (Sands)

Figure 4.14 SPT-DMT Correlations for All Soils at Gapway Site: a) N vs E_D, b) N_{60} vs E_D and c) $(N_1)_{60}$ vs E_D

4.3.3 Hollywood

Figures 4.15 and 4.16 show SPT-DMT correlations using data obtained from HWD-SPTE-1 and HWD-DMT sites. While selecting E_D and N values based on I_D values for the entire soil layer up to a depth of 20 ft (6.1 m), it was observed that all calculated I_D values were greater than 0.6. Therefore, N, N_{60}, $(N_1)_{60}$ and $(N_1)_{60cs}$ values were plotted versus E_D for only silts and sands and new correlations were found. Subfigures (a), (b) and (c) of Figure 4.15 includes data from 16 ft (4.9 m) through 20 ft (6.1 m) and plots above and below the existing regression line (Hajduk, 2006). $(N_1)_{60}$-E_D plot gives a correlation which is closest to the existing relationship as seen in subfigure (c). E_D/N and E_D/N_{60} ratios determined from new correlations are equal to 3.5 and 2.9 respectively and are higher than 2.65 while the ratio $E_D/(N_1)_{60}$ has a lower value equal to 2.4.

For sands, the corrected N_{60} and $(N_1)_{60}$ values were plotted versus E_D at depths 1 to 2 ft (0.3 to 0.6 m) and 10 to 18 ft (3 to 5.5 m) and $(N_1)_{60cs}$-E_D plot at depths 10 to18 ft (3 to 5.5 m) and are denoted by diamond symbols. The data shown in Figure 4.16 (a), (b), (c) and (d), produces similar trends and plots well below the existing relation. The source sand layer falls within this Zone and is denoted by square symbols. Subfigure (b) and (c) both display a low R^2 value of 0.49 while subfigure (a) and (d) display R^2 values of 0.56 and 0.53 respectively. Even though subfigure (a) has a R^2 value closest to that of Hajduk (2006), it is evident from subfigure (d) that $(N_1)_{60cs}$-E_D plot provides a stronger relationship when compared to the relations derived by Hajduk (2006) and Tanaka and Tanaka (1999). The ratios E_D/N, E_D/N_{60}, $E_D/(N_1)_{60}$, $E_D/(N_1)_{60cs}$ obtained from the new correlations are equal to 6.3, 5.6, 3.8 and 3.5 respectively which are found to be higher than that of Hajduk (2006)'s E_D/N_{60} value of 2.43 and Tanaka and Tanaka (1999)'s E_D/N value of 2.5.

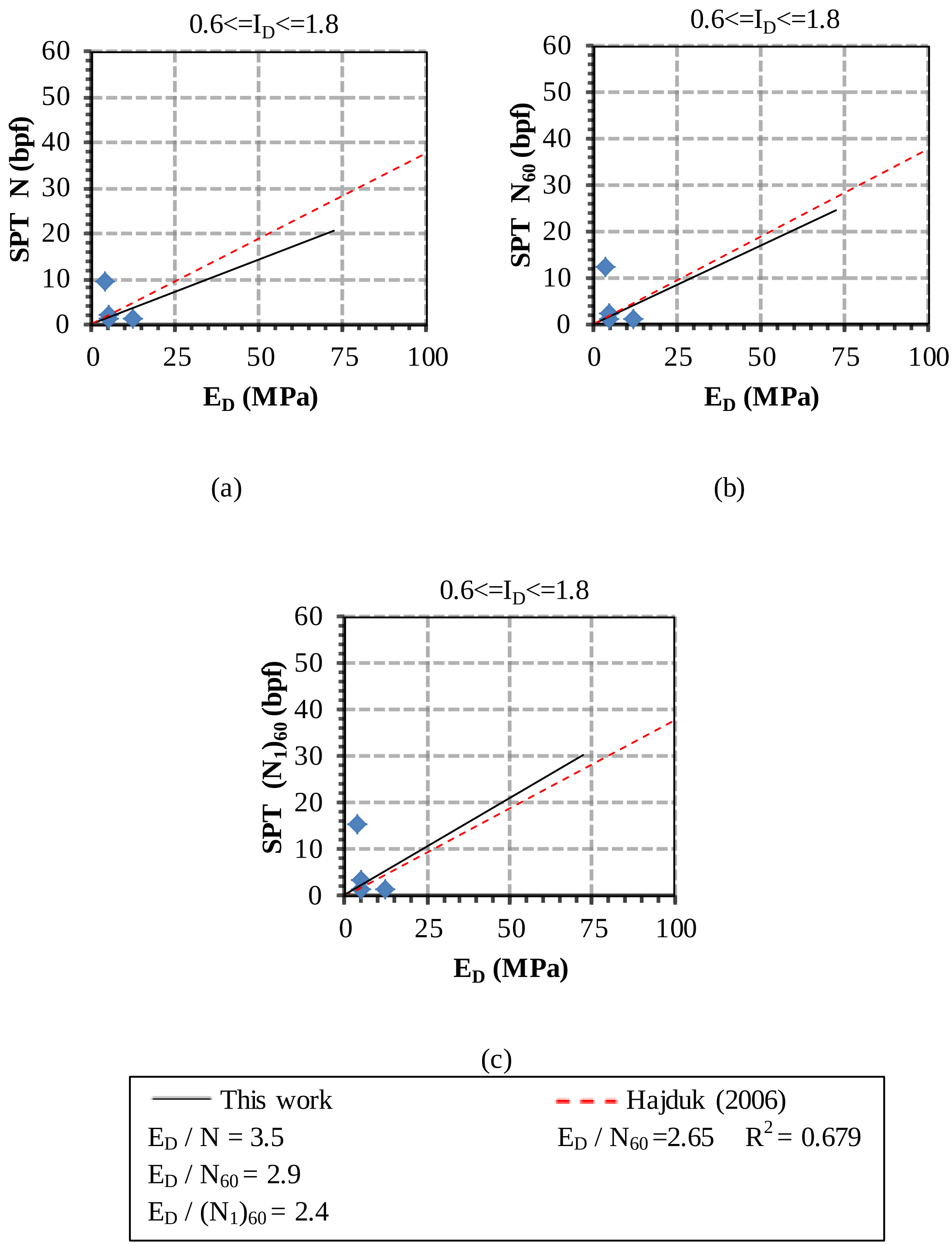


Figure 4.15 SPT-DMT Correlations for Silts at Hollywood Site: a) N vs E_D, b) N_{60} vs E_D and c) $(N_1)_{60}$ vs E_D

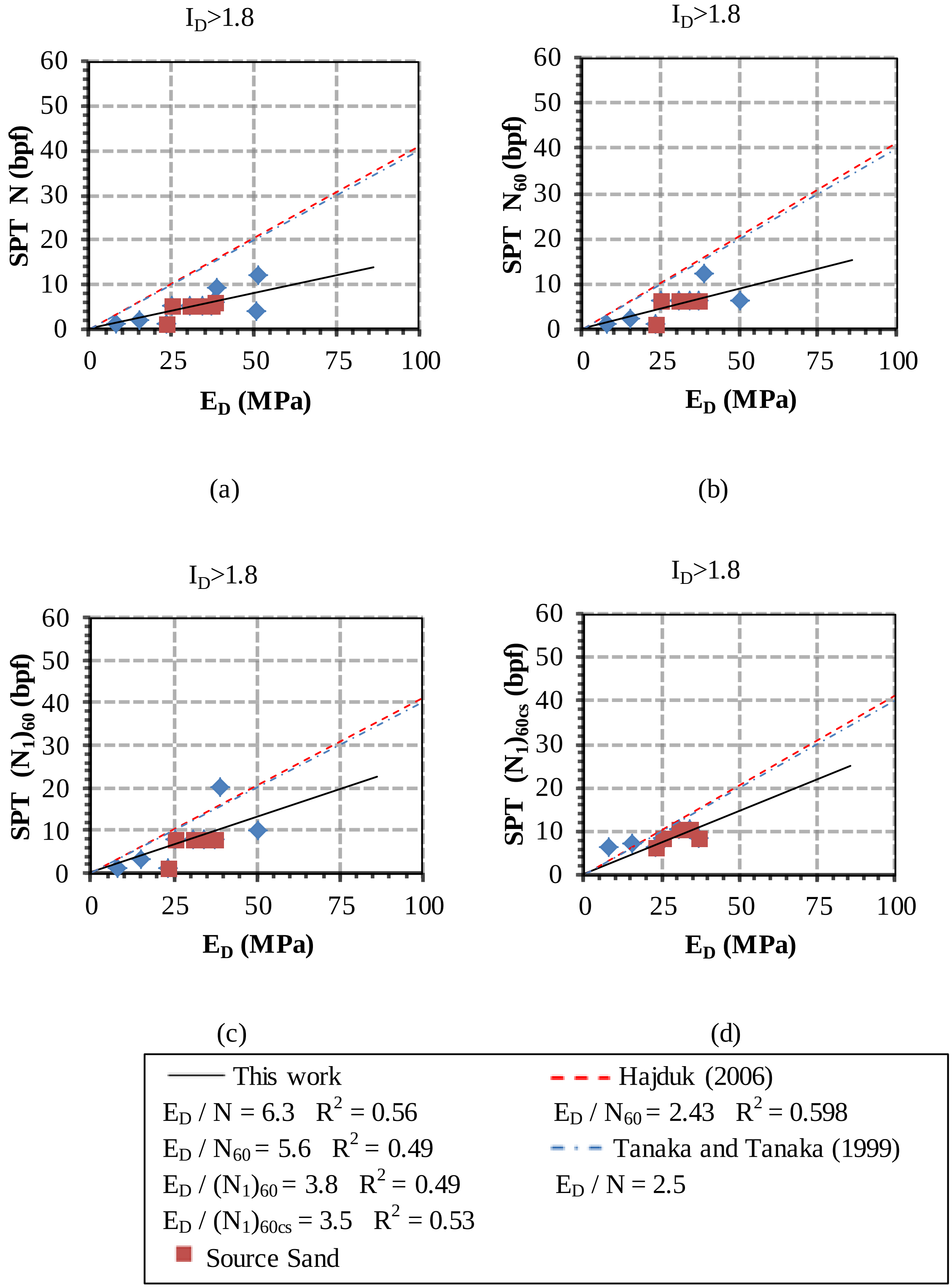


Figure 4.16 SPT-DMT Correlations for Sands at Hollywood Site: a) N vs E_D, b) N_{60} vs E_D, c) $(N_1)_{60}$ vs E_D and d) $(N_1)_{60cs}$ vs E_D

4.3.4 Four Hole Swamp

The results derived from SPT-DMT data for FHS-SPTE-1 and FHS DMT sites are presented in Figures 4.17 through 4.19. For clays, E_D was plotted versus N, N_{60}, $(N_1)_{60}$ and $(N_1)_{60cs}$ at depths 14 ft (4.3 m) and 16 ft (4.9 m). The data plotted in Figures 4.17 (a), (b) and (c) showed that they were in close proximity to the existing regression line. However, since there is only two data points the relationship is weak and no new correlations can be obtained from it.

The SPT-DMT plot shown in Figures 4.18 (a), (b), (c) and (d) based on $0.6<=I_D<=1.8$ included only one data point at a depth of 12 ft (3.7 m). This data point plotted close to the existing regression line for silts. Since, there is one data point available, it was not possible to get new correlations from the data set.

The SPT N value versus E_D was plotted at depths 2, 6, 8 and 10 ft (0.6, 1.8, 2.4 and 3 m) while E_D was plotted with N_{60}, $(N_1)_{60}$ and $(N_1)_{60cs}$ at depths 6, 8 and 10 ft (1.8, 2.4 and 3 m) to obtain new correlations for sands. Hajduk (2006) underestimated the correlations obtained from this data set. The data plotted below the existing regression lines as shown in Figure 4.19 (a), (b), (c) and (d). $(N_1)_{60}$-E_D plot provided an R^2 value of 0.55 which is closest to that of Hajduk (2006). Figures 4.17 through 4.19 suggest that the source sand layer denoted by square symbols consists of a mixture of clays, silts and sands. The ratios E_D/N, E_D/N_{60}, $E_D/(N_1)_{60}$, $E_D/(N_1)_{60cs}$ obtained from the new correlations are equal to 6.9, 9.9, 5.8 and 5.4 respectively which are found to be higher than that of Hajduk (2006)'s E_D/N_{60} value of 2.43 and Tanaka and Tanaka (1999)'s E_D/N value of 2.5.

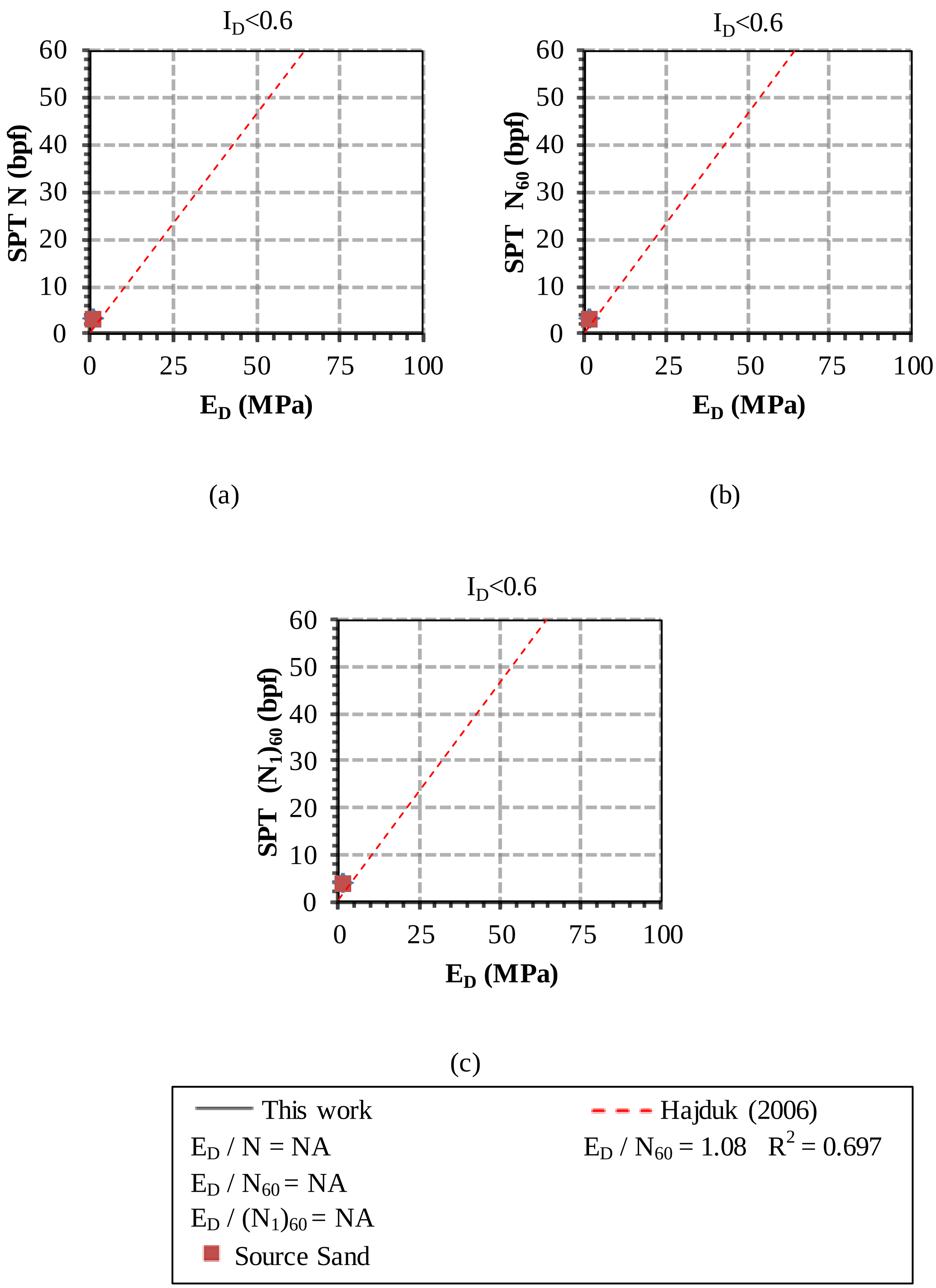


Figure 4.17 SPT-DMT Correlations for Clays at Four Hole Swamp Site: a) N vs E_D, b) N_{60} vs E_D and c) $(N_1)_{60}$ vs E_D

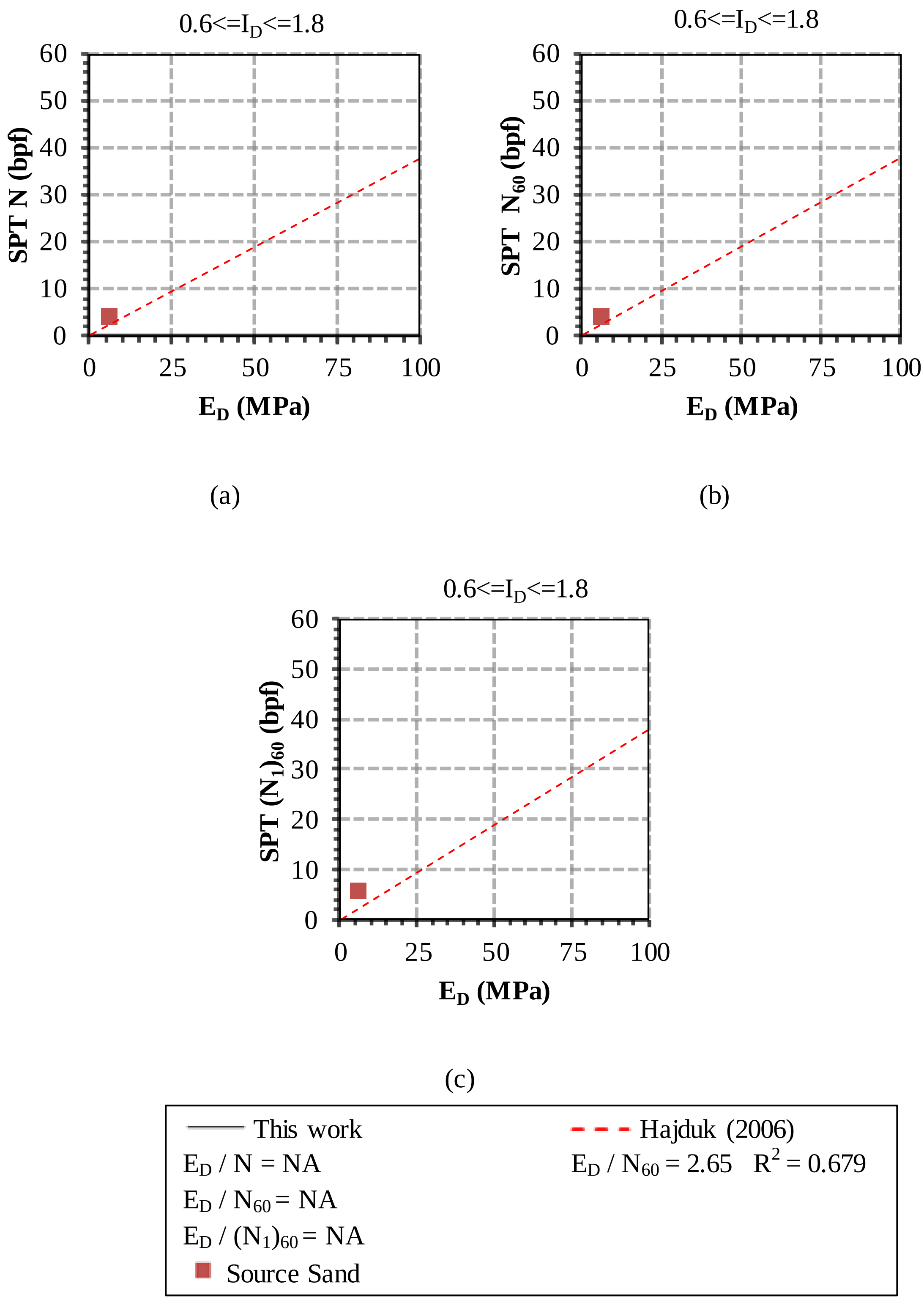


Figure 4.18 SPT-DMT Correlations for Silts at Four Hole Swamp Site: a) N vs E_D, b) N_{60} vs E_D and c) $(N_1)_{60}$ vs E_D

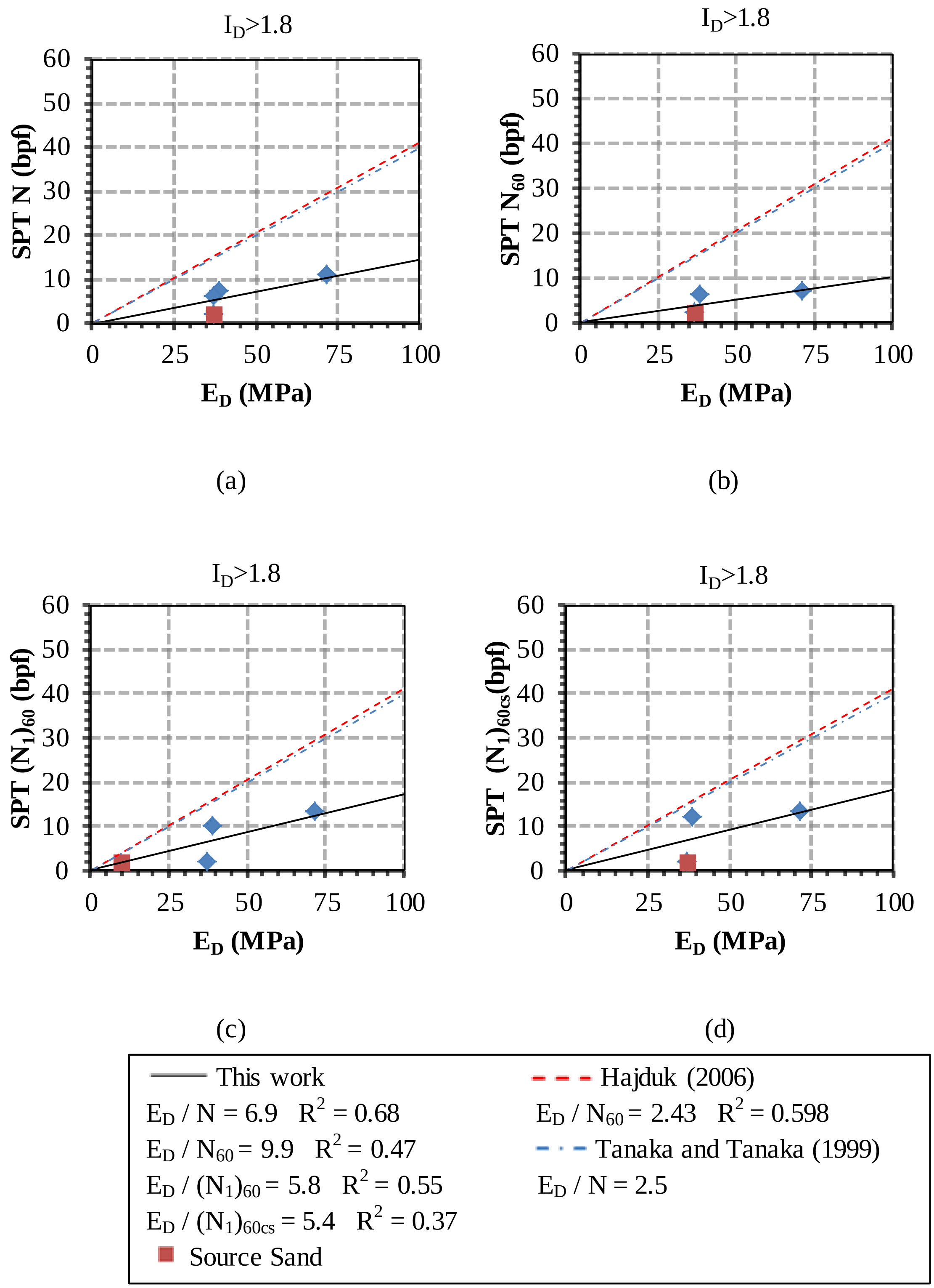


Figure 4.19 SPT-DMT Correlations for Sands at Four Hole Swamp Site: a) N vs E_D, b) N_{60} vs E_D, c) $(N_1)_{60}$ vs E_D and $(N_1)_{60cs}$ vs E_D

Table 4.3 Site Specific SPT-DMT correlations for Source sands

Site	Soil Type	E_D-N relations
Sampit	Silts	E_D / N = 4.1 $E_D / N_{60} = 3.2$ $E_D / (N_1)_{60} = 2.07$
Gapway	Silts	$E_D / (N_1)_{60} = 0.98$
Hollywood	Sands	E_D / N = 6.3 $E_D / N_{60} = 5.6$ $E_D / (N_1)_{60} = 3.8$ $E_D / (N_1)_{60cs} = 3.5$
Four Hole Swamp	Sands	E_D / N = 6.9 $E_D / N_{60} = 9.9$ $E_D / (N_1)_{60} = 5.8$ $E_D / (N_1)_{60cs} = 5.4$
Fort Dorchester	NA	NA

[1] No correlation at Fort Dorchester since SPT were not performed at this site

4.4 All Source Sand Correlations

4.4.1 DMT-CPT

The entire source sand data is plotted on the K_D-Q and E_D/σ'_{vo}-Q chart irrespective of the I_C and I_D values as shown in Figure 4.20 and 4.21 respectively. Since, the source sands are composed of generally granular soils with little fines, hence, these values can be used to represent wide range of soil types. Therefore, the K_D-Q chart for all source sands cannot be used to make comparisons with existing correlations based on K_D-Q chart recommended by Robertson (2009) which have been used to characterize only fine grained soils. As shown in Figure 4.20, a new DMT-CPT correlation i.e $K_D = 0.877Q^{0.5104}$ is established for soil types representing the source sand data for all the sites.

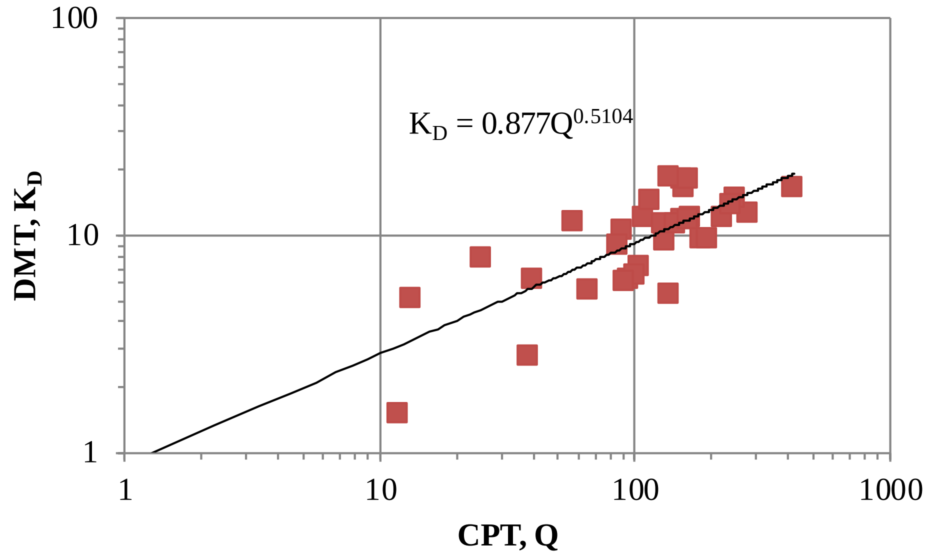


Figure 4.20 Correlation between K_D and Q for Source Sand layer at all sites.

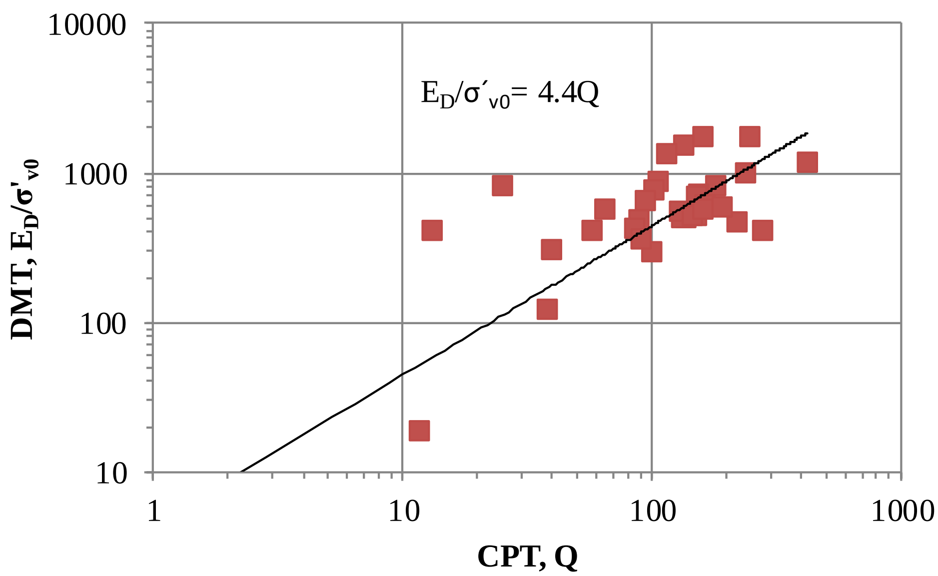


Figure 4.21 Correlations between E_D/σ'_{v0} and Q for Source Sand layer at all sites.

As shown in Figure 4.21, the entire source sand data for all sites gives a new correlation E_D/σ'_{v0} = 4.4 Q and can be compared to the existing correlation based on E_D-Q chart recommended by Robertson (2009) for all soil types. The ratio α = 4.4 in this case falls within the range $2<\alpha<10$ recommended by Robertson (2009) and hence is a good assumption to represent a wide range of soils.

4.4.2 DMT-SPT

As presented in Figures 4.22 through 4.25, the SPT-DMT correlations for source sands is obtained for SAM, GAP, HWD and FHS respectively irrespective of Hajduk (2006)'s soil classification based on I_D values. At Sampit, the ratios E_D/N and E_D/N_{60} are equal to 3.4 and 2.7 and both have the highest R^2 value of 0.74. Both the ratios $E_D/(N_1)_{60}$ and $E_D/(N_1)_{60cs}$ are equal to 1.9 and have lower R^2 values of 0.65 and 0.66 respectively. Due to insufficient data points, the correlation at Gapway is considered to be relatively weak since $E_D/(N_1)_{60}$ value equals 0.92. The ratios E_D/N, E_D/N_{60}, $E_D/(N_1)_{60}$, $E_D/(N_1)_{60cs}$ obtained from the source sand correlations at the Hollywood site are equal to 6.9, 5.9, 4.5 and 3.6. The E_D-N relation provides a higher R^2 value of 0.52 while E_D-$(N_1)_{60cs}$ relation has the lowest R^2 value of 0.33. Both E_D-N_{60} and E_D-$(N_1)_{60}$ relations give a R^2 value of 0.42. At Four Hole Swamp, the data points are limited and hence the relationship is weak. The ratios E_D/N and E_D/N_{60} are equal to 13.9 and the ratios $E_D/(N_1)_{60}$ and $E_D/(N_1)_{60cs}$ are 12.3 and 10.9 respectively. From this analysis, stronger relationships are obtained at SAM when compared to the relations obtained using Hajduk (2006)'s methodology (Refer to Table 4.3). However, the regression correlations at GAP, HWD, and FHS are still considered to be weak.

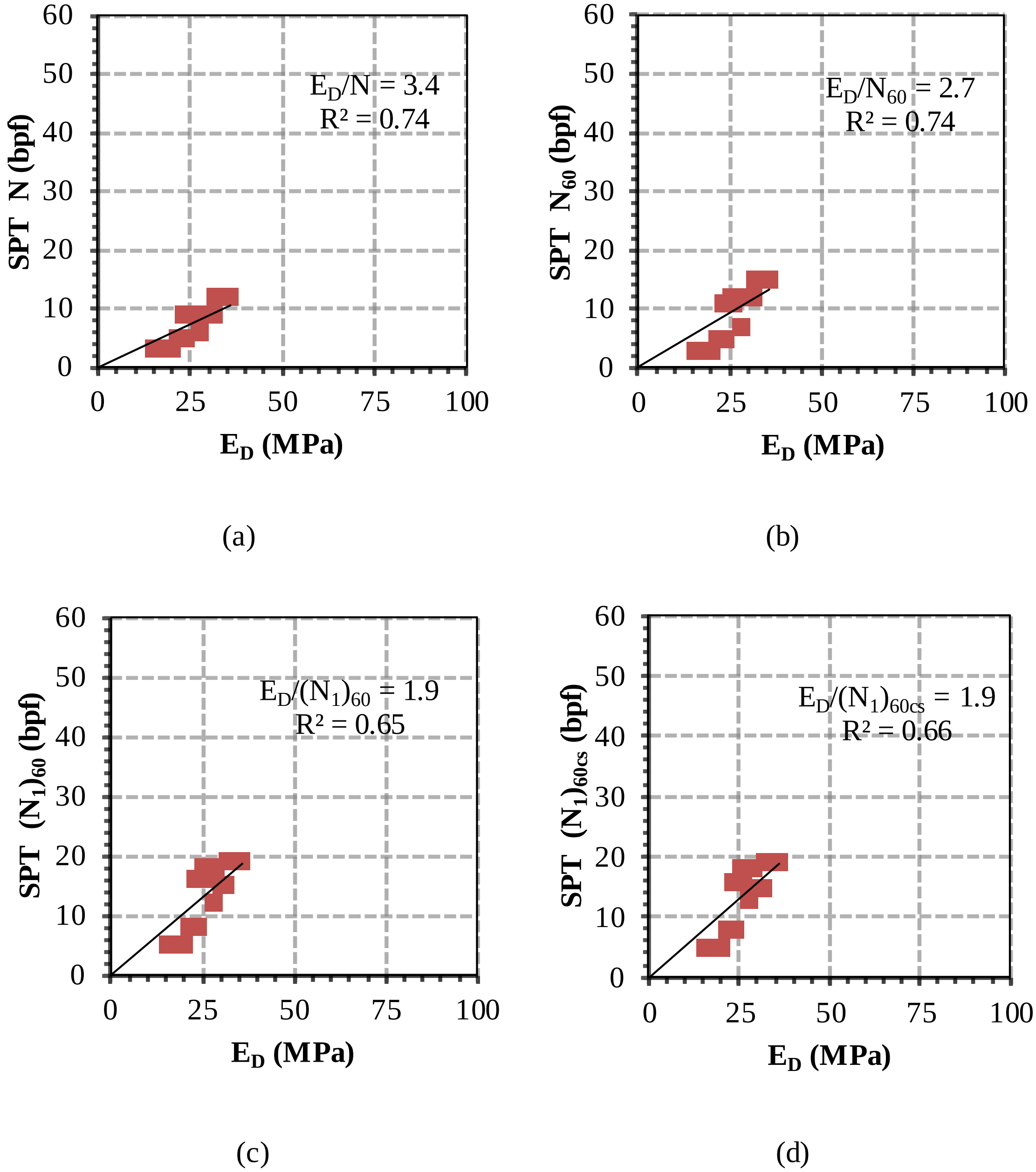


Figure 4.22 SPT-DMT Correlations for Source Sand Layer at Sampit: a) N vs E_D, b) N_{60} vs E_D, c) $(N_1)_{60}$ vs E_D and d) $(N_1)_{60cs}$ vs E_D

The correlations for the combined source sand data for all the sites are also obtained from SPT-DMT plots shown in Figure 4.26. In this analysis, four points were considered outliers in the SPT-DMT plots. This included the data points at a depth of 9 ft and 14 ft below the ground surface at HWD. Both these points lie on the boundary of the source sand layer. An additional outlier is also found at depth of 10 ft below the source sand layer at FHS which has a very high E_D value of 37 MPa and very low blow count of 2 and hence is an anomaly when compared to the rest of the data. Again, the data point on the boundary of the source sand layer at 4 ft was also excluded from the analysis. These outliers were excluded from the analysis since it reduced the R^2 values. It is noted that the data points at Gapway were restricted to the $(N_1)_{60}$-E_D plot. The ratios E_D/N, E_D/N_{60}, $E_D/(N_1)_{60}$, $E_D/(N_1)_{60cs}$ obtained from the combined source sand data are equal to 3.7, 3, 2.1 and 2.1. The corresponding R^2 values obtained are 0.43, 0.44, 0.36, and 0.37 respectively. The R^2 value of 0.37 from $(N_1)_{60cs}$-E_D plot shown in Figure 4.26 (d) is greater when compared to previously published results by Williamson (2013) (Equation 2.42) but lower than that presented by Tsai et. al (2009) (Equation 2.39).

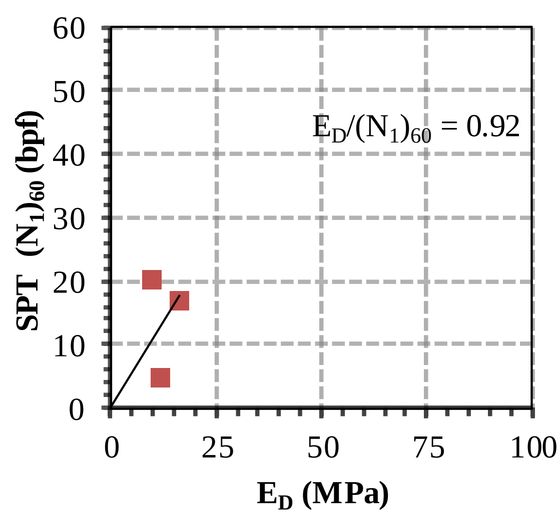


Figure 4.23 SPT-DMT Correlations for Source Sand Layer at Gapway

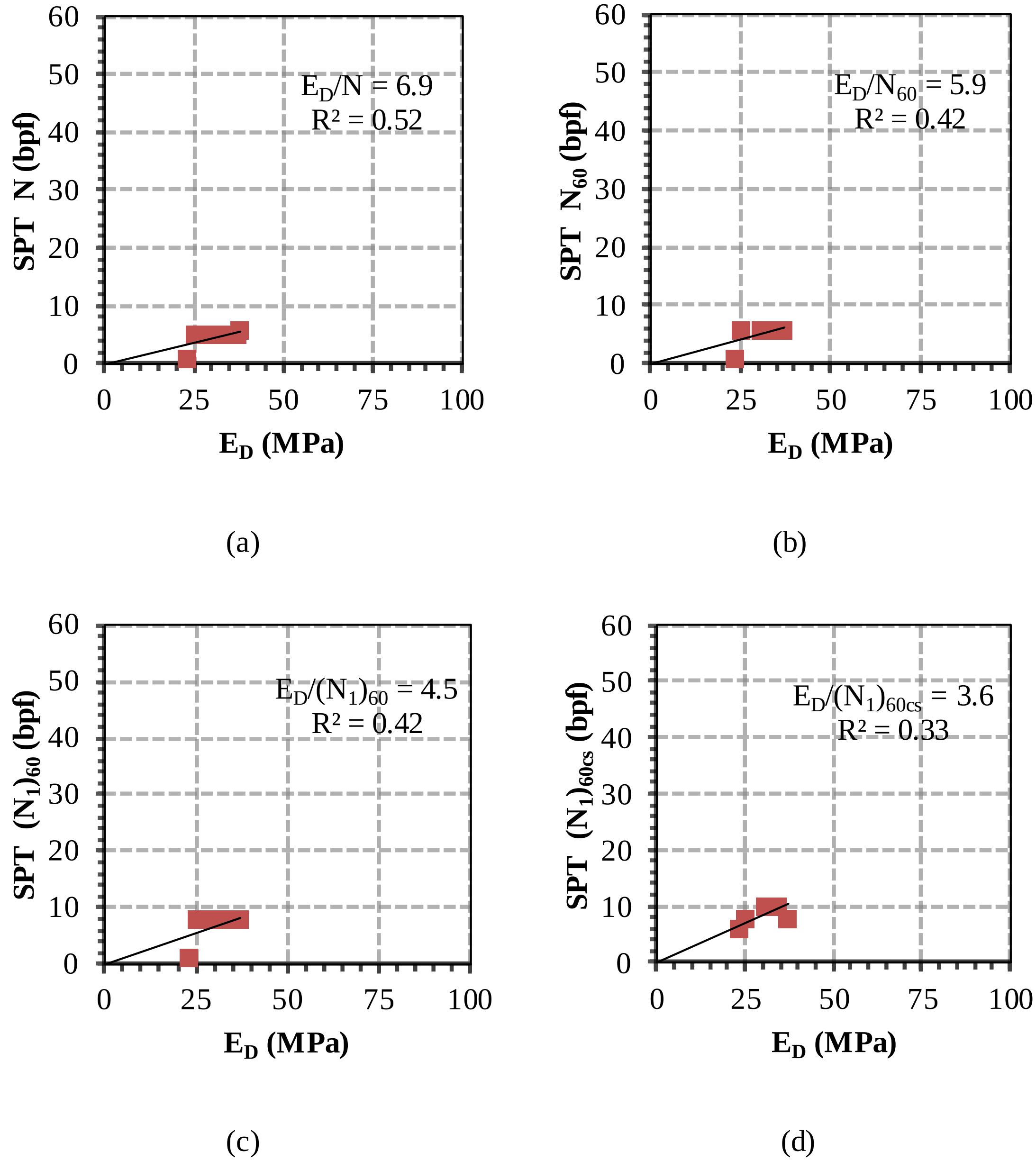


Figure 4.24 SPT-DMT Correlations for Source Sand Layer at Hollywood: a) N vs E_D, b) N_{60} vs E_D, c) $(N_1)_{60}$ vs E_D and d) $(N_1)_{60cs}$ vs E_D

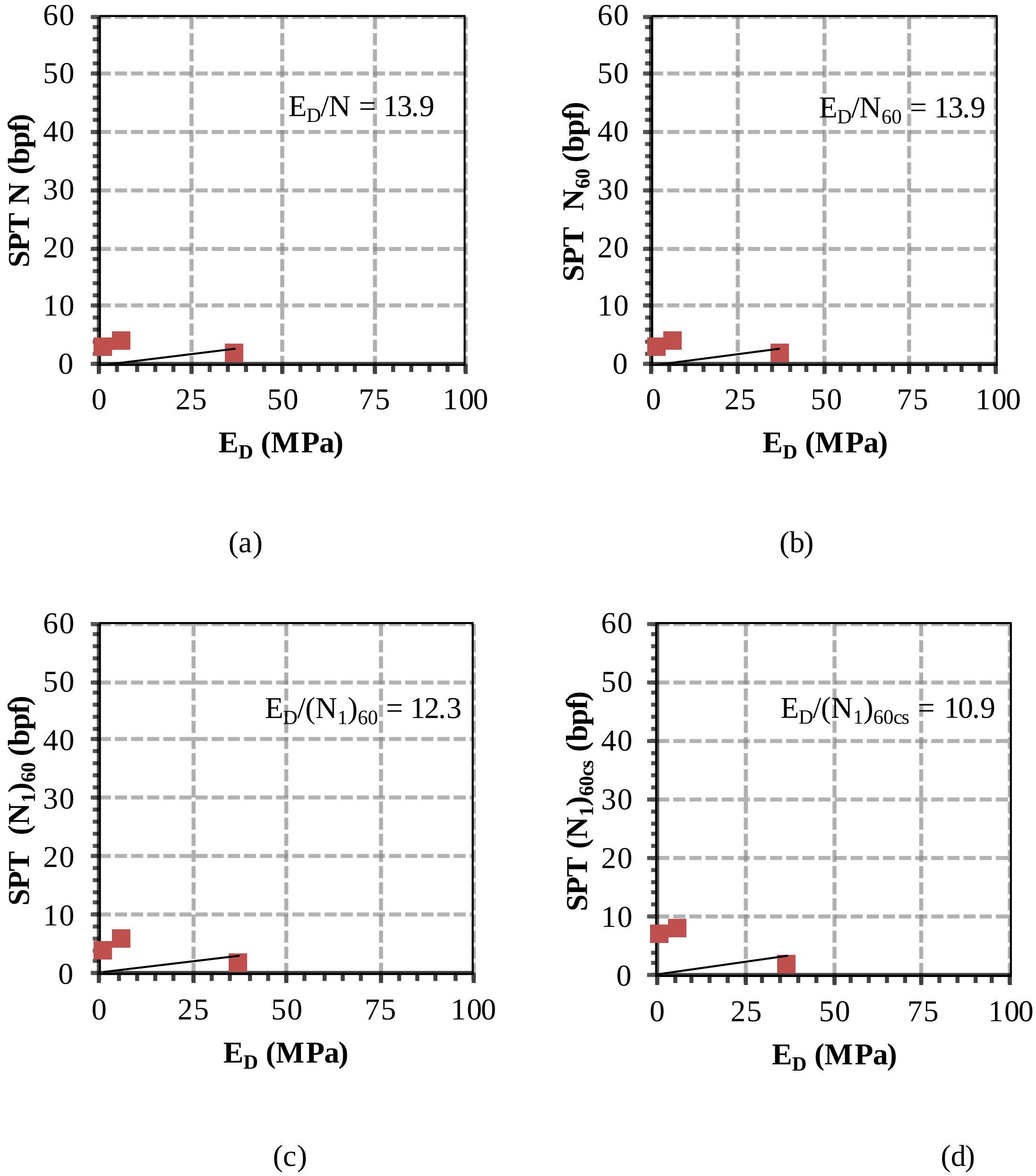


Figure 4.25 SPT-DMT Correlations for Source Sand Layer at Four Hole Swamp: a) N vs E_D, b) N_{60} vs E_D, c) $(N_1)_{60}$ vs E_D and d) $(N_1)_{60cs}$ vs E_D

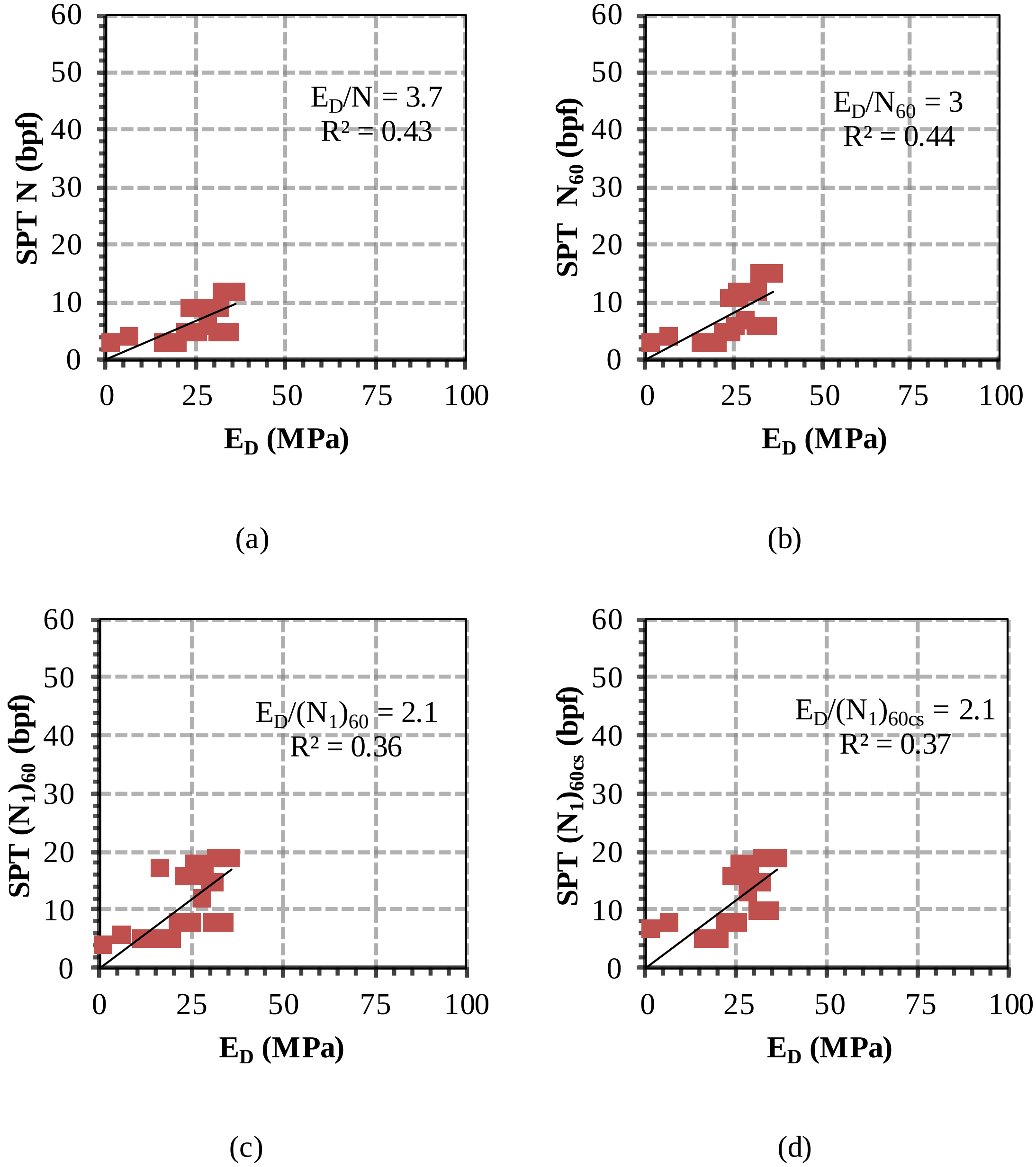


Figure 4.26 SPT-DMT Correlations for Source Sand Layer at all Sites: a) N vs E_D, b) N_{60} vs E_D, c) $(N_1)_{60}$ vs E_D and d) $(N_1)_{60cs}$ vs E_D

4.4 Summary

CPT-DMT and SPT-DMT correlations that are specific to SCCP were derived from adjacent CPT, DMT and SPT profiles for different soil types and compared to the correlations developed by other researchers that were presented in Chapter 2. CPT-DMT correlations include relations between Q and K_D for fine-grained soils and relations between Q and E_D for a wide range of soils similar to those presented by Robertson (2009). SPT-DMT correlations include relations between E_D/σ'_{v0} and N_{60} for three different soil types: clays, silts and sands similar to those provided by Hajduk (2006). The trend lines in the Q-K_D charts showed that the correlations for Sampit and Gapway are in good agreement with those existing correlations for insensitive and sensitive clays, respectively as shown in Table 4.2. Similar CPT-DMT and SPT-DMT correlations were also established for all source sands irrespective of I_D and I_c criteria suggested by Robertson (2009) and Hajduk (2006).

CPT-DMT correlations specific to SCCP were used to estimate α, the ratio between E_D/σ'_{v0} and Q, given by Robertson (2009). α was found to vary with relative density, age and stress history in a manner similar to the variation of the CPT modulus factor α_E (Baldi et al. 1989; Lunne et al. 1997). A summary of α values for all the sites are presented in Table 4.1. The source sand layer at Sampit, Hollywood and Gapway provided α values that fell within specified limits ($2<\alpha<10$) defined by Robertson (2009). α values for Four Hole Swamp and Fort Dorchester sites were found to be 11.5 and 11.8 respectively and did not fall within this previously published range. The combined source sand layer for all sites provided α value of 4.4 and hence is a reasonable assumption to represent a wide range of soils.

The source sand layer at Sampit and Gapway has I_D values which lie within the range of 0.6 to 1.8 and therefore was compared to the N_{60}-E_D charts for silts given by Hajduk (2006). The source sand data at Sampit was shown to plot reasonably well along the existing SPT-DMT regression line. The ratios E_D/N, E_D/N_{60} and $E_D/(N_1)_{60}$ obtained from correlations for silts at the Sampit site were found to be 4.1, 3.2 and 2.07 respectively. At this site, $E_D/(N)_{60}$ equal to 3.2 is higher than Hajduk (2006)'s E_D/N_{60} value of 2.65. While analyzing only the source sand data, the E_D/N_{60} ratio was however found to be 2.7 which also provided the highest R^2 value of 0.74. Again, the ratio E_D/N was found to be 3.4 whereas both $E_D/(N_1)_{60}$ and $E_D/(N_1)_{60}$ were equal to 1.9. The correlation for silts at the Gapway site presented a ratio $E_D/(N_1)_{60}$ equal to 0.98 which were lower than Hajduk (2006)'s E_D/N_{60} value of 2.65 whereas for sands the ratio $E_D/(N_1)_{60}$ of 2.4 was comparable to Hajduk (2006)'s E_D/N_{60} value of 2.43 and Tanaka and Tanaka (1999)'s E_D/N value of 2.5. The correlation for source sands at this site provided a low $E_D/(N_1)_{60}$ value of 0.92.

The source sand layer at Hollywood had I_D values greater than 1.8 and was shown to plot on the E_D-N_{60} charts for sands. The ratios E_D/N, E_D/N_{60}, $E_D/(N_1)_{60}$, $E_D/(N_1)_{60cs}$ derived from the correlations for sands at the Hollywood site were found to be 6.3, 5.6, 3.8 and 3.5 respectively which were relatively higher than that of Hajduk (2006)'s E_D/N_{60} value of 2.43 and Tanaka and Tanaka (1999)'s E_D/N value of 2.5. However, R^2 value of 0.53 from the $(N_1)_{60cs}$-E_D relation was closer to Hajduk (2006)'s R^2 value of 0.598 which indicated a strong relationship between both the correlations. The ratios E_D/N, E_D/N_{60}, $E_D/(N_1)_{60}$, $E_D/(N_1)_{60cs}$ obtained from the correlations for source sands at HWD were found to be 6.9, 5.9, 4.5 and 3.6 respectively which were slightly higher than the correlations for silts. However, the correlations for silts yielded higher R^2 values than those obtained from correlations for source sands.

E_D/N, E_D/N_{60}, $E_D/(N_1)_{60}$, $E_D/(N_1)_{60cs}$ ratios derived from correlations of sands at the Four Hole Swamp site were equal to 6.9, 9.9, 5.8 and 5.4 respectively. These values were much higher than Hajduk (2006)'s E_D/N_{60} value of 2.43 and Tanaka and Tanaka (1999)'s E_D/N value of 2.5. Even the R^2 value of 0.47 obtained from E_D-N_{60} relation was lower than Hajduk (2006)'s R^2 value of 0.598. Given the low R^2 value the relationship for source sands at Four Hole Swamp was found to be weak. Also, the analysis of the source sands at this site provided E_D/N values > 10 which were extremely higher than those obtained from sands.

The E_D/N, E_D/N_{60}, $E_D/(N_1)_{60}$, $E_D/(N_1)_{60cs}$ ratios derived from correlations of combined source sands for all the sites were found to be 3.7, 3, 2.1 and 2.1 respectively. The combination of source sands at all sites provided relatively lower R^2 values with a range of 0.36 to 0.44. Further analysis of the source sands showed that $(N_1)_{60cs}$-E_D relation provided a higher R^2 value of 0.37 when compared to existing R^2 value of 0.33 previously determined by Williamson (2013).

CHAPTER 5

LIQUEFACTION SUSCEPTIBILITY PREDICTION

5.1 Introduction

A CPT based liquefaction susceptibility chart recommended by Hayati and Andrus (2008) is used to screen out layers that are too clay rich for liquefaction. This chart shown in Figure 2.9 in Section 2.3.2 and was based on the revised criteria by Robertson and Wride (1998) where $I_c > 2.6$ or $B_q > 0.5$ represented soils that are non-susceptible to liquefaction. Soils with $I_c < 2.4$ and $B_q < 0.4$ are considered susceptible. Soils between these limits are considered moderately susceptible or another test run may be required for further assessment.

5.2 Methodology

In this thesis, the following two step procedure was used to evaluate liquefaction susceptibility. First, I_c and B_q values were plotted for the CPT test location closest to the DMT. The CPT parameters were selected corresponding to the comparable depths given in DMT. The next step was to calculate average B_q and I_c values for each layer at all the test locations performed at each site as shown in Table 5.1. Note that the test locations at each site were divided into soil layers as previously discussed in Chapter 3. Average values of B_q and I_c were used to represent a specified soil layer at each of the test locations for each site. The CPT data was then analyzed to determine which soil layers fell into the susceptible, non-susceptible and test required zones.

Table 5.1 Summary of Test Locations used in Liquefaction Susceptibility Prediction

Site	Test Locations			
Sampit	SAM-SCPT-1	SAM-SCPT-2	SAM-SCPT-3	
Gapway	GAP-SCPT-1	GAP-SCPT-2	GAP-SCPT-2	
Hollywood	HWD-CPT-4	HWD-CPT-5	HWD-CPT-6	
Four Hole Swamp	FHS-SCPT-1	FHS-SCPT-2	FHS-SCPT-3	
Fort Dorchester	FD-SCPT-1	FD-SCPT-2	FD-SCPT-3	FD-CPT-7a

5.3 Results

SAM-SCPT-1 was conducted in close proximity to the SAM-DMT at the Sampit site. Figure 5.1 shows the I_c-B_q chart proposed by Hayati and Andrus (2008) with data from the Sampit site. The chart indicates that the top 9 ft (2.7 m) thick silty sand layer defined for SAM-SCPT-1 falls into the susceptible zone. Nearly all the source sand data fell into the susceptible zone except the data point plotted at 22 ft (6.7 m). This data point at 22 ft (6.7 m) fell into the moderately susceptible to test required zone because it lies on the boundary of the source sand layer and the clay layer below the source sand. The 9 ft (2.7 m) thick clay layer below the source is considered too clay rich to liquefy and hence the data plots in the non-susceptible zone. The silty sand layer from 31 to 35 ft (9.4 to 10.7 m) falls into the susceptible zone. Average I_c and B_q values were found for Layer A, B, C and D for all the three test locations at Sampit. Layer A, B and D defined for SAM-SCPT-1 as shown in Figure 5.1 are susceptible to liquefaction. Layer C, however, plots in the non-susceptible zone and hence is too clay rich to liquefy. The average I_c-B_q values suggest that for test locations SAM-SCPT-2 and SAM-SCPT-3, all the layers A, B, C and D are susceptible to liquefaction.

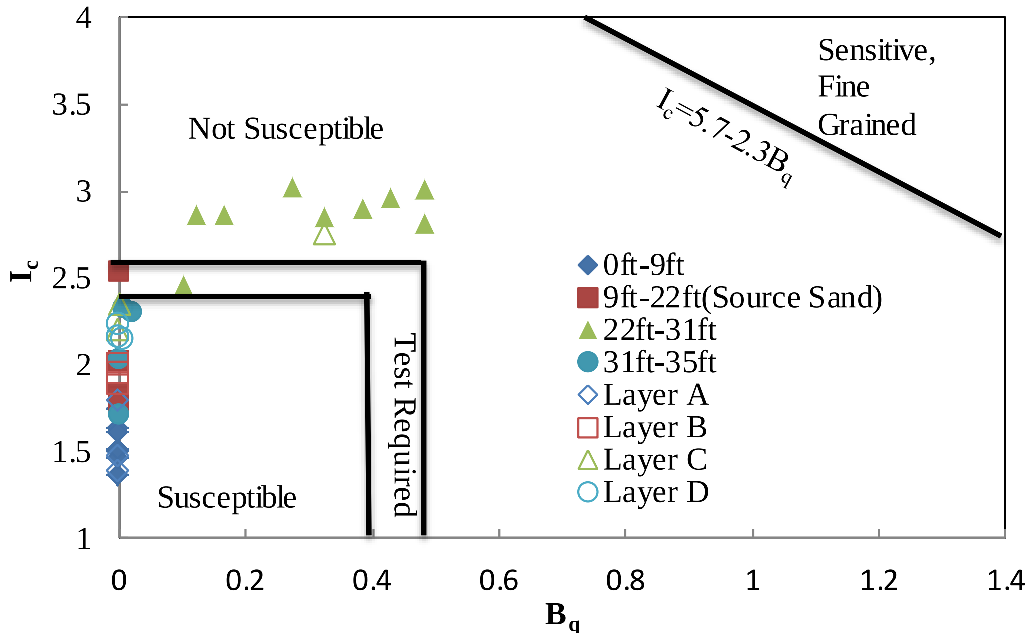


Figure 5.1 CPT-based liquefaction susceptibility chart after Hayati and Andrus (2008) with data from Sampit site

GAP-SCPT-1 was performed closest to GAP-DMT and the CPT data was analyzed to evaluate liquefaction susceptibility. As shown in Figure 5.2, the top 3 ft (0.9 m) mixed sand layer fell into the susceptible zone. However, the data point at 3 ft (0.9 m) fell into the test required zone since it lies on the boundary of the mixed sand layer and the thin clay cap layer. For the thin clay cap layer, CPT data was considered at a depth of 4 ft (1.2 m) which fell into the susceptible zone. This data point lies on the boundary of the source sand layer and plots very near to the data points used to represent the source sand layer. The source sand layer plots in the susceptible region while the clay layer beneath the source sand layer is not susceptible to liquefaction. The coarse sand layer from 15 to 18 ft (4.6 to 5.5 m) plots in the susceptible region. The average I_c and B_q values were calculated for Layer A, B, C, D and E at each of the test locations at Gapway. In Figure 5.2, it is observed that layers A, B, C and E for the three test locations are susceptible to liquefaction. The average I_c-B_q values for the three test locations indicate that Layer D is the only layer which is not susceptible to liquefaction.

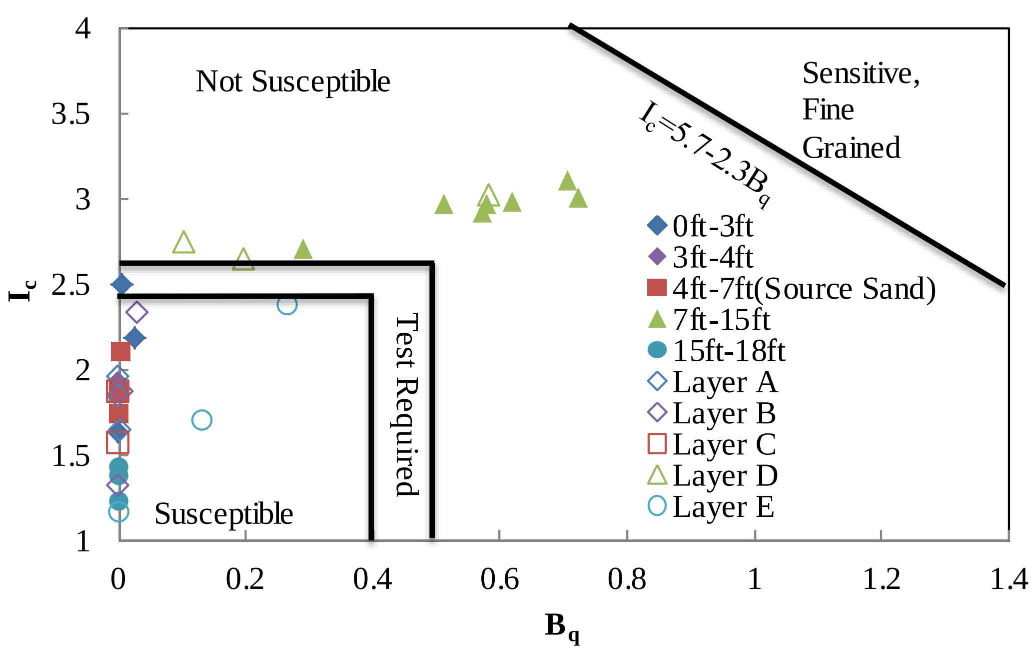


Figure 5.2 CPT-based liquefaction susceptibility chart after Hayati and Andrus (2008) with data from Gapway site

The CPT data at HWD-CPT-4 was studied for liquefaction at depths where DMT data was obtained. The top 9 ft (2.7 m) silty sand layer has I_c values less than 2.4 and B_q values less than 0.4 and hence falls within the susceptible zone as shown in Figure 5.3. All of the data except one in the source sand layer falls in the susceptible zone. The data point is at a depth of 14 ft (4.3 m) lies on the boundary of the source sand layer and the layer beneath the source sand. Since, it plots in the non-susceptible zone the data point can be used to represent the layer below the source sand. The data from the silty clayey sand layer from 14 to 20 ft (4.3 to 6.1 m) plots mostly in the susceptible zone but also in the non-susceptible zone. However, average I_c and B_q values plotted in the Figure 5.3 show that Layer C defined for HWD-CPT-4, -5 and -6 plots within the test required zone. As shown in Figure 5.3, Layer A and B for each of the test locations is susceptible to liquefaction.

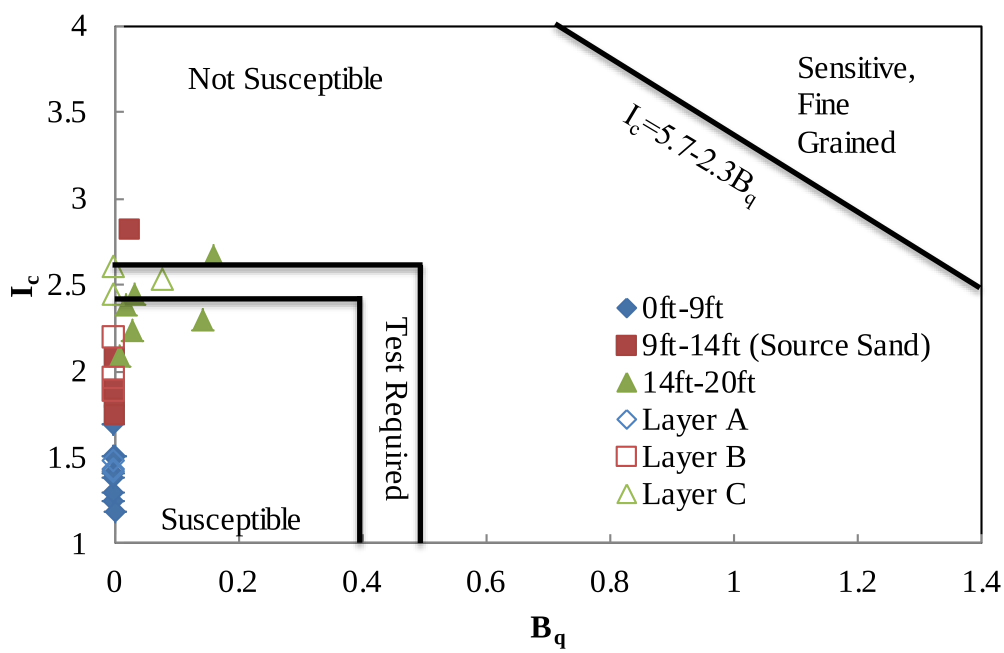


Figure 5.3 CPT-based liquefaction susceptibility chart after Hayati and Andrus (2008) with data from Hollywood site

The CPT liquefaction susceptibility chart is presented in Figure 5.4 for Four Hole Swamp. The top 9 ft (2.7 m) thick silty clayey sand defined for FHS-SCPT-1 plots in the susceptible zone. However, the majority of the data in the source sand region has I_c values >2.6, thereby, indicating that soil is not susceptible to liquefaction. Only one data point at a depth of 12 ft (3.7 m) indicates that the source sand layer falls within the susceptible zone. The clayey sand layer from 15 to 22 ft (4.6 to 6.7 m) plots mostly in the test required zone. Only one data point at a depth of 16 ft (4.9 m) fell into the susceptible zone. The average I_c-B_q values used for layers A and C indicate that the soils at each of the test locations are susceptible to liquefaction. The source sand layer, B, defined for FHS-SCPT-1 fell into the non-susceptible zone. However, the average I_c-B_q values plotted in Figure 5.4 shows that Layer B at FHS-SCPT-2 and -3 is susceptible to liquefaction.

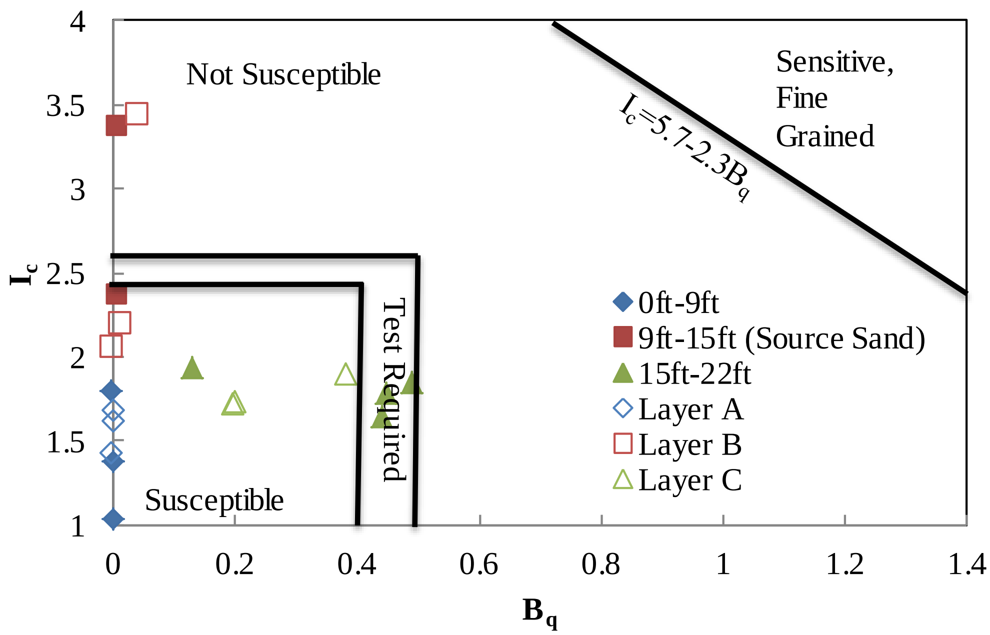


Figure 5.4 CPT-based liquefaction susceptibility chart after Hayati and Andrus (2008) with data from Four Hole Swamp site

FD-SCPT-1 and FD-SCPT-2 was performed in close proximity to FD-DMT-EW and FD-DMT-NS respectively and the results for liquefaction susceptibility are shown in Figures 5.5 and 5.6. Both the charts indicated that the top 5 ft (1.5 m) silty clay layer and source sand layer fell into the susceptible zone. The clayey sand layer from 5 to 8 ft (1.5 to 2.4 m) plotted in the susceptible region as well as in the test required zone for both test locations FD-SCPT-1 and -2. Average I_c-B_q values for SCPT-1 and CPT-7a were plotted in Figure 5.5 while average values for SCPT-2 and SCPT-3 were plotted in Figure 5.6. Layer A and C for all the four test locations are susceptible to liquefaction. Layer B defined for FD-CPT-7A and FD-SCPT-2 showed low susceptibility as the data plotted in the test required zone whereas layer B defined for FD-SCPT-1 and -3 data is susceptible to liquefaction.

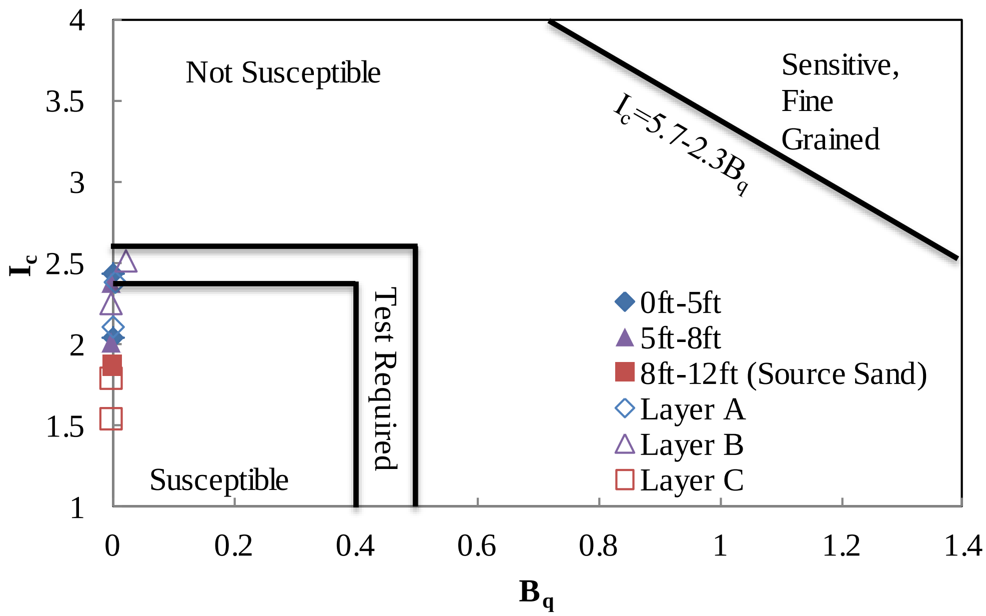


Figure 5.5 CPT-based liquefaction susceptibility chart after Hayati and Andrus (2008a) with data from Fort Dorchester site oriented in E-W direction.

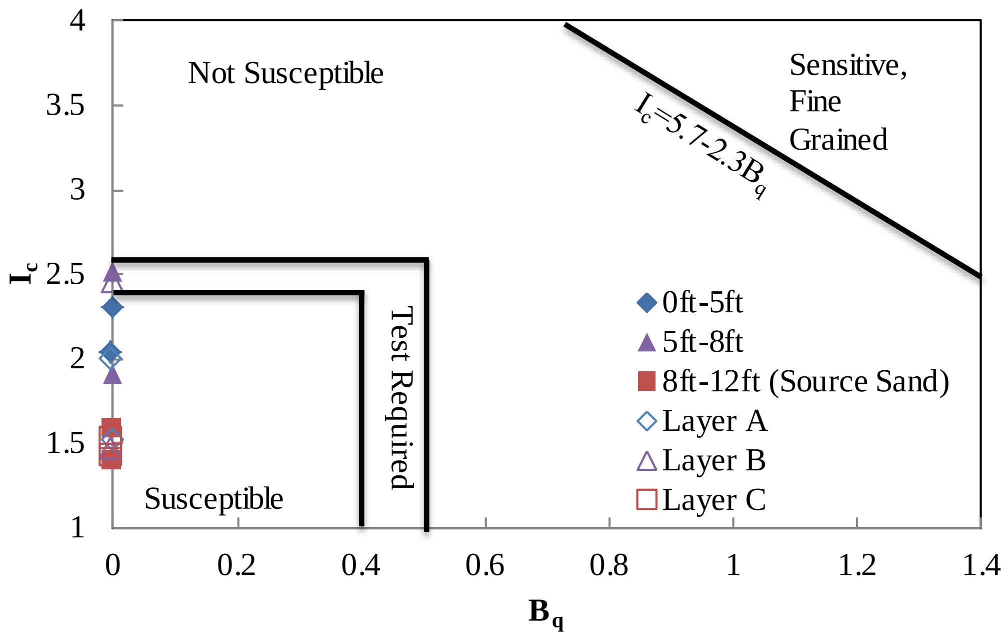


Figure 5.6 CPT-based liquefaction susceptibility chart after Hayati and Andrus (2008) with data from Fort Dorchester site oriented in N-S direction.

5.4 Discussion

The CPT liquefaction susceptibility chart was provided by Hayati and Andrus (2008) to predict whether a soil layer is likely to liquefy or not. The results obtained from the charts showed that the source sand layer delineated for test locations at Sampit, Gapway, Hollywood and Fort Dorchester Site fell into the susceptible zone as shown in Table 5.2. The source sand layer at these sites consists of clean sand to silty sands and had I_c values less than 2.6 thereby indicating that the soil is susceptible to liquefy. At the Hollywood site, the data point at a depth of 14 ft (4.3 m) lying on the boundary of the source sand layer and the clayey silty layer, falls on the non-susceptible zone and hence can be considered to represent the clayey silty layer. From Figure 3.12 in Section 3.2.4 , the source sand layer at Four Hole Swamp is considered to have presence of clays which has I_c>2.6 suggesting that the soil is not capable of liquefying. On the other hand, average I_c-B_q values for test locations FHS-SCPT-2 and -3 indicate that Four Hole Swamp can be considered susceptible to liquefaction.

Table 5.2 Summary of liquefaction susceptibility using average B_q and I_c values

Site	Layer	Liquefaction Susceptibility Chart
Sampit	A	Susceptible
	B (source sand)	Susceptible
	C	Susceptible to Non Susceptible
	D	Susceptible
Gapway	A	Susceptible
	B	Susceptible
	C (Source Sand)	Susceptible
	D	Not Susceptible
	E	Susceptible
Hollywood	A	Susceptible
	B (Source Sand)	Susceptible
	C	Test Required
Four Hole Swamp	A	Susceptible
	B (Source Sand)	Susceptible to Not Susceptible
	C	Susceptible
Fort Dorchester	A	Susceptible
	B	Susceptible to Test Required
	C (Source Sand)	Susceptible

From this research, it was observed that clayey soils at both Sampit and Gapway had I_c values greater than 2.6 indicating that soil is not susceptible to liquefaction. It is noted that Layer C defined for Hollywood and Four Hole Swamp site show similar soil behavior type (see Figure 3.9 in Section 3.2.3 and Figure 3.12 in Section 3.2.4). In Hollywood, the clayey sand layer plots mostly in the susceptible zone but the average data for all the three test locations (see Table 5.1) plot in the test required zone. While comparing this data to Four Hole swamp, the clayey sand layer falls within the test required zone and the average data used to represent Layer C plots in the susceptible zone. Therefore, this layer at both sites can be considered as moderately susceptible to liquefaction or additional testing may be required to determine susceptibility to liquefaction.

Since the source sand layer for Fort Dorchester site was delineated above the predicted water table, I_c and B_q values above the groundwater table was also analyzed for the rest of the four sites. Even though these layers comprised of dense stiff sands and had higher penetration resistance, soil layers above the groundwater table for SAM, HWD, and FHS fell into the susceptible zone. For Gapway, however, the data point at 3 ft (0.9 m) falls in the test required zone because it lies on the boundary of a sand and clay layer. Average I_c-B_q values used at this site indicated that the layer above the groundwater table is susceptible to liquefaction. The CPT liquefaction susceptibility chart provided by Hayati and Andrus (2008) is used to represent soil layers below the water table. However, the water table depth may fluctuate depending on seasonal variability and hence the charts used in this work have been shown to represent all the soil layers below the ground surface. Soil above the groundwater table is generally not considered for liquefaction analyses because liquefaction potential is best evaluated for cohesionless saturated soils. However, the liquefaction potential for unsaturated sands is a valuable topic of research.

Note that there are a few differences in the method used herein compared to Geiger (2010)'s method. In comparison to Geiger's work, the liquefaction susceptibility charts used in this thesis examined all the data points from the CPT test which was conducted in close proximity to the DMT. The scatter obtained from these data points gives a better visualization in characterizing the soil layers in the susceptibility chart. However, the average B_q and I_c values for each layer at test locations for each site are also presented in these charts similar to that of Geiger (2010). It was found that the soils above the groundwater table were considered not susceptible according to Geiger (2010). The average values, however, for topmost Layer A fell into the susceptible zone similar to the results obtained in this thesis.

5.5 Comparison between Liquefaction and Non-Liquefaction Sites

The geotechnical investigation sites presented in this thesis can be used to compare the results with Geiger (2010)'s work. Geiger (2010) studied sites where no liquefaction features have been observed; whereas, there is evidence of liquefaction at the sites studied herein. Previous studies by Talwani et al. (1999) attribute to findings of sandblows in the SCCP which show evidence of paleoliquefaction at SAM, GAP, HWD, FHS and FD sites. The most prolific evidence of paleoliquefaction was observed at the Hollywood site where Obermeir et al. (1985, 1986 and 1987) identified 162 liquefaction features in this site associated with prehistoric earthquakes.

Similar to Geiger (2010), the source sand layer for each of the five sites exhibited lower tip resistances than other susceptible layers and is located close to the ground surface below the water table. The critical sand layer selected for liquefaction analysis at the Hobcaw Barrow, Rest Area Ponds and the Lowcountry Sand and Gravel Site had higher average tip resistances but lower I_c values in comparison to the source sand layer at SAM, GAP, HWD, FHS and FD sites as shown in Table 5.3. The Lowcountry Sand and Gravel site showed the highest average tip resistance values of 21.6 MPa while the lowest average tip resistance of 1.52 MPa was observed at the Four Hole Swamp site.

Table 5.3 Summary of liquefaction susceptibility of source sand and critical sand layers

Type	Site	Test Location	Average CPT data			Liquefaction Susceptibility Chart
			q_t (MPa)	I_c	B_q	
Liquefaction Sites	Sampit	SAM-SCPT-1	6.8	1.92	0.000	Susceptible
	Gapway	GAP-SCPT-1	4.3	1.91	0.001	Susceptible
	Hollywood	HWD-CPT-1	4.9	2.01	0.01	Susceptible
	Four Hole Swamp	FHS-SCPT-1	1.52	3.28	0.03	Non-Susceptible
	Fort Dorchester	FD-SCPT-1	7.8	1.92	0.000	Susceptible
		FD-SCPT-2	16.6	1.63	0.000	
Non-liquefaction Sites	Hobcaw Barrow	HB-1	8.7	1.66	0.006	Susceptible
	Rest Area Ponds	SC-3	8.1	1.86	-0.002	Susceptible
	Lowcountry Sand and Gravel	SC-1	21.6	1.67	0.000	Susceptible

The average tip resistances for SAM, GAP and HWD sites were found to be 6.8, 4.3 and 4.9 respectively whereas the average q_t for Hobcaw Barrow and Rest Area Ponds site were found to be 8.7 and 8.1 respectively. At the Fort Dorchester site, the source sand layer for FD-SCPT-1 showed an average tip resistance of 7.8 MPa while FD-SCPT-2 showed higher average q_t value of 16.6 MPa. Four Hole Swamp was observed to have the highest average I_c value of 3.28. The lowest average I_c value was measured as 1.63 at the FD-SCPT-2 test location. Average I_c values of 1.66, 1.86 and 1.67 were measured at Hobcaw Barrow, Rest Area Ponds and Lowcountry Sand and Gravel sites respectively. GAP and HWD sites showed average Ic values equal to 1.91 and 2.01. Test locations SAM-SCPT-1 and FD-SCPT-1 both showed similar average I_c values equal to 1.92. While I_c was equal to less than 2.6 at all liquefiable and non-liquefiable sites, SCCP sites and the sites presented by Geiger (2010) are all susceptible to liquefaction.

Table 5.4 Summary of average DMT data for source sand and critical sand layers

Type	Site	Average DMT data		
		E_D (MPa)	I_D	K_D
Liquefaction Sites	Sampit	26	1.4	10.9
	Gapway	13.5	1.3	12
	Hollywood	30	2.7	6
	Four Hole Swamp	14.7	1.5	4.1
	Fort Dorchester	73.5	2.5	17.4
		61.5	2.5	15.2
Non-LiquefactionSites	Hobcaw Barrow	35	3.5	12
	Rest Area Ponds	62.2	3.8	42.9
	Lowcountry Sand and Gravel	313.4	3.1	27.9

According to Table 5.4, the average E_D, I_D and K_D values for the critical sand layers at the non-liquefaction sites are higher than the source sand layers at the sites where there is previous evidence of liquefaction. Since, the average tip resistances, E_D, K_D and I_D values measured at the liquefaction sites were lower, these sites are considered to be more susceptible to liquefaction in comparison to Geiger (2010)'s non-liquefaction sites.

5.6 Summary

In this chapter, the soil layers at Sampit, Gapway, Hollywood, Four Hole Swamp and Fort Dorchester sites were assessed for liquefaction susceptibility using the I_c-B_q chart proposed by Hayati and Andrus (2008) based on the revised criteria recommended by Robertson and Wride (1998). I_c and B_q values were plotted on the chart for the CPT test location closest to the DMT to identify all the soil layers susceptible to liquefaction. Average I_c-B_q values were determined for all soil layers at three CPT test locations for each site which also included the CPT test location in close proximity to the DMT (See Table 5.1). The source sand layers for all test locations at SAM, GAP, HWD and FD were susceptible to liquefaction. The source sand layer at FHS-SCPT-1 was found to be non-susceptible but the average values for FHS-SCPT-2 and -3 were in the susceptible zone (See Table 5.2). At all sites, the charts indicated that layers above the groundwater table were found to be potentially liquefiable; however, these layers need to be excluded since the soil is unsaturated. Layers beneath the source sand were either too clay rich to liquefy or were moderately susceptible and required additional testing to assess susceptibility. The average values presented in the charts confirm that the source sand layer at each of the five sites is susceptible to liquefaction. Although liquefaction has occurred at the sites in the past, the sites are more likely to experience it again in the future.

When comparing the results from the sites presented herein where there is evidence of liquefaction to those sites studied by Geiger (2010) where there is no evidence of liquefaction, it was observed that the critical sand layer identified by Geiger (2010) from the CPT Susceptibility Charts at the Hobcaw Barrow, Rest Area Ponds and the Lowland Sand and Gravel Site had higher average tip resistances, E_D, I_D and K_D and lower I_c, values than the source sands for Sampit, Gapway, Four Hole Swamp, Hollywood and Fort Dorchester sites. Therefore, the sites presented herein were considered to be more susceptible to liquefaction than the non-liquefaction sites.

5.7 Future Work

Geiger (2010) used the liquefaction susceptibility chart to determine the soil layer most likely to liquefy at three sites located in the SCCP: Hobcaw Barony Borrow Pit, Rest Area Ponds and the Lowland Sand and Gravel Site. Geiger (2010) used average I_c and B_q values to characterize the soil layers at the test locations for each site. The saturated soil layer closest to the ground surface that fell into the susceptible zone and had lower penetration resistance was selected to evaluate liquefaction potential. Geiger (2010) used several methods to find CRR based on V_{s1cs}, $(N_1)_{60cs}$ and $(q_{t1N})_{cs}$ for liquefaction potential analysis. The results from the study indicated that each of the three sites did not have the potential for liquefaction during the 1886 Charleston earthquake. However, Geiger (2010) found that the sites were most likely to liquefy during a future earthquake estimated using the Magnitude (M) and Peak Ground Acceleration (PGA) from the 2008 USGS Hazard Maps. Similar studies can be done at the five sites studied herein to estimate the liquefaction potential.

CHAPTER 6

CONCLUSIONS

6.1 Summary

The main objective of this thesis was to study the soil behavior type of soils using in situ test data, develop new site specific correlations between CPT, SPT and DMT parameters and evaluate liquefaction susceptibility at the five geotechnical sites in the SCCP where evidence of paleoliquefaction has been observed. Normalized Q and F parameters from CPT tests and E_D and I_D parameters from the DMT tests were used to determine the Soil Behavior type from the CPT Soil Behavior Chart (Robertson, 1990) and DMT Soil Identification Chart data (Marchetti, 1980) for the five sites in the SCCP. DMT, CPT and SPT parameters were used to develop correlations between K_D and Q for fine- grained soils, E_D and Q for a wide range of soils, and E_D and N_{60} for silts, clays and sands in the SCCP. These correlations between the different test parameters were compared to previously published correlations. Based on Robertson and Wride (1998)'s revised criteria, I_c and B_q parameters from CPT tests were used to assess the liquefaction susceptibility from CPT charts developed by Hayati and Andrus (2008a) in the SCCP.

6.2 Major Findings

The following conclusions were drawn based on the work presented in this thesis:

6.2.1 Soil Behavior Type

- The CPT data from the source sand layers at SAM, GAP, HWD, and FD sites fell into Zones 5 and 6 of Robertson (1990)'s CPT Soil Behavior Charts indicating that these layers are composed of clean sands to silty sands to sandy silts and may be susceptible to liquefaction. The source sand layer at FHS fell into Zones 4, 5 and 6 indicating a high percentage of fines and thus would not be considered susceptible to liquefaction.
- The DMT Soil Identification Chart (ASTM D6635) identified the source sand layers at the SAM, HWD, FHS and FD to contain mostly medium to high density sand and silt mixtures; whereas loose sands are generally susceptible to liquefaction. Most of the data in the source sand layer at GAP plotted in the clayey silty region indicating the presence of a significant amount of fines. These results would indicate a low susceptibility to liquefaction.
- Multiple methods such as CPT, DMT and USCS used herein should be used together to provide a comprehensive characterization of the source sand.
- The relative densities calculated from CPT data indicated that the source sand layer consists of very loose to loose soil deposits for SAM, HWD and FHS, medium soil deposits for GAP and medium to dense soil deposits for Fort Dorchester. These densities were in good agreement with the laboratory measurements of relative densities for source sands at SAM, HWD and FHS. The DMT data predicted higher relative densities for all the sites.
- Relative densities found from the new DMT soil behavior chart that was modified based on laboratory measurements of relative densities for source sands at SAM,

HWD and FHS were found to be in good agreement with the relative densities obtained from CPT data.

- The soil behavior of the overburden layer and the current prediction of the water table at the FD site indicated that sandblows are less likely to form during a future seismic event, however, the overburden layer at SAM, GAP, HWD and FHS indicated presence of clean sands to silty sands which would allow the ejection of liquefied sands freely onto the surface.

6.2.2 Site Specific Correlations

- The ratio, α, between E_D and Q for the source sand layers for SAM, GAP and HWD were found to be 3.9, 2.5 and 6.1 respectively which fell within the observed range of $2<\alpha<10$ defined by Robertson (2009) for a wide range of soils. However, α for Four Hole Swamp and Fort Dorchester sites were found to be 11.5 and 11.8 respectively and did not fall within this range. The combined data for all source sands provided an α value of 4.4.
- The relations between Q-K_D for Sampit and Gapway were in good agreement with previously published correlations by Robertson (2009) and Schneider (2008) for insensitive and sensitive clays. The relations between Q and K_D for Hollywood and Four Hole Swamp were not in agreement with these published correlations. More CPT and DMT data is needed to define site specific relations for two sites. A new correlation for Q-K_D was found for all source sands specific to SCCP soils irrespective of I_D and I_c parameters.

- For Sampit, the ratio between E_D and N_{60} for silts was found to be 3.2 which is higher than Hajduk (2006)'s E_D/N_{60} value of 2.65, however, the source sand data provided E_D/N_{60} value of 2.7 along with the highest R^2 value of 0.74. The ratio between E_D and $(N_1)_{60}$ for silts and source sands at Gapway was found to be 0.98 and 0.92 which is lower than Hajduk (2006)'s E_D/N_{60} value of 2.65. The ratios E_D/N_{60} at HWD and FHS for sands were found to be 5.6 and 9.9 which are higher than both Hajduk (2006)'s E_D/N_{60} value of 2.43 and Tanaka and Tanaka (1999)'s E_D/N value of 2.5. However, the ratios at HWD and FHS for source sands were found to be higher but exhibited lower R^2 values.
- The E_D/N, E_D/N_{60}, $E_D/(N_1)_{60}$, $E_D/(N_1)_{60cs}$ ratios derived from correlations of combined source sands for all the sites were found to be 3.7, 3, 2.1 and 2.1 respectively. The $(N_1)_{60cs}$-E_D relation displayed a higher R^2 value of 0.37 when compared to existing R^2 value of 0.33 previously determined by Williamson (2013).

6.2.3 Liquefaction Susceptibility

- From the liquefaction susceptibility chart developed by Andrus and Hayati (2008a), it was found that the source sand layers for all test locations at SAM, GAP, HWD and FD were susceptible to liquefaction. At FHS, the data for the source sand layer at FHS-SCPT-1 was found to be non-susceptible but the average values for FHS-SCPT-2 and -3 were found to be susceptible to liquefaction.

- The source sand layers at SAM, GAP, HWD, FHS and FD sites where there is evidence of liquefaction, were generally found to have lower average q_t, I_D, K_D and E_D values in comparison to the critical sand layers at Hobcaw Barrow, Rest Area Ponds, and Lowcountry Sand and Gravel sites where no evidence of liquefaction has been found. The critical sand layers at Rest Area Ponds and Lowcountry Sand and Gravel had higher average blow counts than the source sands for sites presented in this study. No SPT tests were performed in the Fort Dorchester and Lowcountry Sand and Gravel site. From the comparisons made above, it can be concluded that the source sand layers at the sites where there is previous evidence of liquefaction are more susceptible to liquefaction than those sites where there is no evidence of liquefaction.

6.3 Future Work

- Further research can be conducted to evaluate the liquefaction potential at the five sites in the SCCP using peak ground acceleration and magnitudes of two earthquake scenarios from 2008 USGS Hazard Maps to evaluate liquefaction potential similar to work by Geiger (2010) for the non-liquefaction sites.
- This work can be used with the incoming results of Hasek (2014) on the CRR found from triaxial tests and the petrography studies to better understand the chemical and mechanical mechanisms ("aging") at each site and their relation to the CPT and DMT results.

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