Strength evaluation of soft marine deposits in Atlantic Coastal Plain using in-situ testing methods

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ABSTRACT: The strength of very soft marine deposits can be very difficult to evaluate with the conventional methods such as drilling and laboratory testing of "undisturbed" samples. For these soils that are on the extreme end of the soil consistency spectrum, conventional tools that are designed to test a wide range of soil types and consistencies might not be "optimum" for a geotechnical site investigation. In-situ tools such as the cone penetration test (CPT), dilatometer (DMT) and vane shear test (VST) are well established and well accepted tests, however, they all have limitations in very soft soils. Full flow probes such as the ball and T-bar penetrometers, were developed specifically for very soft soils. This paper compares the measurements from various in-situ methods used on soft soil sites and discusses results.

1 INTRODUCTION

Characterization of soft marine soils presents many challenges to the practicing engineer. When they must be characterized, their low strength ($s_u \leq 500$ psf or 24 kPa) and high compressibility are critically important. Currently, economically practical in-situ methods that can be used to evaluate the compressibility of such soils are limited. There are many in-situ methods, however, that are used to evaluate the strength of soft soils. These methods have highly varying degrees of accuracy and applicability, especially in very soft soils. Some of the limitations of the more commonly used methods have been recognized in the offshore industry for quite some time and alternative test methods, such as full flow penetrometers have been developed as a result. These tools, originally developed for offshore environments, are applicable for land-based investigations as well. The case history presented herein provides an opportunity to compare the results of more traditional soft ground exploration methods with the newer, full flow penetrometer methods.

2 TEST METHODS

2.1 *Cone Penetration Test (CPTu)*

The cone penetration test is a very popular in-situ test for soils that are compatible with direct push methods. Typically, the cone penetrometer used in practice measures tip resistance (q_c), sleeve friction (f_s) and porewater pressure between the tip and sleeve (i.e., the u_2 position). This allows for the correction of the measured tip resistance q_c to account for dynamic pore pressures acting on the back of the tip. The tip resistance, q_c, is corrected by (Lunne, et al 1997):

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

where q_T is the corrected tip resistance and *a* is the end area ratio. For strength evaluations, undrained shear strength is often evaluated using net cone resistance, q_{net} which is defined as:

$$q_{net} = q_T - \sigma_{vo} \tag{2}$$

Where σ_{vo} is the total vertical stress. The undrained shear strength, s_u, is commonly estimated using the following equation (Lunne, et al 1997):

$$s_u = \frac{q_{net}}{N_{kt}} = \frac{q_T - \sigma_{vo}}{N_{kt}} \tag{3}$$

Where N_{kt} is an empirical factor generally between 10 and 20.

The measured tip stress reflects the stress state within the soil, the porewater pressures generated by the penetration of the cone penetrometer, and the soil resistance or strength. In very soft soils with tip stresses typically less than 300 kPa, and in some cases less than 100 kPa, the soil resistance component may be relatively small compared to the stress state and pore water pressure components.

Additionally, the broad range of values of N_{kt} (10 to 20) also poses a problem when attempting to determine shear strength values to use in design. When available, laboratory or other in situ testing results can be used to determine the appropriate factor but a mid-range value of 15 is frequently assumed for production-oriented data processing that is used throughout the industry. This can lead to an underestimation of 50% or an overestimation of more than 30% of the soil's strength.

In very soft soils where the accuracy of the tip measurements may be uncertain, Lunne (1997) suggested estimating s_u from excess pore pressures:

$$s_u = \frac{\Delta u}{N_{\Delta u}} \tag{4}$$

Where Δu is the difference between dynamic pore pressure, u_2, and hydrostatic water pressure and $N_{\Delta u}$ is an empirical factor between 7 and 9 (Mayne & Holtz (1988).

2.2 *Vane Shear Test (VST)*

The vane shear test consists of a four bladed vane typically varying in size from 35 mm to 100 mm. Larger blades, > 150 mm, while not standard can be used for extremely soft soils. As the vane is rotated at a constant rate, the torque required to rotate the vane is recorded as a function of rotation. The torque is then correlated to s_u using the following equation given in ASTM 2573-01:

$$s_u = \frac{12T_{max}}{\pi D^2\left(\frac{D}{\cos(i_T)} + \frac{D}{\cos(i_B)} + 6H\right)} \tag{5}$$

where T_{max}= maximum torque (corrected for rod and apparatus friction); D= vane diameter; H= height of vane; and i_T and i_B are angles of taper for the top and bottom of the vane blades, respectively. It was recognized by Bjerrum (1972) that the s_u estimate must be corrected for use in engineering calculations. The equation is given as:

$$\tau_{mobilized} = \mu_v(s_u) \tag{6}$$

Chandler (1988) recommends the following simplified equation for calculating μ_v:

$$\mu_v = 1.05 - 0.045(PI)^{0.5} \tag{7}$$

Several factors other than soil strength can affect the torque measured during the test. The most predominant are rod friction, apparatus friction and rotation rate. Unfortunately, compared to the other test methods, the equipment to perform the test is not standardized. Test execution can vary from rotating the blade with a hand operated torque wrench to a computerized procedure using electric gear boxes and downhole torsional load cells.

2.3 *Dilatometer Test (DMT)*

As described by Marchetti (1997), the dilatometer consists of a flat blade with a flexible membrane. At select test depths, the cavity behind the membrane is pressurized and the pressures required to expand the membrane flush with the blade (A-reading) and expand the membrane 1.1 mm away from the blade (B-reading) are recorded. The pressure at which the membrane deflates back flush with the blade (C-reading) may also be recorded. These readings need to be corrected for membrane stiffness using:

$$p_o = 1.05(A - Z_M + \Delta A) - 0.05(B - Z_M - \Delta B) \tag{8}$$

and

$$p_1 = B - Z_M - \Delta B \tag{9}$$

where ΔA and ΔB are the pressure readings taken under atmospheric conditions before and after penetration to account for membrane stiffness. Z_M is the gage reading at atmospheric pressure. With standard membranes, a significant portion of the resistance (i.e., applied pressure) in very soft soils is due to membrane stiffness. Typically, membrane stiffness can account for up 0.7 bar of the pressure needed to conduct the test. In very soft soils, A and B readings are typically on the order of < 4 bar (depending on depth). To decrease the influence of membrane stiffness on the results, a special softer membrane can be employed.

For fine grained soils, Marchetti, 1997 presented the following relationship for strength estimation:

$$s_u = 0.22\sigma'_{vo}\left(0.5K_D\right)^{1.25} \tag{10}$$

Where K_D is the horizontal stress index calculated using the A- and B-readings. Schmertmann, 1981 also gives an estimation of undrained shear strength using the following formula (where u_o is hydrostatic pore pressure):

$$s_u = \frac{p_o - u_o}{10} \tag{11}$$

2.4 *Full Flow Penetrometers*

Full flow penetration testing is very similar to cone penetration testing with the exception of the tip geometry. Developed by Stewart and Randolph (1991), full flow penetrometers originally started as a T-Bar configuration. Since then, the ball configuration, which offers some practical advantages with respect to damage resistance, has also emerged. The test can be performed with a purpose built flow penetrometer or by simply installing a modified tip on a cone penetrometer body. The test is only applicable in soils soft enough to fully envelop (i.e. flow around) the tip during penetration. When the soils flow around the tip, the effect of overburden stresses on the measured values is reduced because a significant portion of the overburden stresses acting on the tip counteract one another. Strength evaluation using the results is similar to the correlation for CPT data and is given by the equation below:

$$s_u = \frac{q_{net}}{N} \tag{12}$$

Where N is an empirical factor generally between 9 and 13 and q_{net} is defined as:

$$q_{net} = q - \left[\sigma_{vo} - u_2(1-a)\right]\frac{A_s}{A_p} \tag{13}$$

Where A_s is the cross sectional area of the shaft and A_p is the projected area of the tip. Note that if $A_s = A_p$ (as with a cone penetrometer), the equation simplifies to equation 3. As indicated by eq. 13, the greater the projected area of the tip compared to the shaft, the smaller the influence of overburden stresses and pore pressure effects on the measured values. However, deployment of the probe increases in difficulty as the projected area increases. The most commonly cited area ratio (A_p/A_s) is 10, but Yafrate et al, 2007 suggested that the benefits of a full flow failure mechanism are realized when A_p/A_s is > 5.

The increase in tip area also increases the "apparent" resolution of the resistance values measured by a given load cell as compared to tip measurements conducted with a standard conical tip penetrometer. Another advantage is the ability to measure the response of the soils during cycling of the probe. This allows one to observe the remolded behavior of the soil after several retract and thrust cycles of the probe (typically over a 1-meter span). There are several publications that illustrate the accuracy of the strength evaluation of full flow probes in soft soils; notably Stewart & Randolph (1994), Lunne, et al (2005), DeJong, et al (2004) and Weemees, et al (2006).

3 FIELD TESTING PROGRAM

3.1 *Site and Geology*

Data (via CPT, DMT, VST, and Full Flow Penetrometer Testing) were collected at a soft ground coastal plain site in North Charleston, South Carolina. The property, which will eventually support a new container terminal, consists of salt marshes, filled salt marshes and tidal flats, and fine-grained dredge spoil. Comparative data were collected at four locations. Conditions at test locations B-34 and B-40, generally consisted of relatively undisturbed, high plasticity, soft marine deposits. Conditions at test Locations SE-1 and SE-7 consisted of 4 to 5 meters of predominately coarse-grained non-plastic fill overlying fine-grained, highly plastic, dredge spoil. Typical CPT measurements for locations B-34 and B-40 consisted of q_{net} on the order of 100- 300 kPa and f_s on the order 4- 7 kPa. For the SE locations q_{net} is on the order of 100- 300 kPa and f_s is generally 7- 15 kPa.

3.2 *Testing and Apparatus*

The cone penetration testing was conducted with a 10 cm^2 digital cone with the pore pressure measured in the u_2 position. The cone and data acquisition system was manufactured by Vertek. A reported tip load cell capacity of 100 kN with an accuracy of 0.2% is given for this penetrometer. The strength estimations using the CPT data used N_{kt} and $N_{\Delta u}$ factors of 11.5 and 8 respectively.

The dilatometer and a manual pressure control box were manufactured by GPE. Standard membranes were used for the testing. Membrane stiffness' ranged from ΔA = 0.10 to 0.15 bar and ΔB= 0.60 to 0.70 bar.

The vane shear testing was conducted with a 92 mm field vane manufactured by Acker Drill Company. The system uses a manually operated, geared drive-head to apply torque and the resulting force is measured using a Dillon X-FG force gauge (dial) with a 445 N (100 lb) capacity and 4.4 N (1 lb) increments. The gauge was mounted on a 300 mm (1 ft) moment arm.

The full flow testing using T-bar and ball configurations was conducted with a 10 cm^2 cone penetrometer manufactured by Adara Systems. A tip load cell capacity of 50 kN was used. The T-bar and Ball tips have a cross-sectional area of approximately 60 cm^2 (A_p/A_s = 6). The strength estimations for both the T-bar and ball data used an N factor of 11.5. An assumed unit weight of 15.7 kN/m^3 (100 pcf) was used in the total stress calculations.

3.3 *Results*

The plots given in Figure 1 compare the strength estimations of various in-situ test methods performed at four different locations on the site.

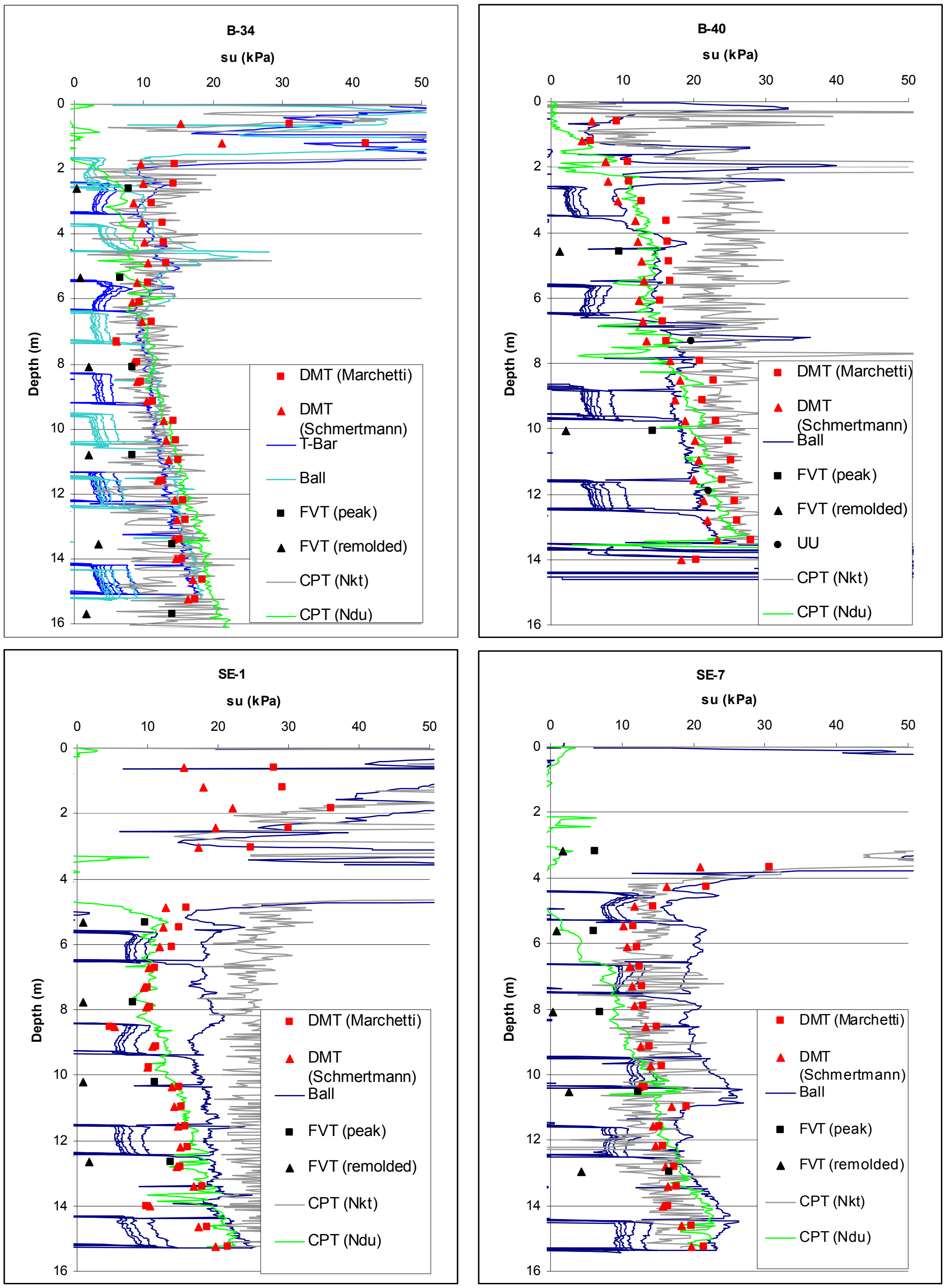

Figure 1. Shear strength (s_u) estimations at North Charleston, South Carolina. The Ball and T-Bar full flow penetrometer data include load cycling to determine remolded strength values.

4 DISCUSSION

The results presented in Figure 1 indicate very good agreement between most of the test methods in locations B-34 and B-40. The strength estimation using the CPT N_{kt} method was on average reasonable but with substantial scatter. This is most likely due to the resolution of the load cell used.

In the SE locations, the dilatometer, vane shear and CPT ($N_{\Delta u}$) estimations had good agreement. In the middle portion of the profile (5 to 11 meters), the full flow strength estimation after one cycle was in closer agreement with the other test methods. At the lower portion of the sounding (11 to 15 meters), the ball estimations were more in line with the other test methods. This could be caused by flow of the soils around the ball not fully occurring during initial insertion in the shallower depths. The partial flow would cause a greater portion of the in-situ stresses acting on the tip to occur on the leading side of the ball and increase the measured values. Again, the strength estimations using the CPT tip value and N_{kt} factor include substantial scatter, which is likely due to the accuracy of the cone load cell.

5 CONCLUSIONS

Two main factors need to be considered when interpreting data taken in very soft soils: resolution of measuring system and the influence of environmental factors, such as pore pressure effects and overburden stresses, on the measured values. While this conclusion should not be anything new to the reader, these factors are many times not considered when planning explorations in very soft soils.

All of the in-situ tests presented in this paper can accurately predict the strength of soft soils if deployed properly. The CPTu and full flow probes offer the advantages of a nearly continuous profile and speed over the vane and dilatometer test. An additional advantage to the full flow probes is that remolded strength behavior can also be characterized. To have confidence in the strength estimations using these tests, the engineer must understand and account for the factors (other than soil strength) that effect the measurements taken in the field. Otherwise, the only conclusion that one could confidently draw from the data is that the soils are “very soft” and one could surmise the same conclusion by much cruder methods such as SPT borings or geological maps.

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