Dilatometer experience in the Charleston, South Carolina region

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ABSTRACT: The soil stratigraphy in the Charleston, SC area present ideal conditions for conducting soil explorations using insitu testing methods. The overburden soils in this region typically consist of Pleistocene marine deposits of loose to medium dense sands and very soft to firm clays and silts. The relative loose/soft nature of the overburden soils, coupled with the high seismic design issues of the region, often lead to liquefaction and/or settlement concerns during site geotechnical explorations.

Within the past ten years, traditional soil borings with the Standard Penetration Test (SPT) used for site geotechnical explorations in the region have been replaced or augmented with insitu testing methods. The most common insitu testing methods are flat blade dilatometer testing (DMT) and piezocone cone penetration testing (CPTu). As a result of the insitu testing methods, refined geotechnical analyses can be performed and improved foundation solutions can be implemented.

The following paper presents six case histories in the Charleston, SC area where SPT soil borings, flat blade dilatometer tests, and piezocone penetration testing were performed. Comparisons of the soil classifications, liquefaction susceptibility, and other geotechnical analyses at these sites were conducted to evaluate the different soil exploration methods. These comparisons have shown that the flat blade dilatometer accurately classifies soils in the region and the test provides insitu soil data that allow for more refined geotechnical analyses than those performed using soil boring SPT and/or CPTu data.

1 INTRODUCTION

In the Charleston, South Carolina region, insitu testing is increasingly being used to perform subsurface investigations. Within the last ten years, flat blade dilatometer (DMT) and piezocone penetration testing (CPTu) have supplemented or supplanted traditional soil test borings and the standard penetration test (SPT). The amount of insitu testing is dependent on a variety of factors, such as cost, availability of the testing equipment, accessibility of the site, and size/complexity of the project. Within the last few years, insitu testing is almost used exclusively for smaller projects in the area.

Charleston, South Carolina lies within the Lower Coastal Plain geological province of the Atlantic Ocean coast. The near surface "overburden" soils consist primarily of Pleistocene deposits of the Quaternary Period. These Pleistocene formations generally consist of sand and clay deposits with varying amounts of shells and occasional organics. Beneath the "overburden" soils lies a highly calcareous soil stratum called the Cooper Group, known locally as the Cooper Marl Formation. The Cooper Marl Formation is a marine deposit of late Eocene to Oligocene Periods that underlies a significant portion of the Charleston Area. These soil formations are ideal for insitu testing, since they generally lack stiff/hard soils and/or rock formations that prevent penetration of standard DMT and CPTu tests.

The speed, cost, and amount of data from insitu testing, coupled with the need for increased geotechnical data caused by increases in the magnitude of the design earthquake within the relevant building codes, has driven the expanded use of insitu testing in the region. However, published comparisons of the various subsurface testing methods within the Charleston, SC region are scarce. Therefore, geotechnical engineers must rely on experience and judgment when using these various test methods.

The following paper presents comparisons of DMT with SPT and CPTu data from six (6) project sites in the Charleston, SC area with respect to soil classification, main testing result parameters (i.e. DMT E_D, SPT N and CPTu q_t values), liquefaction analysis, and settlement analysis.

2 CASE HISTORIES

Data from six (6) case histories (i.e. project sites) in the Charleston, SC area where DMT was performed adjacent to traditional soil test borings with SPT (hereafter referred to as SPT) and/or CPTu was complied. The DMT at these sites was conducted in accordance with ASTM D6635-01. The CPTu testing was conducted in accordance with ASTM D5778-95 (2000). The SPT was conducted in accordance with ASTM D1586-99. SPT N values were corrected to N_{60} values using the procedures described by Skepton (1986).

From the six (6) case histories, ten (10) DMT-CPTu test comparisons and nine (9) DMT-SPT test comparisons were conducted. Table 1 presents a summary of the case histories and the relevant subsurface testing data from each. Figure 1 presents the project site locations relative to the Charleston, SC area. Figures 2 and 3 present typical results of subsurface tests relative to the soil profile determined from the SPT for case histories 1 and 5, respectively.

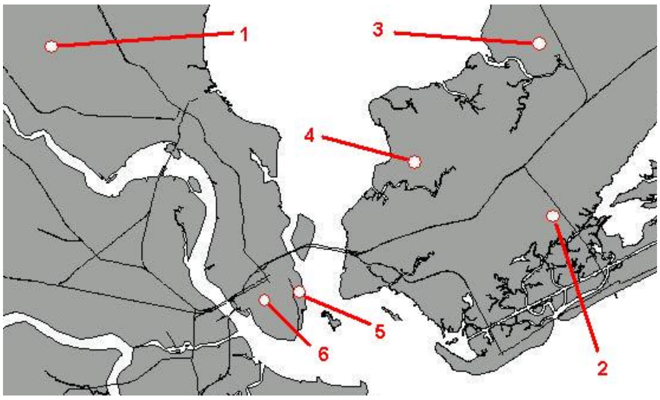

Figure 1. Subsurface Testing Project Site Locations Relative to the Charleston, SC Area.

Table 1. Case History Summary.

Case	Location	DMT[1]	Depth[2] (m)	CPTu[1]	Depth[2] (m)	Dist.[3] (m)	SPT[1]	Depth[2] (m)	Dist.[3] (m)
1	Charleston, SC	11	6.4	12	5.9	23	11	6.1	3
		18	7.4	17	6.0	23	18	6.1	3
2	Mt Pleasant, SC	5	13.7	10	6.3	30	4	6.1	30
		11	13.7	12	6.4	30	7	12.2	30
3	Mt. Pleasant, SC	2	7.5	1	7.2	12	NA	NA	NA
4	Mt. Pleasant, SC	2	6.3	1	12.1	12	NA	NA	NA
5	Charleston, SC	1	36.0	1	37.8	3	3	40.1	3
		2	35.8	3	36.6	3	2	40.1	3
		3	36.6	NA	NA	3	1	36.6	3
6	Charleston, SC	4	9.1	3	18.1	18	2	22.9	18
		5	10.3	3	18.1	18	1	22.9	18

NOTES:
1. Number assigned to DMT (a.k.a. D), CPTu (a.k.a. C), or SPT (a.k.a. B).
2. Depth of test below existing ground surface.
3. Distance from DMT.

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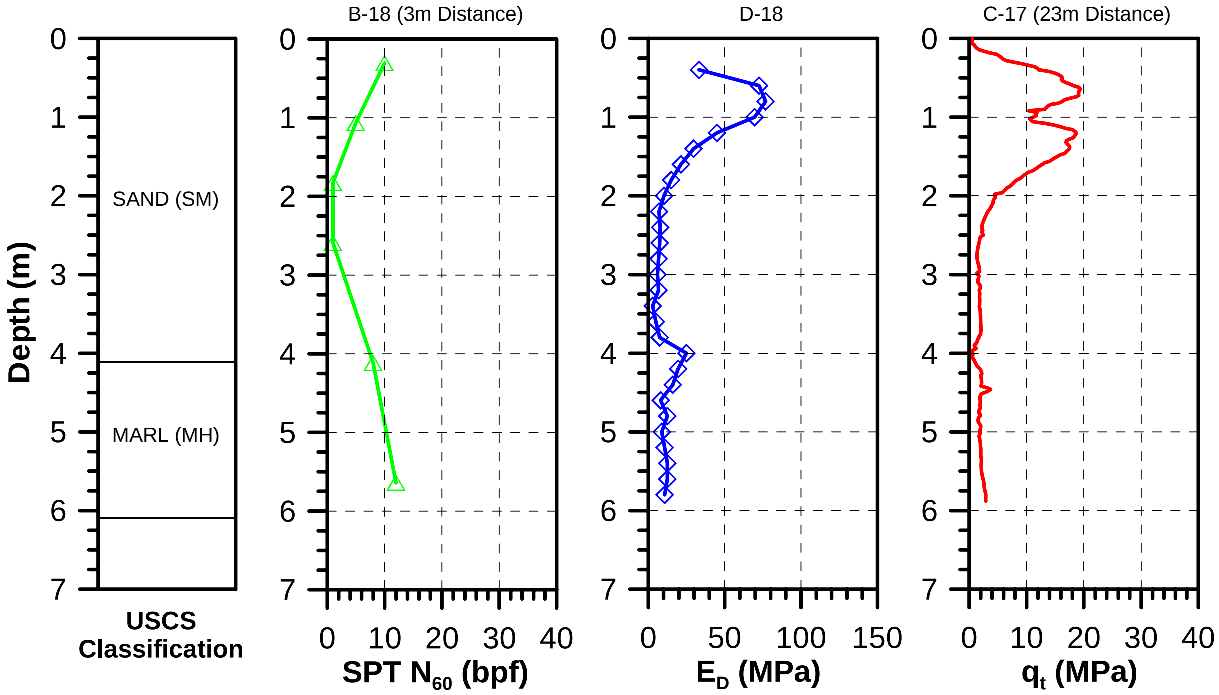

Figure 2. Comparison of Subsurface Testing Data (SPT N_{60}, E_D, and q_t) with USCS Classification for Case History 1.

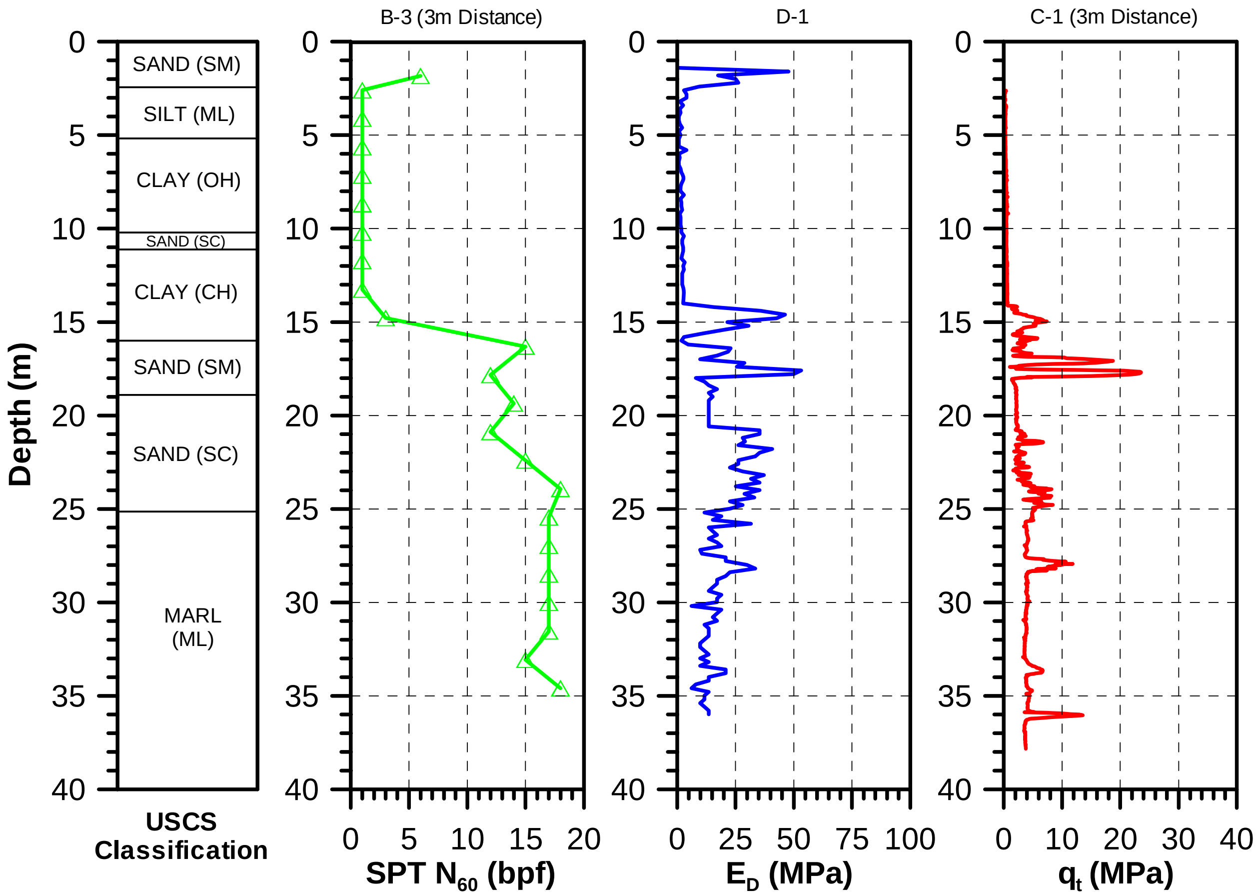

Figure 3. Comparison of Subsurface Testing Data (SPT N_{60}, E_D, and q_t) with USCS Classification for Case History 5.

Each site was relatively level within the limits of the subsurface testing (i.e. the ground surface did not vary in elevation more than 0.15m (6 inches) between test locations). However, ground surface elevation measurements were not taken. Therefore, no attempt was made to correlate the depths of the various subsurface tests with elevation. The small variance in elevation was deemed to not significantly affect the comparison of the three subsurface testing methods.

To minimize the effects of changes in soil stratigraphy during the test comparisons, only projects where the DMT, CPTu, and/or SPT were within

30m (100ft) were used. Furthermore, data from the other available subsurface tests not presented in this paper were examined to determine if the site soil profiles were sufficiently uniform to allow for test distances greater than 3m (10ft) to be used in this study.

3 SOIL CLASSIFICATION

Soil classification using the DMT for this study was done using the Material Index (I_D) and the relationships presented by Marchetti (1980). A summary of soil classification using I_D presented by Marchetti (1980) is shown in Table 2.

Soil classification using the DMT is based on mechanical behavior of the soil and not grain size and therefore is better termed a soil behavior classification. In general, I_D provides an expressive profile of soil type, and, in "normal" soils, a reasonable soil description. Note that I_D sometimes misdescribes silt as clay and vice versa. A mixture of sands and clays would generally be described by I_D as silt (Marchetti et al., 2001).

Table 2. Soil Classification Based on I_D (Marchetti, 1980).

Soil Type	Material Index (I_D) Range	
Peat/Sensitive Clays	<0.10	
Clay	0.10	0.30
Silty Clay	0.30	0.60
Clayey Silt	0.60	0.90
Silt	0.90	1.20
Sandy Silt	1.20	1.80
Silty Sand	1.80	3.30
Sand	<3.30	

Soil classification of soil samples collected via SPT was conducted in accordance with the Unified Soil Classification System (USCS). Refer to ASTM D2487-00 for additional details concerning the USCS.

A comparison of the USCS soil classifications at the SPT locations compared to the DMT soil behavior classifications at the same depth is presented in Figure 4.

Soil classification using the CPTu data was conducted based on the methods developed by Robertson et al. (1986) and Robertson (1990). Soil classification using CPTu data, as with the DMT, is based on mechanical behavior of the soil and is better categorized as a soil behavior classification.

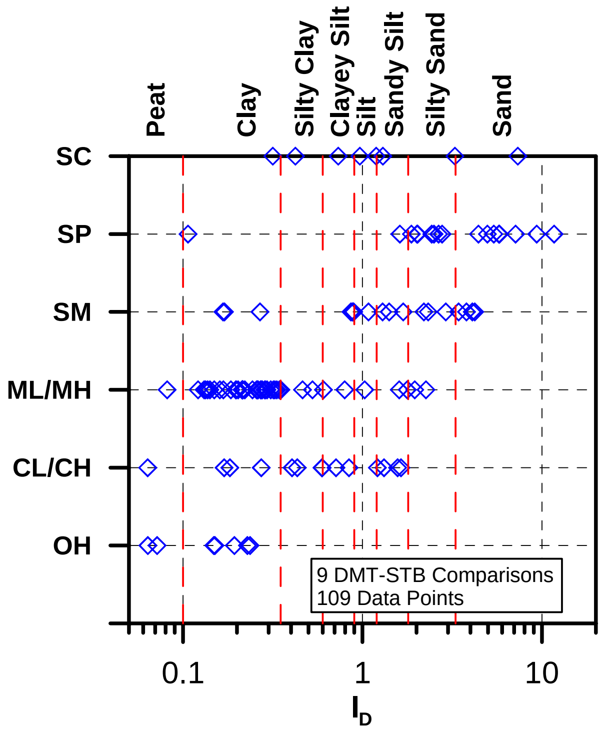

Figure 4. Comparison of USCS and DMT Soil Classifications.

As shown in Figure 4, the DMT and USCS soil classifications are in good overall agreement, with cohesionless soils (i.e. sands) and cohesive soils (i.e. clays and silts) groups generally aligning with each other. Soils classified as silts according to the USCS are generally classified as clays by the DMT. Although the DMT is known to mis-classify clays and silts (Marchetti et al., 2001), the majority of this mis-classification is due to a local soil strata known as the Cooper Marl Formation (CMF). Although the CMF typically classified according to the Unified Soil Classification System as a low plasticity sandy silt (ML) or sandy clay (CL), its USCS classification can range between CH, CL, MH, ML, SM, or SC.

The additional scatter between the USCS and DMT soil classifications is most likely due to differences between the methods. As previously stated, the DMT classifies soils not by grain size but by mechanical behavior.

Comparisons of the CPTu and DMT soil behavior classifications at the same depth is presented in Figure 5 for the Roberston et al. (1986) classification method and Figure 6 for the Robertson (1990) classification method, respectively.

As with the USCS-DMT soil classification comparison, the CPTu-DMT soil behavior comparisons in general show good overall agreement between cohesionless soils (i.e. sands) and cohesive soils (i.e. clays and silts) groups. However, a wide range of scatter exists between the soil behavior correlations between the two CPTu classifications methods and the DMT classification. This is clearly illustrated in the CPTu soil behavior classification for sand to silty sand in Figure 5. The correlating DMT soil behavior classification ranges from peat/sensitive clays to sand, with a relatively even distribution of data points across the various DMT classifications. These differences are most likely based on differences in the testing methods; i.e. CPTu classification is based primarily on vertical penetration resistance while the DMT is a horizontal expansion into the soil.

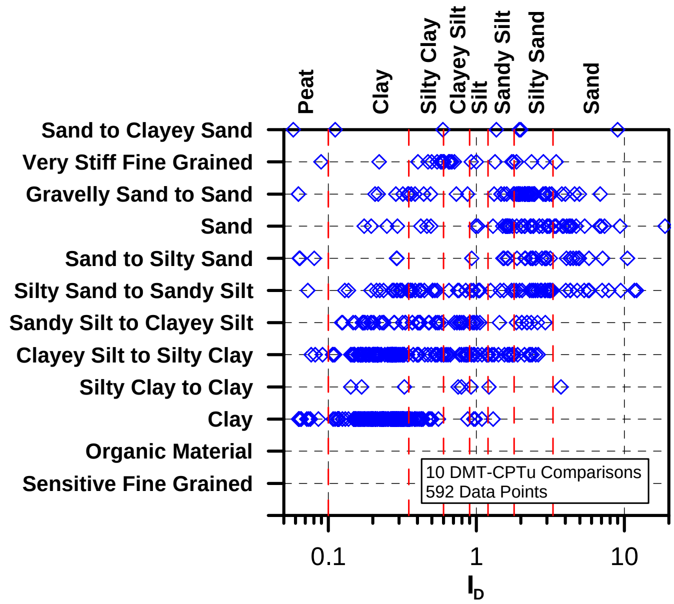

Figure 5. Comparison of CPTu Robertson et al. (1986) and DMT Soil Behavior Classifications.

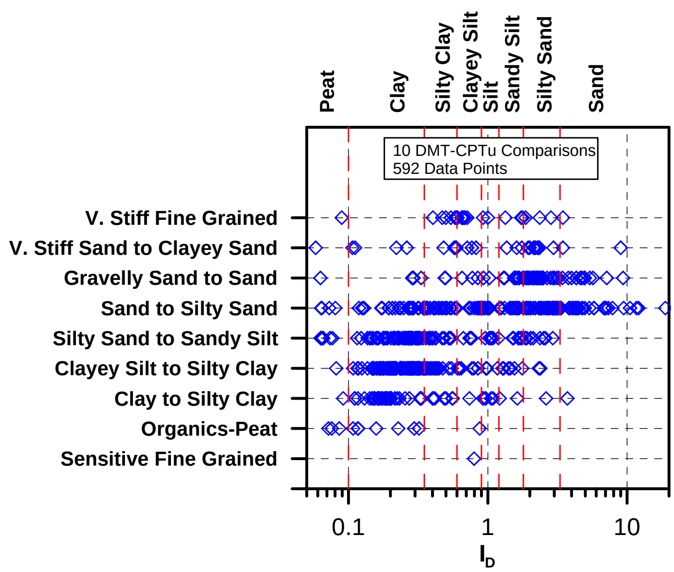

Figure 6. Comparison of CPTu Robertson (1990) and DMT Soil Behavior Classifications.

4 MAIN TEST RESULTS COMPARISON

Comparisons were made between main testing result parameters for each subsurface test; i.e. the DMT dilatometer modulus (E_D), SPT N_{60} value, and the CPTu corrected tip resistance (q_t). These testing results are generally the main parameters used in majority of design methodologies for the three test methods.

A qualitative comparison between the three main testing parameters in Figures 2 and 3 shows excellent correlations with depth. General trends in soil stiffness are observed within all three testing parameters. Quantitative comparisons were also conducted to examined relationships between the three testing parameters. A comparison of E_D and SPT N_{60} values is presented in Figure 7, while Figure 8 presents E_D vs. q_t. Within Figures 7 and 8, the results are divided into the three main soil behavior classifications from the DMT based on I_D data: clays ($I_D < 0.6$), silts ($0.6 \leq I_D \leq 1.8$), and sands ($I_D > 1.8$).

As shown in Figure 7, the E_D vs. SPT N_{60} comparisons shows general correlations between the two parameters for the three soil behavior types, although a wide range of scatter is observed for the three soil groups. In addition, the correlations vary in magnitude between the soil types (e.g. E_D (MPa) $= 1.08N_{60}$ for clays, $2.65N_{60}$ for silts).

A comparison of Tanaka and Tanaka (1999) E_D-N_{60} correlation in sands is also presented in Figure 7. The current data set shows a significant amount of scatter, while the Tanaka and Tanaka (1999) data noted good general agreement between the parameters. Tanaka and Tanaka (1999) had a D_{50} varying between 0.2mm to 0.4 mm, which is the same general range of sand particles found within the Charleston, SC region. Since the soil particle size between the two correlations is the same, the differences in the correlations are due to other factors not examined in this paper.

As shown in Figure 8, no clear relationships exist between E_D and q_t for the three soil groups.

5 LIQUEFACTION ANALYSIS COMPARISON

Due to its past earthquake history and changes/updates in the relevant building codes, the design earthquake in the Charleston, SC area has peak ground accelerations (PGA) ranging from 0.30g to 0.45g. Given the relatively loose nature of the overburden sandy soils in the region and these high PGA values, liquefaction is a major concern in the Charleston, SC area. Therefore, insitu testing methods should have an accepted design methodology for assessing the potential for liquefaction for them to be effectively used in the region. The lack of an effective and accepted liquefaction potential analysis procedure could prevent a test method from being used in the region.

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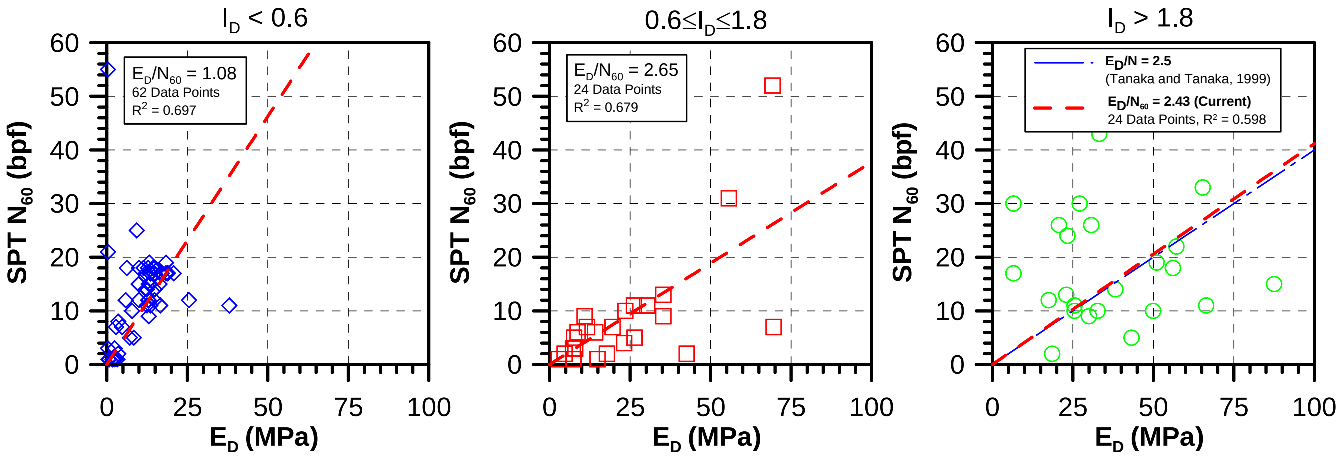

Figure 7. Comparison of Dilatometer Modulus (E_D) and SPT N_{60} Values.

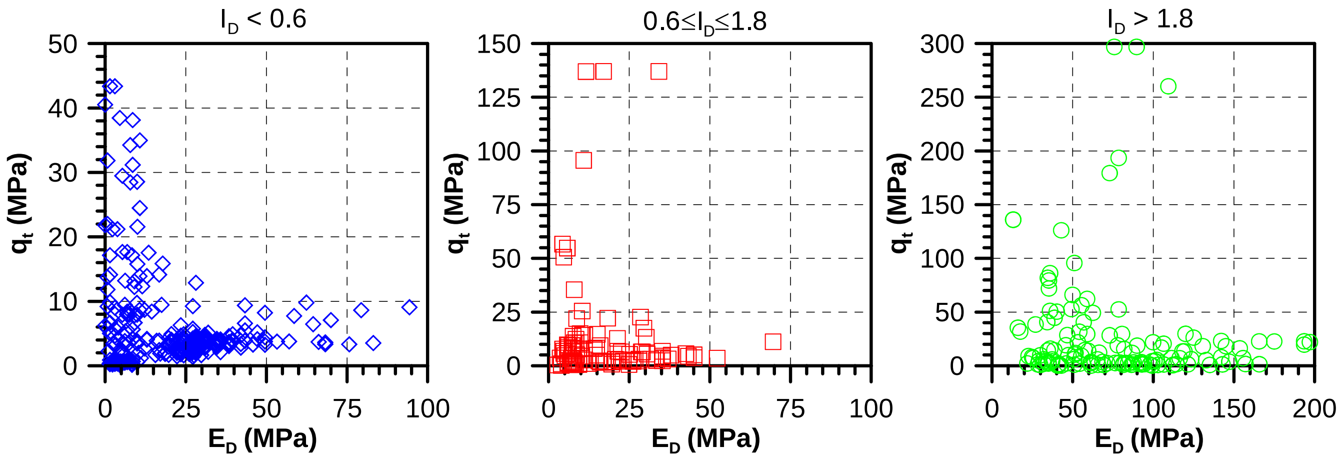

Figure 8. Comparison of Dilatometer Modulus (E_D) and CPTu Corrected Tip Resistance (q_t).

Liquefaction potential analysis via subsurface testing has been examined by a variety of researchers. In general, these analyses consist of comparing the seismic demand on the soil generated by the design earthquake (i.e. the cyclic stress ratio or CSR) to the capacity of the soil to resist liquefaction (i.e. the cyclic resistance ratio or CRR).

Liquefaction potential analysis comparisons were made for two (2) of the project sites. A design earthquake with a peak horizontal acceleration of 0.4 g and earthquake moment magnitude of 7.3 was used in our analysis. These parameters are typical for a design earthquake in the Charleston, SC area based on local building codes. The methods for evaluating liquefaction potential detailed by Youd and Idriss (2001) were used for the SPT and CPTu data. The methodology presented by Monaco et al. (2005) was used to evaluate the DMT data. The results of the liquefaction potential analyses are shown in Figures 9 and 10 for Case Histories 1 and 5, respectively.

As shown in Figures 9 and 10, the CRR's evaluated with the CPT and DMT are consistent to some extent in the sandy soils as encountered. However, the DMT is highly effective in demonstrating the liquefaction potential in the Cooper Marl Formation, which is a highly cemented silt and is unlikely to liquefy to the design earthquake. The SPT and CPTu analyses indicate that these layers would liquefy.

6 SETTLEMENT ANALYSIS COMPARISON

Settlement analysis comparisons for shallow foundations were made between the three (3) subsurface test methods at five (5) of the project sites. These sites have predominantly near surface sandy soils. The other two sites were not selected for settlement analysis due to large deposits of soft cohesive soils, which made them unsuitable for shallow foundations. Deformation estimates for the DMT, CPT, and SPT were conducted using the procedures described by Marchetti et al. (2001), Schmertmann (1978), and Burland and Burbidge (1985), respectively. In the analyses, an allowable soil contact pressure of 100 kPa and a square footing of 3 m were used. This allowable soil contact pressure and footing size are typical for commercial buildings in the area. A summary of the various settlement analyses results is presented in Table 3.

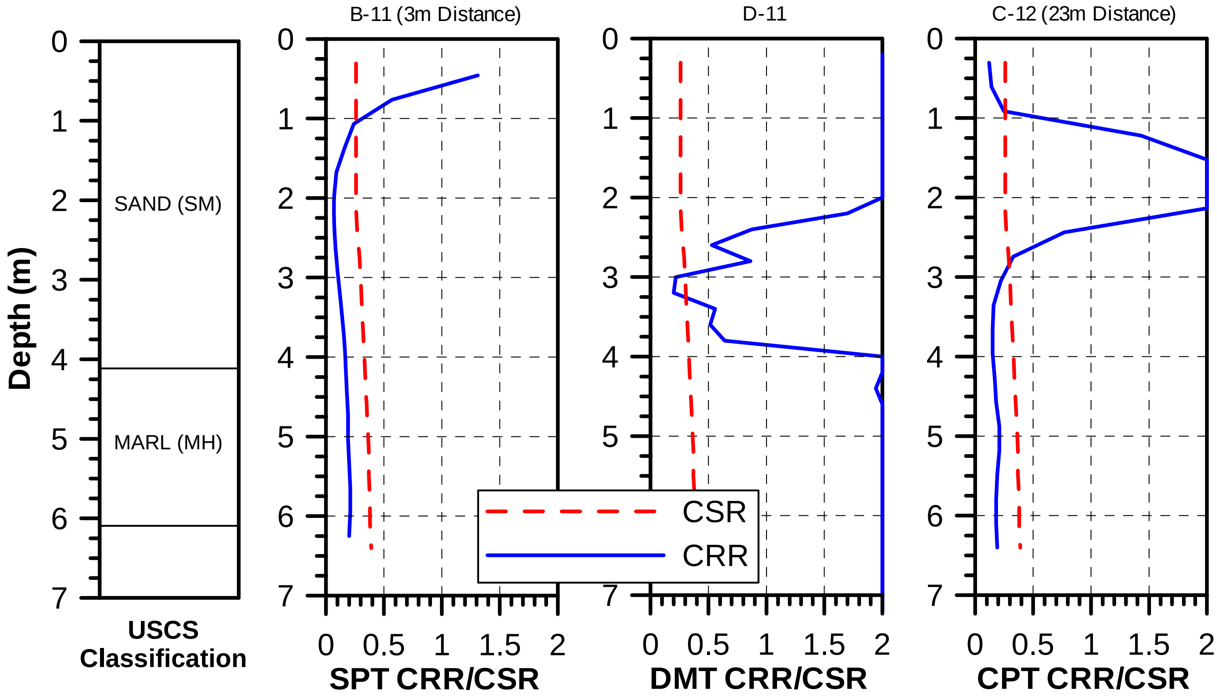

Figure 9. Comparison of Liquefaction Potential Analyses for Case History 1.

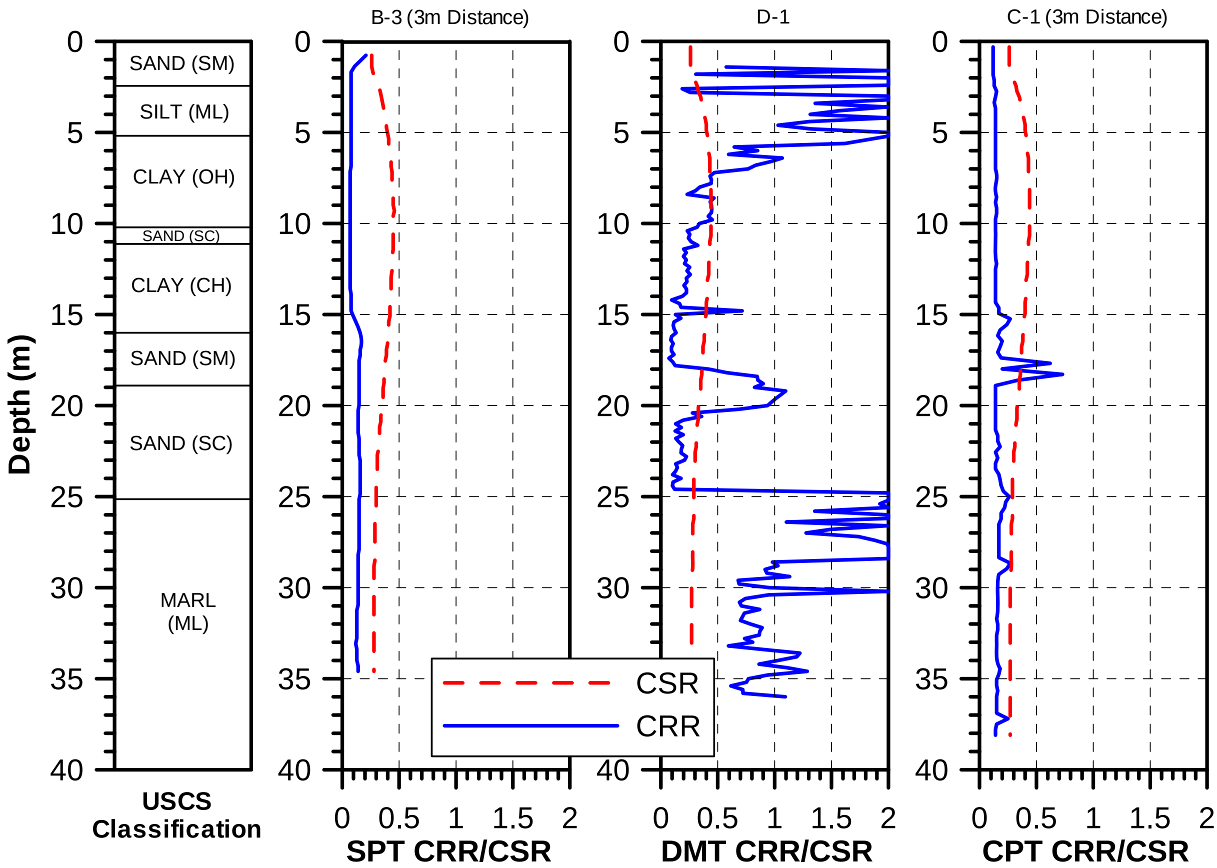

Figure 10. Comparison of Liquefaction Potential Analyses for Case History 5.

As shown in Table 3, the settlement estimates from the CPTu are in close agreement with those from the SPT. The settlements from the DMT are on the order to 2.3 to 4.4 times less than the CPTu/SPT measurements. Although limited data exists between DMT predicted and observed settlements in the Charleston, SC area, DMT settlement estimates are commonly preferred due to their past agreement in the technical literature (e.g., Lacasses and Lunne (1986), Hayes (1990), Woodward and McIntosh (1993)).

Table 3. Settlement Analysis Summary.

Case	Calculated Settlement (cm)		
	DMT	CPT	SPT
1	1.1	2.5	2.5
2	0.4	1.7	1.8
3	2.7	7.1	NA

7 CONCLUSIONS - RECOMMENDATIONS

DMT, SPT, and CPTu subsurface testing data from six (6) project sites in the Charleston, SC were presented. Comparison of the data from these sites showed the following:

Soil classifications between the three insitu tests showed overall general agreement between the major soil types (i.e. cohesionless and cohesive soils). Significant scatter was observed in the comparisons for more detailed soil classifications (e.g. silty sands) within the three test methods. However, given the major difference in the insitu testing methods (i.e. vertical penetration for the CPTu and horizontal expansion for the DMT), differences can and should be expected for soil behavior classifications from these tests.

General correlations exist between E_D and N_{60} values for the Charleston, SC area. However, significant scatter exists within these correlations. When coupled with the limitations of SPT design methodologies, we recommend the use of E_D directly instead of correlating to N_{60} values.

No correlations exist between E_D and q_t for the Charleston, SC area.

Settlement estimates for shallow foundations calculated using the DMT in the Charleston, SC area are considerably less than those calculated by CPTu and SPT methods. The DMT is commonly used for settlement calculations in the region based on the known limitations of the SPT and CPTu methods and past research showing good correlations between DMT estimates and observed settlements.

The DMT effectively evaluates the potential for liquefaction in sandy soils in the Charleston, SC area when compared to SPT and CPT analyses. In addition, the DMT shows that the Cooper Marl Formation is not susceptible to liquefaction, while the other two test types in general show a potential for liquefaction in this soil layer.

Based on the above conclusions and presented data comparisons, the DMT is shown to be an effective insitu testing tool in the Charleston, SC area.

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