COMPARISON OF IN-SITU SHEAR STRENGTH MEASUREMENT TECHNIQUES OF SOFT CLAYS

Jeff Schaeffers, ConeTec Investigations Ltd., Richmond, BC, Canada
Ilmar Weemees, ConeTec Investigations Ltd., Richmond, BC, Canada

ABSTRACT
Undrained shear strength and soil stiffness are profiled at one soft soil site in Surrey, BC. Improvements to the measurement of undrained strength have occurred recently with the adoption of the Ball Penetrometer Test and the electric vane shear device. The use of a computer controlled torque recording unit has greatly enhanced the accuracy of the field vane test. Data is presented from both test methods for peak and remolded strengths. These results are also compared to the standard CPTu and the Dilatometer. Small strain soil stiffness data based on shear wave velocity is also presented using both in-situ and surface methods.

Key words: Ball, CPTU, Seismic CPTU, Dilatometer, Vane, Undrained Shear Strength, MASW, In-Situ Testing

1. INTRODUCTION

Geotechnical engineering design in the Lower Mainland of British Columbia frequently requires characterization of undrained shear strength (s_u) in saturated soft sediments. S_u is commonly determined from in situ testing, typically either electronic piezo-cone penetration (CPTU) or vane shear testing (VST). The CPTU offers the advantage of continuous soil parameter profiling including estimates of s_u. The VST offers a direct measurement of s_u. and is generally the reference test to which other tests are compared. Site specific correlations are frequently developed by carrying out adjacent CPTU soundings and VST boreholes.

Pore pressure effects, cone geometry and overburden stresses significantly affect measured CPTU tip resistance in soft cohesive soils. All of which must be corrected for prior to calculating s_u and can be a considerable source of error and variability. It is in response to this uncertainty that the development of full flow penetration testing has occurred.

Manually operated VST devices typically obtain an up hole measurement of torque, based on a recording unit calibration, which is then converted to shear strength based on a vane constant. The two most common, and arguably most significant, sources of error while using these systems are rod friction (and the incorrect interpretation thereof) and human introduced operator error (for example applying the incorrect rate of loading to the vane).

The purpose of this paper is to present the results of experience at a site in South Surrey, BC with two new tools: the full-flow Ball penetrometer (Ball PT) and the Electric VST. Profiles of estimated s_u are provided and compared to values interpreted from CPTU and dilatometer (DMT).

2. BACKGROUND

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

$$s_u = \frac{q_t - \sigma_{vo}}{N_{kt}} = \frac{q_{net}}{N_{kt}} \quad (1a)$$

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, σ_{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 s_u 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 s_u for very soft soils (Equation 1b).

$$s_u = \frac{u_2 - u_o}{N_{\Delta u}} \quad (1b)$$

In an effort to reduce the inaccuracies due to these large corrections but to continue to achieve a continuous profile of resistance, the full-flow testing (T-bar) was introduced first in the centrifuge (Stewart and Randolph, 1991) and then in the field (Stewart and Randolph, 1994). 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., 2004). Subsequently the use of the Ball penetrometer, a spherical ball mounted on the end of the push rods (Chung and Randolph 2004, DeJong at al 2008) has become more common.

During full-flow penetration testing, soil is assumed to flow around the tip (ball) and so the overburden pressure is equilibrated above and below, except at the shaft. The corrections are therefore reduced compared to that for the standard cone tip. The analysis procedure is based on the plasticity solution of Randolph and Houlsby (1984), which shows the undrained strength is determined by:

$$s_u = \frac{q_{net}}{N} \qquad (2)$$

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:

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

where q_c is the measured resistance, *a* is the area ratio, u_2 is the pore pressure measured just behind the tip, 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 = 1 and Equation 3 reduces to the standard expression q_{net} = q_t-σ_{vo}. For the 100 cm^2 flow penetrometers A_s/A_p = 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 testing tools were used at the test site (see Figures 1,2 and 3):

- Standard $10cm^2$ Seismic CPTU with full scale tip capacity of 50 MPa
- 100 cm^2 Ball tip (Ball PT) used on the same CPTU probe as used for the CPTU
- Electric Vane Shear (Electric VST) using a rectangular vane: 75mm wide x 150mm long
- Flat Plate Dilatometer (DMT)
- Multichannel Analysis of Surface Waves (MASW)

The flow penetrometer ball tip was deployed on a $10cm^2$ CPTU module replacing the regular cone tip, as shown in Figure 1. When a 50 MPa capacity cone is used, the maximum capacities are a function of the size of tip used.

Tip	Projected Area (cm^2)	Capacity (MPa)
Standard cone	10	50.0
Ball - 113 mm diameter	100	5.0

Table 1. Details of Penetrometers

Figure 1. CPTU and Ball PT probes

CPTU and Ball penetration tests were carried out at the standard rate of 2 cm/s, with tip, friction sleeve and u_2 pore pressure data recorded every 5 cm. Friction sleeve and pore pressure recorded in the Ball soundings cannot be used with conventional CPTU correlations to soil behaviour type. Friction sleeve measurements from the Ball PT are generally not used in any interpretations as the soil has been significantly affected from flowing around the ball. Pore pressure measured from the Ball PT in the u_2 position is primarily used for net area end effects.

Vane shear tests were carried out using Adara System's Electric Vane System. The electric vane shear system employs an uphole electric motor that applies torque at a constant, operator adjustable, rate. The torque load cell is located downhole 0.35 cm behind the vane (see Figure 2). The primary advantage of this configuration is that all rod friction corrections are eliminated, which can be proportionally significant in low strength soils. In all cases the vane was deployed through 4.25 inch hollow stem augers, with the middle of the vane pushed 0.6 metres below the bottom of the hollow stem auger bit. All vane tests were performed using a rectangular shaped vane, measuring 75mm wide by 150 mm long. The field vane testing was carried out in accordance with ASTM D 2573-01 (2001).

Figure 2. Torque Load Cell, Extension Rod and Vane

DMT testing 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 (see Figure 3).

Figure 3. Flat Plate Dilatometer (DMT)

Surface wave seismic testing is a non-intrusive in-situ test that uses the principles of elasticity and surface wave dispersion to determine the variation of shear wave velocity with depth at a site. Multichannel Analysis of Surface Waves (MASW) testing (Park et al. 1999) was performed by measuring the surface wave velocity as a function of frequency along an array of receivers using an impulsive source. The testing equipment comprises a Geometrics Geode Seismograph, 24 receivers, and seismic source. The receivers are highly sensitive 4.5 Hz resonant frequency geophones. Energy was delivered to the ground using a 12 pound sledge hammer (for shallow profiling) and a 90 pound drop weight (for deeper profiling). The geophones were coupled to individual steel spikes inserted approximately 2-3 inches into the ground surface. The source offset used ranged from 2 to 20 metres, with source impacts delivered on either side of the geophone string.

3.2 Test Site

The site is located in the Serpentine River lowland on 40th Avenue, just west of 168th Street in South Surrey, BC. The geological history suggests that surficial soils should be normally consolidated although water level and climatic variations may have resulted in some light overconsolidation. 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 test site is covered by approximately 1.0 metre of peat. The peat is underlain by a layer of clayeysilt to silty clay which extends to about 5.0 to 6.0 metres depth. These surficial soils are underlain by an extensive deposit of marine clayey silt to silty clay, which extends to a depth of about 15 metres.

4. TESTING RESULTS

4.1 Resistance and Seismic Results

Figure 4 shows typical profiles of uncorrected and net resistance calculated using Equation 2 for Ball and standard cone at the site. The reduced importance of the correction in the Ball test is clear when compared to the CPTU profiles. Therefore uncertainty in the estimation of unit weight will not significantly effect the results from the Ball PT.

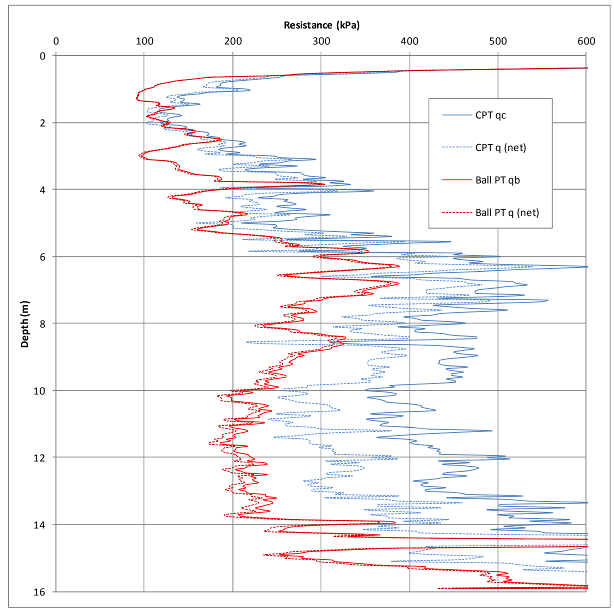

Figure 4. Measured and net resistance for CPTU and Ball-PT.

Figure 5 shows the measured shear wave velocities (Vs) as determined by the SCPTU and MASW. Generally there is good agreement between the two methods; however below 8 metres depth there appears to be some deviation between the two techniques. This may be a result of the averaging effects over increased layer thicknesses with increased depth, inherent to the MASW technique.

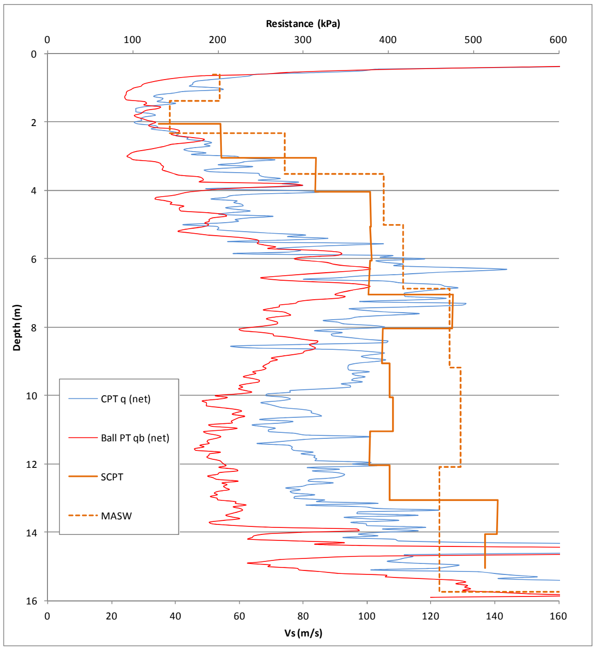

Figure 5. Seismic CPTU and MASW V_s results

4.2 Electric Vane Shear Test Results

Figure 6 shows the Electric VST from 6.5 m depth. The geological history and index properties at the site suggest that the soils may have been leached and are sensitive (Crawford and Campanella, 1991). Therefore a brittle behaviour is expected in the vane test. The post peak failure modes from the vane shear tests performed support this, and is evident in the test performed at 6.5 m depth.

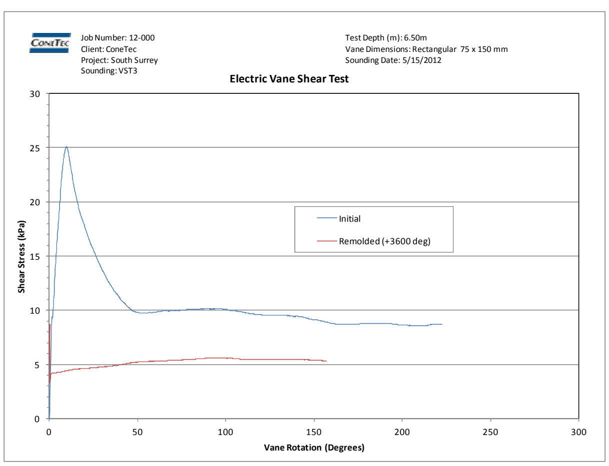

Figure 6. Electric VST from 6.5 m depth.

4.3 Undrained Shear Strength Profiles

Figure 7 compares the results of the CPTU, Ball PT, DMT and Electric VST. The N values used for the CPTU and Ball PT profiles were back-calculated based on the Electric VST results, and are shown in Table 2. The initial peak s_u N factor was evaluated separately from the remould N factor as recommended by DeJong et al (2010). The remoulded N factor increases with increased sensitivity (S_t).

Test	N Factor
CPTU	13.0
Ball PT_{PEAK}	10.8
Ball $PT_{REMOULD}$	10.0

Table 2. Summary of calculated N Factors

An undrained shear strength profile determined from the DMT using the standard Marchetti method is shown in Figure 7. The s_u predictions using the DMT are in good agreement until 10 metres depth, at which point the DMT begins to overestimate s_u when compared to the Ball PT and Electric VST.

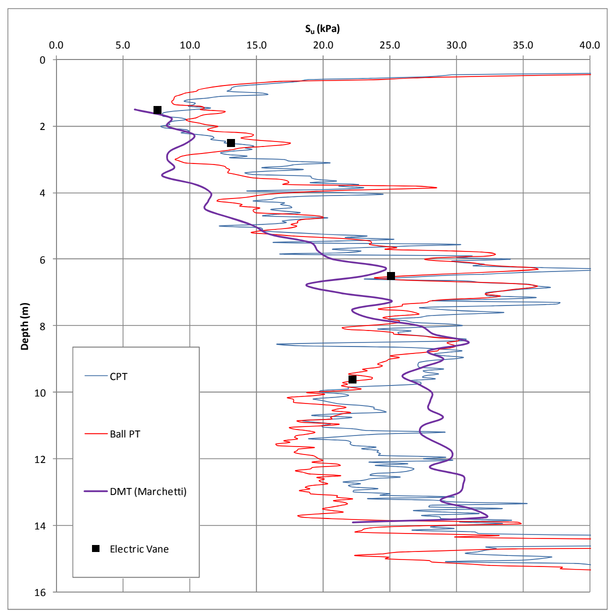

Figure 7. s_u profile from CPTU, Ball PT, DMT and Electric VST

Figure 8 shows only the results of the Ball PT and Electric VST. The peak, post-peak (residual) and remoulded results are compared. The first cycle sounding (after the initial Ball PT sounding) is estimated as the pseudo post-peak value. Cycles were then performed over 1 metre depths, at 1 metre intervals, effectively creating continuous residual and remoulded resistance profiles with depth. Cycles were continued until resistance is observed to show no change, indicating the soil has achieved a remoulded state. Typically this requires at least 10 cycles. The last and second last cycles are presented in the Figure 8, and compared to the remoulded values from the Electric VST. The Ball PT's peak s_u and remoulded data, using N Values of 10.8 and 10.0 respectively (Table 2), are in very good agreement with the Electric VST.

Unit weights used in the CPTU and Ball PT profiling of s_u were calculated (Table 3) using Mayne's V_s-effective stress method (Mayne 2005, see Equation 4 below) using the results from the Seismic CPTU data. The unit weights calculated below are in good agreement to previous data from a nearby site (Weemees et al 2006) where shelby tube samples were collected at average depths of 4.9 and 7.7 metres. Lab tests produced unit weight results of 17.0 and 16.7 kN/m^3 respectively.

$$\gamma = 8.64 Log(V_s) - 0.74 Log(\sigma_{vo}') - 0.4 \qquad (4)$$

Mid Layer (m)	Interval Start Depth (m)	Interval End Depth (m)	V_s (m/s)	Unit Weight (kN/m^3)
1.55	1.05	2.05	35	12.2
2.55	2.05	3.05	54	13.8
3.55	3.05	4.05	84	15.3
4.55	4.05	5.05	101	15.9
5.55	5.05	6.05	101	15.9
6.55	6.05	7.05	101	15.8
7.55	7.05	8.05	127	16.6
8.55	8.05	9.05	105	15.8
9.55	9.05	10.05	107	15.9
10.55	10.05	11.05	108	15.9
11.55	11.05	12.05	101	15.6
12.55	12.05	13.05	107	15.8
13.55	13.05	14.05	141	16.8
14.55	14.05	15.05	137	16.6

Table 3. Unit weights from Mayne V_s-Stress method

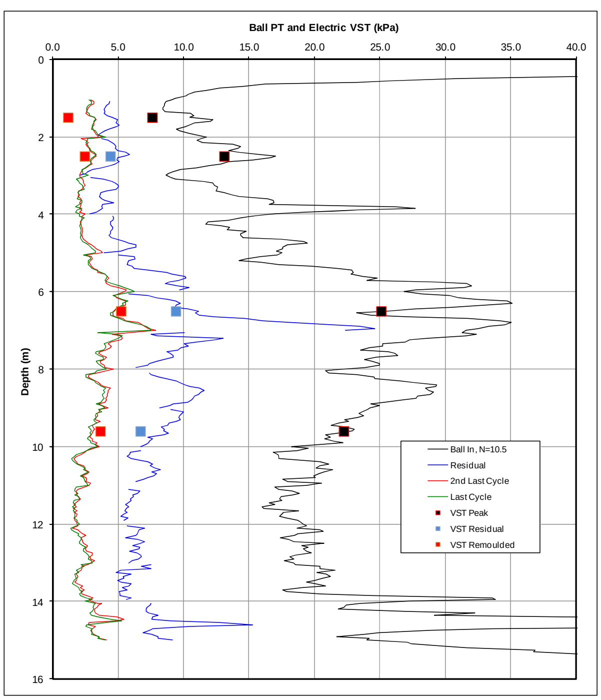

Figure 8. Ball PT and Electric VST results

4.4 Remoulded Strengths and Sensitivity

The sensitivity, S_t, is calculated from the Ball PT and Electric VST as the ratio of the peak to remoulded s_u. Lunne et al. (1997) suggest that the CPT friction sleeve, f_s, is close to the remoulded s_u. Therefore S_t can be estimated to a first approximation using $(s_u)_{peak}$ estimated from q_{net}, see Equation 5 below.

$$S_t = \frac{q_{net}}{f_s x N} \qquad (5)$$

Figure 9 shows the results of the remoulded strengths. Below 7 m the data from the CPTU, Ball PT and Electric VST appear to provide a similar result, however above 7 m the f_s data appears to underestimate the remoulded strength. This could be a result of the resolution and sensitivity of the f_s load cell in the upper lower strength material and the effects of o-ring friction within the penetrometer.

A plot of sensitivity is shown in Figure 10. Again the test results indicate good agreement between the CPTU, Ball PT and Electric VST, except above 7 m, where the CPTU results appear to overestimate S_t (resulting from the low f_s values as described above).

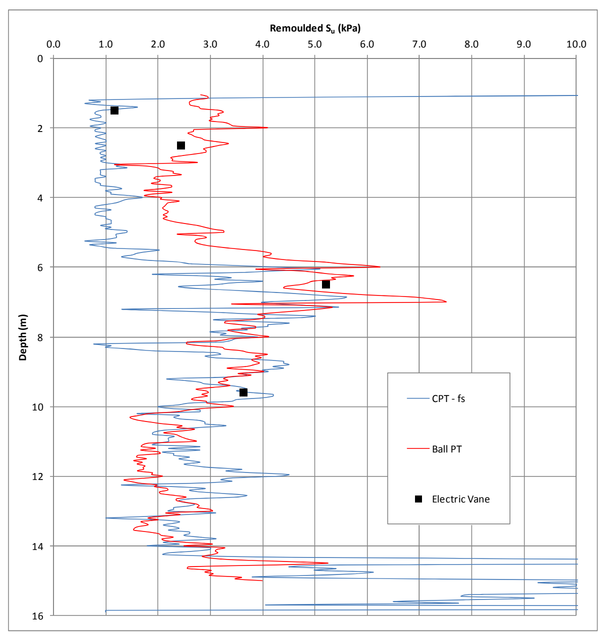

Figure 9. Remoulded shear strength comparison

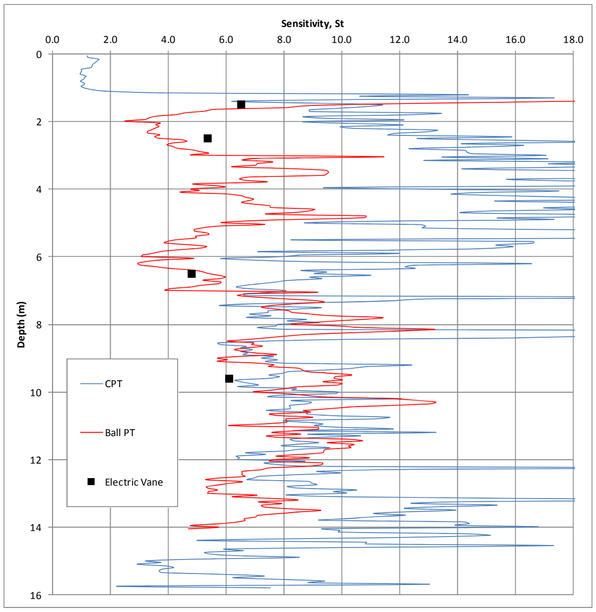

Figure 10. Comparison of sensitivity (S_t)

5. DISCUSSION AND CONCLUSION

Both CPTU and Ball PT methods show good overall agreement in their determination of peak s_u. However, for deeper, low strength, undrained sediments the Ball PT has the advantage of reducing the correction effect of stress and of the tip load cell geometry condition that is effected by dynamic pore pressure. These effects can be observed in Figure 7 below 8 metres, where the CPTU is slightly overestimating s_u compared to the Ball PT.

The Electric Vane Shear device has proven to be an extremely accurate tool for measuring s_u, especially when compared to typical up-hole manually operated techniques. In very low strength soils where a high quality measurement of in-situ peak and remoulded s_u is required the Electric VST provides a result that is less impacted by operator error and data interpretation.

However, penetration tests have a significant advantage over vane shear tests when it comes to efficiency and data coverage. Furthermore, the near continuous nature of penetration testing may uncover thin zones of interest that drilling and vane shear testing may not reveal. An example of this is shown in Figure 8 where the Electric VST at 6.5 metres tests a thin zone with s_u = 25 kPa between slightly stiffer soil layers where s_u reaches up to 35 kPa, as estimated from the Ball PT.

The Ball PT is an accurate and efficient tool that can be used to profile shear strengths in weak silts and clays. This relatively new test can complement many site investigations and offer advantages over traditional CPTU for strength profiling.

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