Observations from Insitu Testing within a Calcareous Soil

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ABSTRACT: Flat Blade Dilatometer Testing (DMT) and Piezocone Penetration Testing (CPTu) within a calcareous soil formation in the Greater Charleston, SC area along with laboratory tests are reviewed. The calcareous soil investigated during the study is typically classified as a young lightly cemented overconsolidated clayey silt, which is known locally as the Cooper Marl Formation, and demonstrates relative uniformity throughout the area. Typical material index (I_D), dilatometer modulus (E_D), and horizontal stress index (K_D), corrected tip resistance (q_t), sleeve friction (f_s), and pore pressure behind the cone tip (U_2) were summarized for the CPTu and DMT, respectively. Due to the difficulty and uncertainty in characterizing the side friction from calcareous soils, the DMT and CPTu along with Osterberg-cell test results from drilled shaft load tests were used to improve the existing understanding of the marl behavior for engineering applications.

1 INTRODUCTION

Calcareous soils have been encountered in many regions around the world. In the last two decades, they have been studied as problematic materials in numerous cases regarding deep foundation design and construction practices. According to Jewell and Khorshid (1999), a very large gas production platform was supported on deep foundations bearing within lightly consolidated calcareous sediments on the North West Shelf of Western Australia. The actual friction capacity of the large open ended driven piles was substantially lower than the design values and after this occurrence many studies were then focused on the friction behavior of calcareous sediments by almost all the major international geotechnical researchers.

Unlike this problematic sediment, the calcareous soil formation in the Charleston, SC region, known locally as the Cooper Marl Formation (CMF), is a primary bearing stratum for supporting deep foundations in the area. The CMF is a relatively homogeneous formation, as determined by local geotechnical experience and a comprehensive examination of data from several project sites in the area (Meng et al., 2005). Unlike other problematic calcareous sediments, experience and testing in the CMF has shown it to a stable formation for deep foundations.

The following paper presents representative DMT testing results within the CMF along with the CPTu findings and some laboratory summaries in the greater Charleston area. Fundamental characteristic parameters of the CMF with the two testing methods are also presented and discussed. In a case study, Osterberg load cell test results were compared to the calculated undrained shear strengths derived from CPTu and DMT tests. The side shear resistance developed along the shaft side was measured with an Osterberg-cell test, which is often used to measure both end bearing and side shear resistance and provides estimates ascribed to each part. Unlike most other studies within the CMF (e.g., Camp, 2004), the drilled shaft was physically detached from the overlying non-marl soils and the test therefore provides a unique advantage of interpreting only the side shear resistance within the marl. Effectiveness of the interpretation of the strength parameters from CPTu and DMT testing results is discussed by using the Osterberg load cell test results.

2 CHARLESTON, SC AREA GEOLOGY

Charleston is located within the Lower Coastal Plain geological province of South Carolina along the Atlantic Coastal terraces, which is approximately 120 km in width. The "overburden" of the area consists of soft and loose Pleistocene and Recent marine deposits of the Quaternary Period. The area is primarily underlain by young marine deposits in chronologic age from Upper Cretaceous to Recent, which lie on ancient crystalline rocks (granites, gneisses, and schists such as the Black Mingo Formation). Immediately overlying the rocks is the "Great Carolinian Bed" consisting of Upper Cretaceous limestone (i.e., the Santee Limestone) and Eocene cementious marl (e.g., the Cooper Marl Formation). Figure 1 shows the typical geological strata underlying the Greater Charleston area.

3 GEOTECHNICAL CHARACTERIZATION OF THE COOPER MARL

A large quantity of testing results within the CMF is available from consulting projects across the area. Laboratory testing results including the index properties (i.e., natural water content, gradation, and Atterberg Limits), calcium carbonate content, and undrained shear strength are summarized in Table 1. The reviewed data were arbitrarily divided into the downtown Charleston and the Inland Charleston groups according to their geographic closeness and locations of the samples origin. According to the Unified Soil Classification System (USCS) (ASTM D2487), the CMF is classified as silt (ML) to elastic silt (MH) by using the averages in Table 1. In addition, the CMF has calcium carbonate contents between 60% to 70% and undrained shear strengths between 0.21 MPa and 0.25 MPa. In terms of statistics, there appears little difference between the two groups regarding the considered parameters and the CMF may be considered relatively uniform in the area. This conclusion matches experience by local practicing geotechnical engineers.

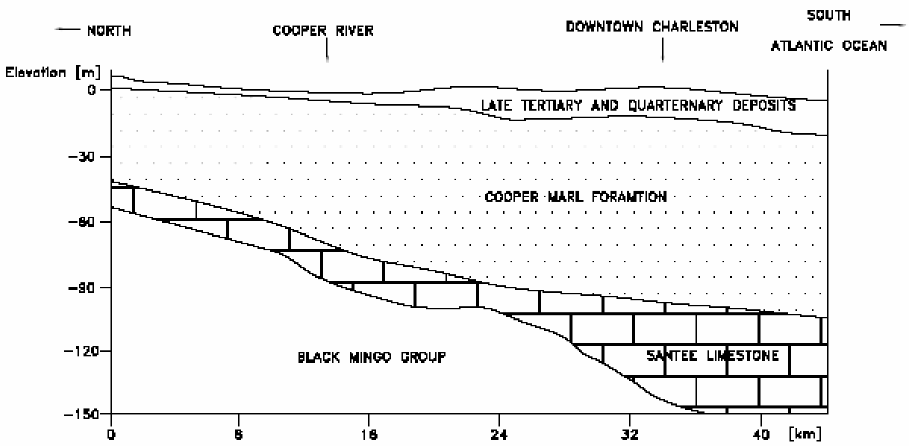

Figure 1. Geological profile of the Charleston area (Modified after Klecan et al., 2001).

Table 1. Summary of Laboratory Results of the Cooper Marl.

Location	Statistic	Wn (%)	FC <#200 (%)	Atterberg Limits LL	Atterberg Limits PI	$CaCO_3$ (%)	S_u (UU) (MPa)	Reference
Downtown Charleston	# of Tests	23	14	21	21	6	22	Klecan et al. (2001)
	Average	46	75	49	20	67	0.25	
	Stdev	5	13	5	6	9	0.05	
	Max	58	94	58	35	77	0.34	
	Min	32	49	40	12	57	0.17	
Inland	# of Tests	8	4	18	17	13	42	Unpublished Test Results
	Average	42	74	62	29	66	0.21	
	Stdev	6	6	22	14	4	0.16	
	Max	48	79	146	79	71	0.72	
	Min	30	65	44	13	60	0.02	

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From insitu tests, the CMF is typically identified by uniform testing parameters such a dilatometer modulus (E_D) for the DMT and corrected tip resistance (q_t) for the CPTu. For piezocone CPTu testing (i.e. CPTu), the CMF is also distinctly noted by the sharp increase in penetration pore pressure after encountering the marl. This pore pressure increase typically ranges from 1 MPa to 4 MPa regardless of embedment depth. This pore pressure increase phenomenon has been consistently observed in CPTu data within the CMF in the area and therefore serves as a signature of identification. Figure 3 shows typical DMT and CPTu results from adjacent testing (i.e. within 3 m) for a site in downtown Charleston, South Carolina. The material index (I_D), dilatometer modulus (E_D), corrected tip resistance (q_t) and sleeve friction (f_s) within the CMF are relatively uniform at values of 0.2 to 0.4, 150 to 200 bar, 3 to 5 MPa and 20 to 50 kPa, respectively. As shown in Figure 3, occasionally seams of increasing sand content in the CMF are encountered as observed at depths of 27 m and 33 m. These increased sand content seams typically increase the measurements of E_D and q_t.

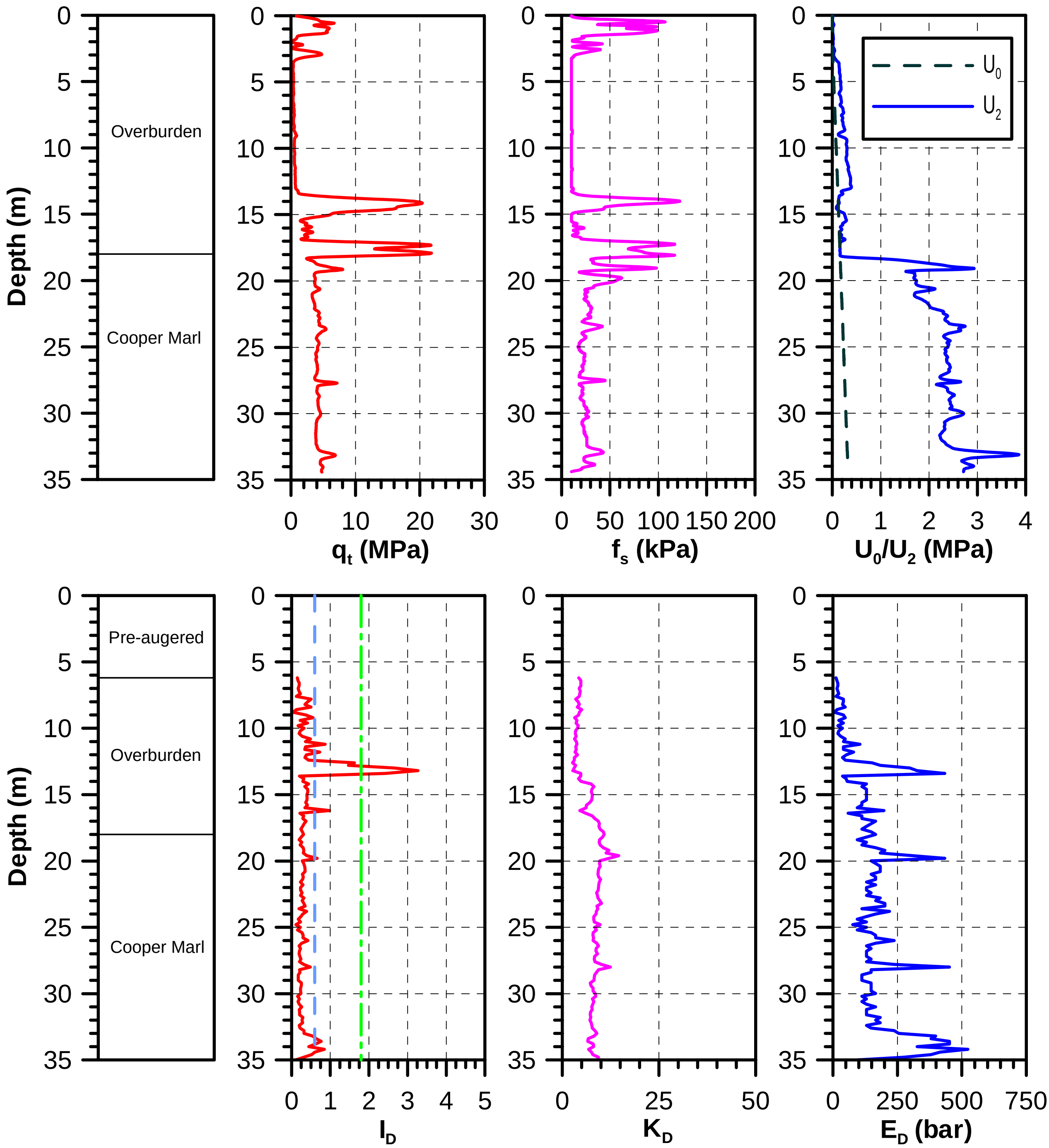

Figure 3. Representative soil profile from CPTU and DMT from downtown Charleston, SC site.

Given the noticeable increase in U_2 to delineate the CMF and the lack of a comparable parameter for the DMT, the DMT is often used as a complementary means of insitu testing for deeper subsurface investigations. Therefore, the DMT is used less frequently by local engineers for deep foundation designs.

Although there in no unique feature (i.e. signature) that identifies the CMF in the three "intermediate" DMT parameters, it is evident that the parameters are as effective in characterizing the CMF as a uniform silty clay to clayey silt. The material index (I_D) for the CMF ranges between 0.2 and 0.4 identifies it as clay to silty clay, which deviates from the typical laboratory classification based on the index properties. The original classification system by Marchetti (1980) was based on experience from normal soils instead of calcareous soils. It is very likely the CMF behaves more like clay to silty clay due to the cementation between the silt particles of the marl. Therefore, the CMF behaves more like a clay than silt and since the identification of the soil type from the DMT material index is based on soil behavior rather than the index properties, the DMT classification shows how the soil behaves insitu. The horizontal stress index (K_D) of the CMF ranges between 6 and 10 and demonstrates a modest decreasing trend versus the embedment depth.

4 O-CELL TESTING ON A DRILLED SHAFT

For a parking garage project in Charleston, SC, DMT and CPTu tests were predominantly used for the geotechnical exploration. Given the high structural loadings, the structure was founded on drilled shafts embedded within the CMF, which was located approximately 6 m below the existing ground surface. Figure 4 presents the location of the project relative to the downtown Charleston, SC area.

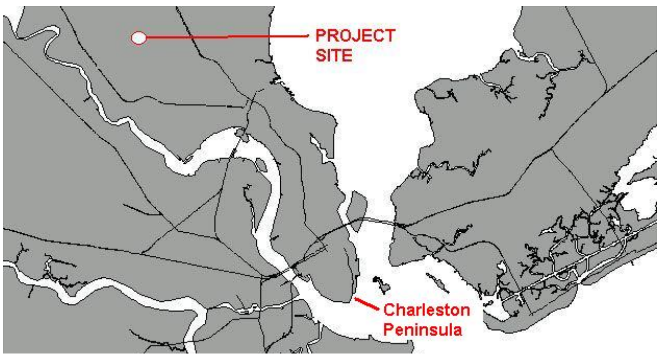

Figure 4. Drilled Shaft Testing Site relative to Charleston.

To verify the design and production procedures, a test drilled shaft was installed at a non-production location. The test shaft had a nominal diameter of approximately 1.4 m and a total length of 10 m. The test shaft was embedded 5 m into the CMF. The shaft was constructed such that the overburden soils above the CMF were not in contact with the shaft. An Osterberg Load Cell (i.e. O-Cell) was installed at the base of the shaft. Refer to Osterberg (1995) for additional details of the O-Cell. DMT and CPTu results adjacent to the test drilled shaft are presented in Figure 5.

Nine days after concrete placement, static load testing was conducted using the O-Cell. During the test, load was applied to the shaft stepwise through a hydraulic pump and was maintained at the load level for a minimum of 8 minutes before a next step load was added. Each load step was uniformly set at 177 kN. When the total load reached approximately 2.8 MN, the test shaft was pushed upward approximately 76.2 mm, which was considered a sign of side friction failure. At the time, the end bearing of the shaft had a downward displacement of approximately 8.6 mm. The results of the static load testing using the O-Cell are presented in Figure 6.

The side friction from the O-Cell static load testing was determined by the following formula:

$$Q_s = f_s \cdot A_s \qquad (1)$$

where Q_s is the side friction capacity around the shaft, f_s is the side friction along the shaft, and A_s is the contact area between the shaft and its surrounding soils. For Q_s = 2.8 MN and A_s = 22 m² (based on a shaft diameter of 1.4 m in the CMF), f_s was determined to be 127 kPa. It was therefore concluded that design side friction of 127 kPa can be used for production shafts for the CMF on this site. This result agrees closely with typical values for skin friction in the CMF for drilled shafts based on local experience (e.g., Wagoner et al., 1984).

The results of the DMT and CPTu were analyzed to evaluate the use of undrained shear strength values from these tests in determining the design skin friction within the CMF. These calculated CMF skin friction values were then compared to the results of the O-Cell test.

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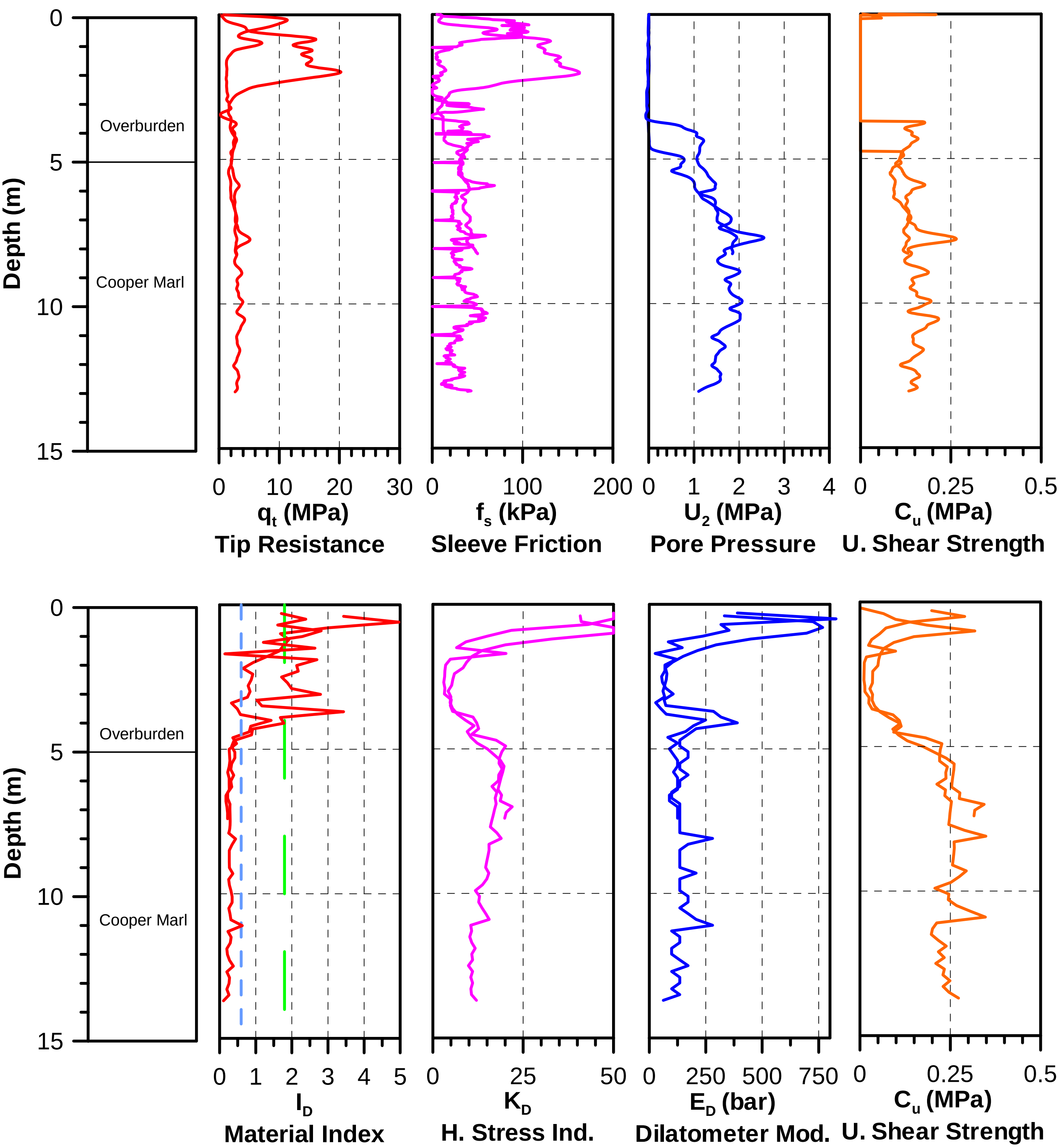

Figure 5. CPTu and DMT adjacent to the test shaft location

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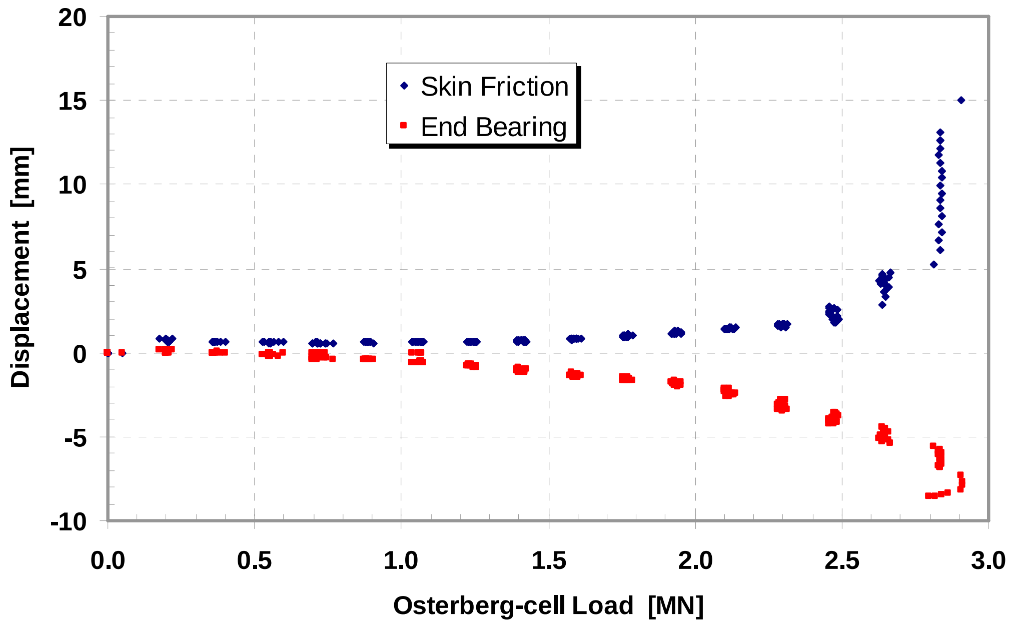

Figure 6. Osterberg-cell test results showing the shaft side and end displacement versus the applied load.

Correlations between CPTu results and soil strength parameters have been well established for common soils, whereas there is little information available for the fine-grained calcareous soils (Lunne et al., 1997). A correlation between the undrained shear strength and cone tip resistance from Beringen et al. (1982) for calcareous clays is presented in the following equation:

$$C_{u\_CPT} = \frac{q_c}{N_k} \tag{2}$$

where q_c is the uncorrected cone tip resistance and N_k is a regression coefficient between 15 and 20 based on study of offshore Bombay and North Sea clays. In this study, N_k was determined to be 15 based on the authors' local experience and the corrected tip resistance (q_t) was used in place of the uncorrected tip resistance (q_c). The estimated undrained shear strength based on the cone tip resistance was between 0.1 to 0.2 MPa as shown in Figure 5.

From the DMT results presented in Figure 5, it is evident that the CMF has a uniform material index (I_D) between 0.1 and 0.6 and therefore is expected to behave as a clay. The horizontal stress index (K_D) is in a range between 10 and 20, which has a decreasing trend with the embedment depth. In addition, the dilatometer modulus was calculated to be approximately 100 to 120 bars, except for the values distorted by denser sand seams. These three "intermediate" DMT parameters indicate that the CMF is a lightly cemented calcareous soil that should still be characterized as a normal soil without significant deviation. However, it is noted by the authors of this paper that most of the available empirical formula for calculating DMT parameters are based on general cohesive soils without previous verification for use on the cemented materials such as calcareous soils. The undrained shear strength is interpreted by using the horizontal stress index, K_D, in the following formula proposed by Marchetti (1980):

$$C_{u\_DMT} = 0.22\sigma'_{v0}\left(0.5K_D\right)^{1.25} \tag{3}$$

where σ'_{v0} is effective stress. The undrained shear strength of the CMF is between 0.2 and 0.3 MPa as shown in Figure 5.

The data indicates that the estimated undrained shear strength of the CMF from the DMT is approximately 50% higher than that from the CPTu. Although the undrained shear strength from the DMT compares better to the averages of the reviewed laboratory results as shown in Table 1, it is difficult by large to claim a better estimate regarding the uncertainties of each individual correlation.

Poulos (1999) proposed a correlation between the unconfined compressive strength and skin friction for moderately to well-cemented calcareous sediments as Equation (4) below:

$$f_s = A\left(q_u\right)^{0.5}\ \text{kPa} \tag{4}$$

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where q_u is the unconfined compressive strength in MPa and A is 200. The unconfined compressive strengths from CPTu and DMT are determined to be between 0.2 to 0.4 and 0.4 to 0.6 MPa, respectively. By using Eq. 4, the side frictions from CPTu and DMT are estimated to be approximately 89 to 126 kPa and 126 to 155 kPa, respectively. When these estimated side frictions are compared with the O-Cell test result, it appears that the estimate from the DMT is closer to the side friction of 127 kPa determined from the O-Cell test.

5 CONCLUSIONS – RECCOMENDATIONS

Insitu testing including Flat Blade Dilatometer Testing (DMT) and Piezocone Penetration Testing (CPTu) was primarily used to characterize the geotechnical behavior of a calcareous soil formation in the Greater Charleston, SC area. The calcareous soil investigated during the study was a young lightly cemented clayey silt, which is known locally as the Cooper Marl Formation (CMF). Previous testing experience in this formation has shown that it is a relatively uniform soil deposit. Typical material index (I_D), dilatometer modulus (E_D), and horizontal stress index (K_D), corrected tip resistance (q_t), sleeve friction (f_s), and penetration pore pressure behind the cone tip (U_2) were summarized for the DMT and CPTu, respectively. Due to the difficulty and uncertainty in characterizing the side friction from calcareous soils, Osterberg-Cell test results from a test drilled shaft were used to improve the existing understanding of the CMF behavior for engineering applications.

Our study concluded that design side friction of 127 kPa between the marl and drilled shaft can be established. This result agrees closely with typical values for skin friction in the CMF for drilled shafts based on local experience. When these estimated side frictions from CPTu and DMT are compared with the O-Cell test result, it appears that the estimate from DMT is closer to the estimated side friction from the O-Cell test.

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