IMPROVED TECHNIQUES FOR THE IN-SITU DETERMINATION OF UNDRAINED SHEAR STRENGTH IN SOFT CLAYS

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ABSTRACT
Undrained shear strength results from the T-bar and Ball penetrometers are compared with those obtained from the field vane, piezo cone, and dilatometer at three sites in the Lower Mainland of British Columbia. The sites include deltaic deposits of soft clay silts and moderately to highly sensitive clays. The sites consist primarily of normally consolidated soils. Test procedures and methods of interpretation are described for each in situ test and lab test. The ability of the T-bar and Ball penetration test to accurately and reliably determine undrained shear strength of clayey soils is discussed in relation to the field vane test, piezo cone test, and the flat dilatometer test.

RÉSUMÉ

Key words: T-bar, Ball, CPT, CPTU, Dilatometer, Vane, Undrained Shear Strength, In-Situ Testing, Unconsolidated Undrained

1. INTRODUCTION
Geotechnical engineering design in the Lower Mainland of B.C. frequently requires characterization of the undrained shear strength ($s_u$) profile in saturated soft sediments. Most commonly, $s_u$ is determined from in situ test results, typically comprising electronic piezometer cone penetration testing (CPTU) or field vane shear testing (FVT). The CPTU offers the advantage of a continuous profile of parameters which allow interpretation of stratigraphy as well as estimates of $s_u$. Site specific correlations are frequently developed by carrying out adjacent CPTU and FVT soundings.

In very soft sediments, errors introduced by large corrections to the raw data, and the resulting uncertainty and variability of correlation factors between $s_u$ and primarily CPTU parameters has led to the development of new in situ tools for use in these soils, especially in the offshore.

The purpose of this paper is to present the results of experience in the Lower Mainland with two new tools, the T-bar and the Ball penetrometers, examples of full-flow penetrometers. Both the size and the shape of the full-flow penetrometers provide advantages over the standard CPTU in soft soils. The increased size results in better measurement resolution and the full-flow movement of soil around the probes result in only minimal influence of overburden pressure on the calculation of shear strength. The rationale behind the development of the tools is provided and guidelines for the selection of equipment, data collection and reduction of the results are presented. Profiles of estimated $s_u$ are provided for three sites and are compared to values interpreted from CPTU and dilatometer (DMT) profiling.

2. BACKGROUND
The $s_u$ profile is typically determined from the CPTU net tip resistance, $q_{net} = q_t - \sigma_v$, using the following relationship:

$$s_u = \frac{q_t - \sigma_v}{N_{kt}} = \frac{q_{net}}{N_{kt}}$$

where $N_{kt}$ is an empirical factor, $q_t$ is the measured tip resistance, $q_c$, corrected for unequal end area pore pressure effects on the cone tip.
In very soft, normally to lightly overconsolidated sediments, $\sigma_{vo}$ can be a significant proportion of $q_c$ and the pore pressure can be similar in magnitude to $q_c$. These effects introduce uncertainty to the estimated values of $u_2$ and are considered the likely reason for the large scatter in published $N_{kt}$ values. For this reason, Lunne et al. (1997) recommended the use of excess pore pressure instead of $q_{net}$ to derive $u_2$ for very soft soils.

In an effort to reduce the inaccuracies due to these large corrections but to continue to achieve a continuous profile of resistance, the T-bar test was introduced first in the centrifuge (Stewart and Randolph, 1991) and then in the field (Stewart and Randolph, 1994). The T-bar is a cylindrical bar mounted at 90 degrees to the push rods. Since its introduction, field testing has been carried out at well-characterized sites in Australia (Chung and Randolph 2004), Norway (Lunne et al. 2005), Ireland (Long 2005), and the USA (DeJong et al., 2005). The Ball penetrometer, a spherical ball mounted on the end of the push rods, has been mainly assessed in the centrifuge (Watson et al. 1998) or by numerical modelling (Lu et al. 2000).

In full-flow penetrometers, the soil is assumed to flow around the cylinder or ball during penetration and so the overburden pressure is equilibrated above and below, except at the shaft. The corrections are thus much smaller than for the cone. The analysis procedure is based on the plasticity solution of Randolph and Houlbsby (1984), which shows that the undrained strength is determined by:

$$s_u = \frac{q_{net}}{N}$$  \hspace{1cm} (2)

where $q_{net}$ is the net resistance and $N$ is a bearing capacity factor. The general equation for net resistance for push in tools is as follows:

$$q_{net} = q_c - [\sigma_{vo} - u_2(1-a)] \frac{A_s}{A_p}$$  \hspace{1cm} (3)

where $q_c$ is the measured resistance, $a$ is the area ratio, $u_2$ is the pore pressure measured at the standard location, just above the shoulder of a standard cone or just behind the joint between the T-bar or Ball and the push rods, $A_s$ is the cross sectional area of the cone shaft, and $A_p$ the projected area of the tip. For the CPTU, the area ratio $A_s/A_p$ is unity and Equation 3 reduces to the standard expression $q_{net} = q_c - \sigma_{vo}$. For the 100 cm² flow penetrometers $A_s/A_p$ is 0.1, resulting in a much smaller difference between $q_c$ and $q_{net}$ than is typical for the CPTU.

3. TESTING PROGRAM AND TEST SITES

3.1 Testing Equipment and Procedures

The following insitu testing tools were used at the test sites:

- Standard 10cm² CPTUs with full scale tip capacities of 25 and 100 MPa
- Nilcon Field Vane (FVT)
- Flat Plate Dilatometer (DMT)
- Two T-bars and a Ball with dimensions given in Table 1.

The flow penetrometer tips were deployed on a 10cm² CPTU module replacing the regular cone tips, as shown in Figure 1. When a 100 MPa capacity cone is used, the maximum capacities are a function of the size of tip used.

<table>
<thead>
<tr>
<th>Tip</th>
<th>Projected Area (cm²)</th>
<th>Capacity (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard cone</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Small T-bar 160mm span x 35.7mm diameter</td>
<td>57.1</td>
<td>17.6</td>
</tr>
<tr>
<td>Large T-bar 250mm span x 35.7mm diameter</td>
<td>89.3</td>
<td>11.2</td>
</tr>
<tr>
<td>Ball 113 mm diameter</td>
<td>100</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Table 1. Details of Penetrometers

Figure 1. T-bar and Ball Penetrometer Tips

CPTU, T-bar, and Ball penetration tests were carried out at the standard rate of 2 cm/s, tip, friction and $u_2$ pore pressure data being recorded at 5 cm depth intervals. Sleeve and pore pressure recorded in T-bar and Ball soundings give an indication of stratigraphy but cannot be used with conventional CPTU correlations to soil behaviour type. End resistance of the T-bar and Ball penetrometers was also measured during retraction of the probes. Previous researchers have roughened the surface of the T-bar by sandblasting as theory suggests that $N$ factors vary with surface roughness. This was not done in this testing program.

Field vane testing was carried out using a Nilcon field vane. In some cases, the field vane was advanced from surface, and at other times, the vane testing was performed in conjunction with mud rotary boreholes. The field vane testing was carried out in accordance with ASTM D 2573-01 (2001). The Nilcon field vane allows separation of the rod friction from the torque required to turn the shear vane, which is a significant correction when advancing the vane from surface.
The flat dilatometer test was carried out in accordance with the procedures outlined by Marchetti et al (2001). A special soft membrane was used due to the low strength of the soil being tested.

Piston samples were also obtained from mud-rotary boreholes using a hydraulically actuated sampler. Conventional 3 inch diameter galvanized sample tubes conforming to ASTM 1587-00 (2000) were used. Samples were used for classification testing and undrained shear strengths were measured by unconsolidated undrained (UU) triaxial compression tests.

3.2 Test Sites

Field testing was carried out at three sites in the Lower Mainland of BC, two in the Serpentine River lowland and one in the Fraser River delta. The geological history suggests that surficial soils at all three should be normally consolidated although water level and climatic variations may have resulted in some light overconsolidation. Details of the sites are given below.

3.2.1 Colebrook

The Colebrook site is located under the Highway 99A overpass over Colebrook Road and the adjacent BC Railway (BCR) line, in South Surrey, B.C. It is in the northwest corner of the Serpentine River lowland, 2.5 km east of the sea at Mud Bay. The subsoils in the western region of the Serpentine River lowland are Salish Sediments, which are post-glacial deposits of the Quaternary period that were laid down between 10,000 and 5,000 years ago, and include both terrestrial and marine sediments (Armstrong, 1984).

The ground surface at the site lies below sea level, varying between –1.1 and –1.3 m elevation. The test site is covered with a 0.5 to 0.7 m thickness of fill material overlying 0.2 to 0.3 m thickness of peat, which formed the original ground surface. The peat is underlain by a layer of clayey silt interbedded with seams of fine sand to sandy silt which extends to about 2 m depth. These surficial soils are underlain by an extensive deposit of marine clayey silt to silty clay, which extends to a depth of about 25 metres. More details are provided in Weech and Howie (2001).

3.2.2 Mud Bay

The Mud Bay site is located south east of the Colebrook site in the same geological sequence as the Colebrook site but further to the south-east. Here the organic and marine sediments overlying the Vashon Drift are about 15m thick.

3.2.3 Richmond (Vulcan Way)

This site is located in the Fraser River Delta. Soil conditions consist of overbank deposits (clayey silt) with fine sand layers overlying deltaic distributary channel fill sediments.

4. TESTING RESULTS

4.1 Effects of corrections

Figure 2 shows typical profiles of uncorrected and net resistance calculated using Equation 2 for T-bar and standard cone at the Colebrook site. The reduced importance of the correction in the T-bar test is clear when compared to the CPTU profiles.

4.2 Comparisons of $q_{\text{net}}$ and derivation of N factors

Figure 3 shows $q_{\text{net}}$ versus depth for the cone, Ball and small and large T-bars, also at Colebrook. For all three sites, it was observed that $q_{\text{net}}$ was similar for the various full flow tips, while for the CPT, the net resistance was higher by about 10 to 15%. For each site, N factors were calculated from the $q_{\text{net}}$ profiles using Equation 2 and the vane shear strengths, ($s_u$)$_{\text{FV}}$, as a reference. The values obtained and their standard deviations are shown in Table 2. For the T-bars and Ball, N varies from 10.0 to 12.0 and for the CPT from 11.8 to 15.0. These numbers are in the same range as those obtained elsewhere and predicted by theory.

<table>
<thead>
<tr>
<th>Test</th>
<th>Colebrook</th>
<th>Mud Bay</th>
<th>Richmond</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPT</td>
<td>13.4</td>
<td>15.0</td>
<td>11.8</td>
</tr>
<tr>
<td></td>
<td>(2.9)</td>
<td>(4.2)</td>
<td>(2.7)</td>
</tr>
<tr>
<td>Large T-bar</td>
<td>10.7</td>
<td>12.0</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>(2.0)</td>
<td>(3.0)</td>
<td>(2.8)</td>
</tr>
<tr>
<td>Small T-bar</td>
<td>10.8</td>
<td>11.6</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>(2.1)</td>
<td>(3.4)</td>
<td>(2.8)</td>
</tr>
<tr>
<td>Ball</td>
<td>10.3</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>(1.8)</td>
<td>(2.0)</td>
<td>(2.0)</td>
</tr>
</tbody>
</table>

Table 2. Summary of calculated N Factors – standard deviations shown in brackets.
4.3 Undrained Shear Strength Profiles

Figures 4, 5 and 6 show profiles of predicted \( \left( s_u \right)_{FV} \) at the three sites based on the back-calculated N values in Table 2. The measured field vane shear strengths and the results of triaxial UU tests are also shown. Values of \( s_u \) interpreted from DMT profiling using the standard Marchetti method are shown for the Mud Bay site.

As site specific N factors were used, agreement between the estimated and measured \( (s_u)_{FV} \) values is excellent. Use of a standard \( N_{kt} = 15 \) with CPTU data at all sites would have underestimated strengths at Colebrook and Richmond. Conversely, if the recommended average value of \( N = 10.5 \) had been used with the T-bar resistances (Chung and Randolph, 2004), the shear strengths would have been overestimated at Mud Bay but would have been accurate at the other sites.

The \( s_u \) predictions by DMT using standard correlations underestimate shear strength at Mud Bay in the regions for which vane shear data are available. The data suggests that a different N value may be appropriate for the zone below 10 m depth.

Shear strengths measured in UU triaxial tests are comparable to \( \left( s_u \right)_{FV} \) at shallow depths but are considerably lower at greater depths.
4.4 Post Peak and Remoulded Strengths

The geological history and index properties at Colebrook and Mud Bay suggest that the soils may have been leached and sensitive. They would thus be expected to exhibit brittle behaviour in the field vane test. The sensitivity, $S_t$, is determined from the field vane shear test as the ratio of the peak to remoulded $s_u$. Figure 7 shows $S_t$ vs depth for Colebrook. The test results indicate the soils at Colebrook and Mud Bay to have a FVT sensitivity of about 5 to 10, with $S_t$ increasing with depth. Weech (2002) and Crawford and Campanella (1991) observed $S_t$ values ranging from 6 to 26 in the soils at Colebrook.

Lunne et al. (1997) suggest that the CPT friction sleeve, $f_s$, is close to the remoulded $s_u$ and so $S_t$ can also be estimated to a first approximation using $(s_u)_{peak}$ divided by $f_s$. As an alternative, Newson et al (2004) have used the ratio of $(s_u)_{net}$ measured while pushing to $(s_u)_{net}$ measured during retraction to make an estimate of sensitivity. Chung and Randolph (2004) suggest that the ratio of the peak $q_{net}$ to the ultimate resistance after cyclic extraction-penetration tests will ensure complete remoulding and thus may also give a better estimate of $S_t$. Measuring the resistance during retraction of the full flow probes adds very little time to the test procedure, and provides a continuous profile. However, it may not result in full remoulding of the soil.

Plots of sensitivity calculated from FVT, CPTU, T-Bar and Ball are presented in Figure 7 for Colebrook and in Figure 8 for Richmond. The CPT sensitivity is lower than the FVT values at the Colebrook but is a reasonable first estimate. The ratio of peak $q_{net}$ to retraction $q_{net}$ appears to be more representative of the ratio of peak to post peak $s_u$ from field vane testing.
While the sleeve friction measurement is not presented in full flow penetrometer results it does provide some indication if full flow occurs around these tools. In the case of the soft soils at the Colebrook and Mud Bay site the sleeve friction measured by the CPTU and during full flow probe soundings were not too different. This was also the case with the CPTU and the T-bar at the Richmond site. The low sleeve friction measured during the Ball penetration test in Richmond suggests that at low overburden stresses full flow was not occurring, and that the Ball penetrometer should be use with caution in similar soil conditions.

5. DISCUSSION AND CONCLUSION

The test data indicate that in soft sediments, full-flow penetrometers provide values of \( q_{\text{net}} \) that are smaller than those from CPTU profiles. This is despite the much greater plan area of the flow tools compared to the standard 10 cm \(^2\) cone. The \( q_{\text{net}} \) values from two different sized T-Bars and the Ball are very similar to each other and require less adjustment for overburden stress and unequal end area pore pressure effects than conventional CPTs. Because of their large size and the shadow effect of the tools on the pore pressure element location and friction sleeve, the flow penetrometers are less sensitive to stratigraphic variations than CPTU parameters. It is thus preferable that they should be used for estimating \( s_u \) in very soft to soft soils to complement the profiling capability of the CPTU.

The data also show that with good attention to details of calibration and transducer baselines, it is possible to obtain data of similar quality using standard cone equipment. The use of low capacity load cells in the CPTU can also improve its performance and reduce the likelihood of errors being introduced to the data.

For purposes of estimating \( s_u \), it is always preferable to derive site specific values of \( N \) to be applied in Equation 2. In the absence of site specific values, the average value of \( N_{1\text{-bar}}=10.5 \) suggested by others was shown to provide reasonable estimates of \( s_u \) for preliminary analyses. Similarly, a value of \( N_{\text{lab}} \) of from 13 to 15 was shown to provide preliminary profiles of \( s_u \) acceptable for preliminary analyses. Again, these values are in agreement with conventional practice.

It is important to be clear on the specific type of shear strength that is obtained from use of Equation 2 and the \( N \) factors indicated. In this paper, an estimate of \( (s_u)_{\text{FFV}} \) is obtained. For low plasticity soils, \( (s_u)_{\text{FFV}} \) in triaxial compression would be expected to be greater than \( (s_u)_{\text{FFV}} \) (Ladd, 1991). Figures 5 and 6 show that values of \( (s_u)_{\text{UU}} \) from unconsolidated undrained triaxial compression tests are close to peak \( (s_u)_{\text{FFV}} \) values at shallow depth but are closer to post peak values of \( (s_u)_{\text{FFV}} \) at greater depths. These results are consistent with increasing disturbance of samples occurring with depth. The disturbance occurred during sampling, extrusion and sample preparation for testing. In one case, it proved impossible to prepare a sample from a depth of 7.2 m at Colebrook due to its rapid deterioration during handling. From this experience, it is concluded that UU triaxial compression tests are unlikely to provide useful shear strength parameters in routine investigations. In order to achieve useful measurements of \( (s_u)_{\text{peak}} \) from laboratory testing in these soils, it will be necessary to employ advanced techniques of sampling, sample preparation and testing. Recent advances in field sampling and laboratory testing techniques for Lower Mainland soils are discussed in Sanin and Wijewickreme (2006) and Wijewickreme and Sanin (2006).

Evidence from this study suggests that the ratio of the intact and retraction values of \( q_{\text{net}} \) were closer to the ratio of \( s_u \), peak to post peak than to \( S_s \) values from the FVT. Some authors have suggested that cyclic extraction-penetration tests at selected depth intervals can give an estimate of \( (s_u)_{\text{remoulded}} \) and sensitivity. The procedure is to carry out cyclic extraction and penetration of the probe over a depth range of \( \pm 0.5 \) m during a pause in penetration. Typically, the probe is cycled back and forth six times or until a constant resistance is observed. This procedure is quite possible but is time consuming and would only be utilized to produce semi-continuous profiles. DeJong et al (2004) suggested that such cyclic remoulding using the T-bar may create a cylindrical void space. The limited cyclic T-bar testing performed in this investigation at the Richmond site resulted in negligible resistance after cycling, indicating that a void was forming. This would suggest that for medium to stiff clays at low confining stress the full flow mechanism is not occurring.

The application of \( (s_u)_{\text{CPT/FFV}} \) as a means of predicting FVT sensitivity was inconclusive, although the results provided a reasonable first estimate of \( S_s \). Use of a CPTU with a low capacity sleeve would be expected to provide better results.

In conclusion, full-flow penetrometers appear to show promise for estimation of \( s_u \) in soft sediments, particularly where they can be pushed from surface. The advantage over the CPTU is the greatly reduced correction for \( q_{\text{net}} \), a somewhat smaller range of bearing capacity \( N \) values, and increased resolution due to the increased pushing area. This also results in smaller potential zero load error corrections as compared to a standard capacity CPTU.

The deployment of full-flow probes can be hindered if drilling out, or casing is required. In these cases, a Ball penetrometer may be easier to deploy. Ball penetrometers appear to give similar net resistances to both sized T-bars. Some data suggested that full flow conditions did not always occur around the Ball penetrometer. Also due to the much larger projected area of the T-Bar and Ball, they will meet refusal at much lower tip resistances than the CPTU.

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