# Comparison on in-situ shear strength measurement techniques of soft clay


Jeff Schaeffers, Ilmar Weemees, and Mark A. Styler
*ConeTec Investigations Ltd., Richmond, BC, Canada*



ABSTRACT
Improvements to the measurement of undrained shear 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. Undrained shear strength and soil stiffness are profiled at one soft soil site in Surrey, BC. Data is presented from both test methods for peak and remoulded strengths. These results are also compared to the standard CPTU and Dilatometer. Small strain soil stiffness data based on shear wave velocity is also presented using both in-situ and surface methods. The combination of the Electric Vane Shear testing and flow penetrometer testing provides a site investigation approach applicable to slope stability hazards.


## 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. It is required to analyze the undrained stability of excavations and slopes. The $s_u$ parameter is commonly determined from in-situ testing, typically either vane shear testing (VST) or electronic piezocone penetration (CPTU). At selected discrete depths, 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. The CPTU offers the advantage of continuous soil parameter profiling including estimates of $s_u$. A continuous profile of $s_u$ permits the identification of thin weak layers that may become critical failure surfaces.

Pore pressure effects, cone geometry and overburden stresses significantly affect measured CPTU tip resistance in soft cohesive soils. All of these factors 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. Full flow penetration testing advances a sphere or a T-bar rod through the subsurface. These geometries lend themselves to theoretical interpretations and have a lower magnitude of systematic error corrections.

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 human introduced operator error. Rod friction develops at the interface of the deployment rods and soil between the bottom of casing and top of the vane. It depends on the insertion length and interface friction. The rod friction error develops from the incorrect interpretation of this contribution to the up-hole torque measurements.

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 the 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:

$$s_u = \frac{q_t - \sigma_{vo}}{N_{kt}} = \frac{q_{net}}{N_{kt}} \qquad [1]$$

where Nkt 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 and $\sigma_{vo}$ is total vertical stress.

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 $s_u$ and are considered the likely reason for the large scatter in published Nkt values.

In an effort to reduce inaccuracies due to these large corrections and to continue to achieve a continuous profile of resistance, full-flow testing with a T-bar tip was first introduced in centrifuge testing (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 et al 2008) has become more common.

During full-flow ball 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 theoretical plasticity solution of Randolph and Houlsby (1984), which shows the undrained strength is determined by:

$$s_u = \frac{q_{net}}{N} \quad [2]$$

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:

$$q_{net} = q_c - [\sigma_{vo} - u_2(1-a)]\frac{A_S}{A_P} \quad [3]$$

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 probe shaft, and $A_P$ is 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 $q_{net} = q_t - \sigma_{vo}$. 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 TEST PROGRAM AND TEST SITE

### 3.1 Testing Equipment and Procedures

The following testing tools were used at the test site (see Figures 1, 2, 3 and 4):

- 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 by 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, see Table 1 below.

Table 1. Details of penetrometers

| Tip | Projected Tip Area ($cm^2$) | Capacity (MPa) |
|---|---|---|
| Cone | 10 | 50.0 |
| Ball | 100 | 5.0 |

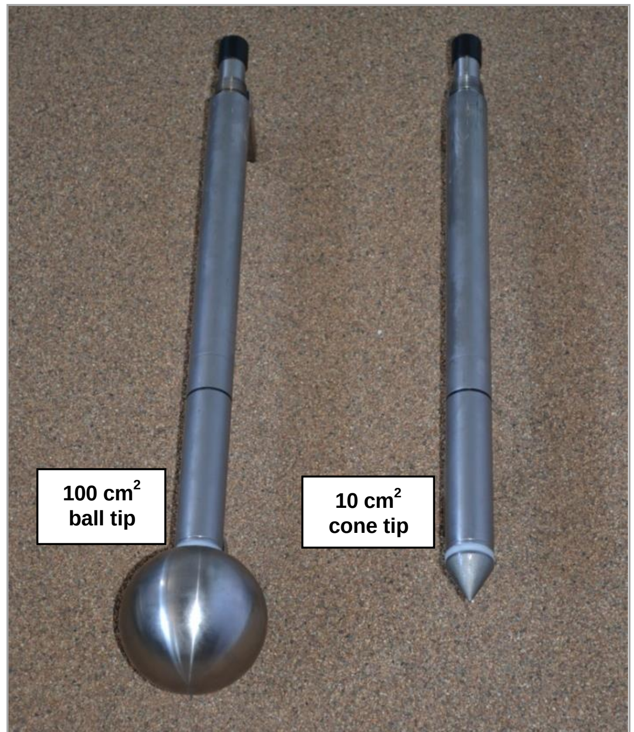

Figure 1. $100cm^2$ Ball PT and $10cm^2$ CPTU Probes

CPTU and Ball PT 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 PT 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).

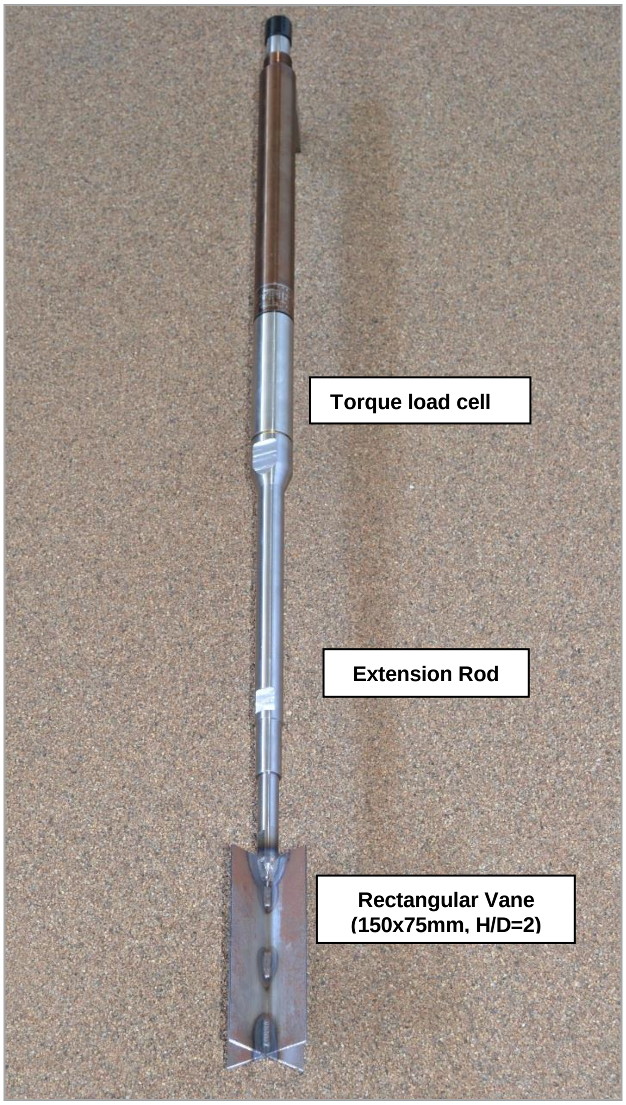


Figure 2. Torque Load Cell, Extension Rod and Vane

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. Figure 3 depicts the DMT blade which is continuously penetrated into the ground.

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 consists of 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. A typical MASW setup is shown in Figure 4.

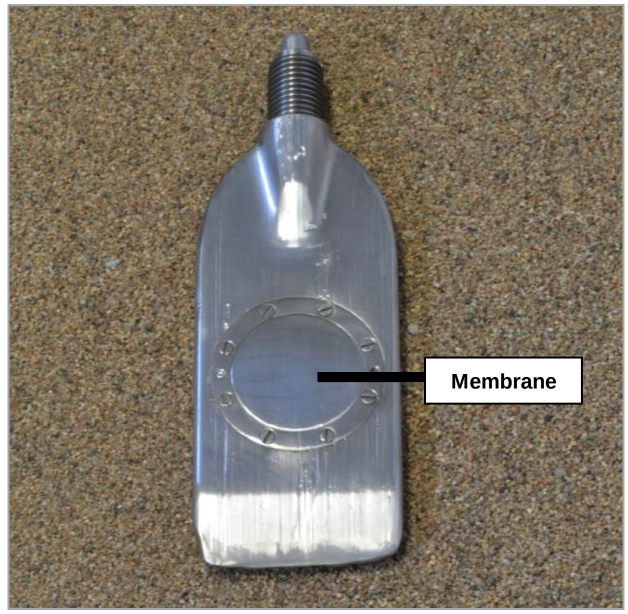


Figure 3. Flat Plate Dilatometer (DMT)

Figure 4. MASW Testing System

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 (see Figure 5). 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 metres of peat. The peat is underlain by a layer of clayey silt to silty clay which extends to a depth of about 5.0 to 6.0 metres. 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. This site was selected due to accessibility, convenience, location, and previous knowledge of the sub-surface soils.


Figure 5. Test location in South Surrey, BC

## 4 TEST RESULTS

### 4.1 Resistance and Seismic Results

Figure 6 shows profiles of uncorrected and net resistance calculated using Equation 2 for Ball PT and CPTU at this site. The reduced importance of the correction in the Ball test is clear when compared to the CPTU profiles. This is seen in Figure 6 as the difference between the measured and net tip resistance for the Ball PT and CPTU. Therefore uncertainty in the estimation of unit weight will not significantly affect the Ball PT results.

Figure 7 shows the measured shear wave velocities ($V_S$) as determined by the SCPTU and MASW. The shear wave velocity scale is on the bottom axis. 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 7 also includes the net penetration resistances from Figure 6. The VS measurements are depend on the very small strain elastic stiffness, while the net penetration would be a large strain strength measure.

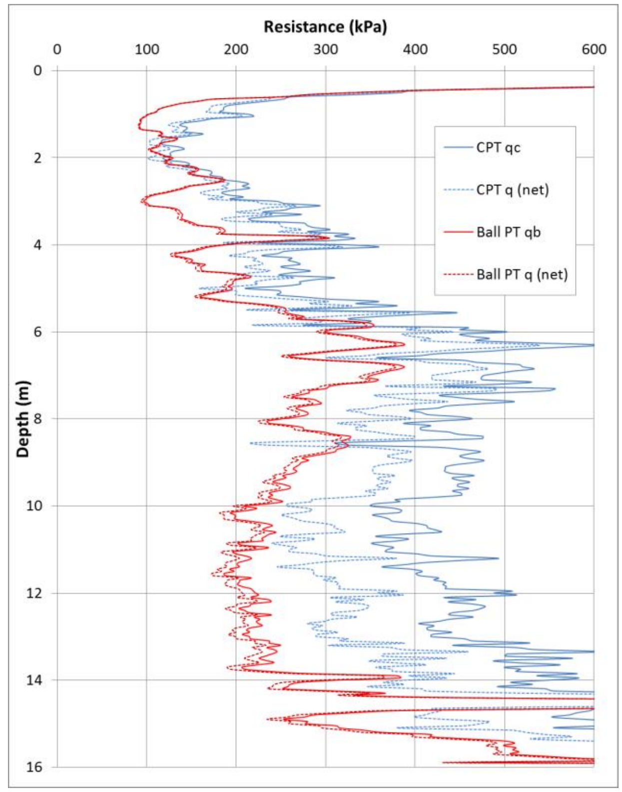


Figure 6. Measured and net resistance for CPTU and Ball-PT.

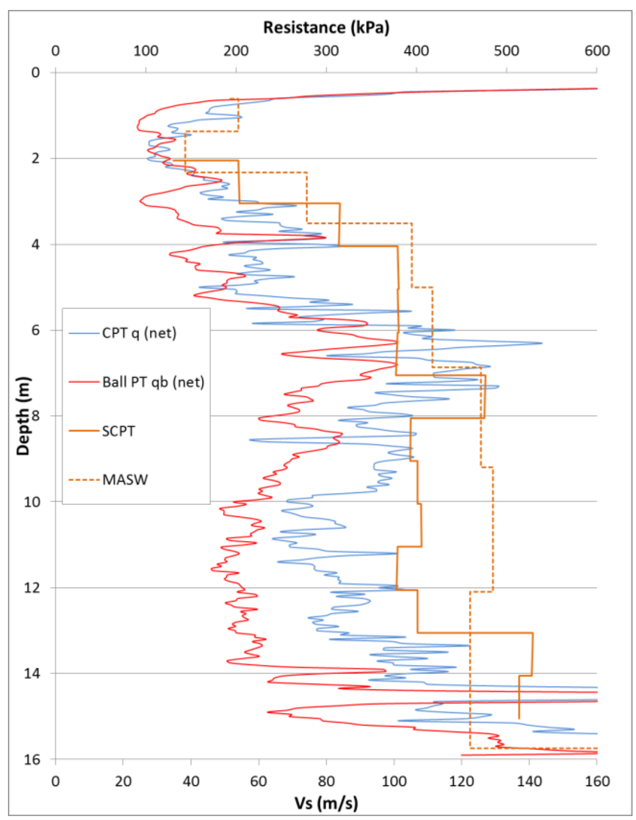


Figure 7. Seismic CPTU and MASW $V_s$ results

### 4.2 Electric Vane Shear Test Results

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 8 shows the Electric VST results at this depth. There is a sharp peak in the initial curve (blue line) up to the reported $s_u$ of 25 kPa. After the initial test the vane is rotated 10 times to remold the soil. The remolded test is depicted as a red line. This soil has an almost 5-fold reduction in strength at this location and depth.

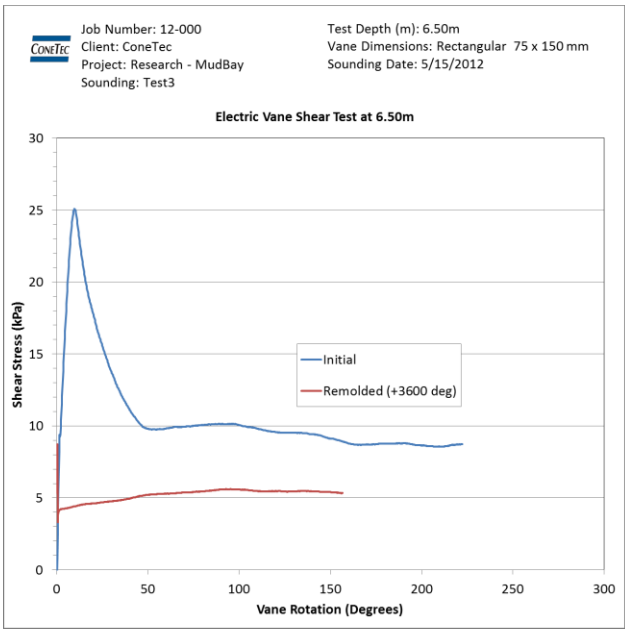


Figure 8. Electric VST from 6.5 m depth.

### 4.3 Undrained Shear Strength Profiles

Unit weights used in the CPTU and Ball PT profiling of $s_u$ were calculated (Table 2) using Mayne's Vs-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.

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

where $\gamma$ is the total saturated unit weight, $V_S$ is the shear wave velocity, and $\sigma'_{v0}$ is the vertical effective stress.

Figure 9 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 detailed in Table 3. The initial peak $s_u$ N factor was evaluated separately from the remould N factor as recommended by DeJong et al (2010). An undrained shear strength profile determined from the DMT using the standard Marchetti method is also shown. 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.

Table 2. Total unit weights from Mayne 2005 $V_S$-Stress relationship

| Mid layer (m) | Interval start (m) | Interval end (m) | $V_S$ (m/s) | $\gamma$ (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. Summary of calculated N Factors

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

Figure 10 shows only the results of the Ball PT and Electric VST. The peak, post-peak (residual) and remoulded results are compared. The Ball PT test can be cycled to measure post-peak and remoulded undrained shear strength. This is performed by repeatedly advancing and retracting the ball probe over 1 meter in depth. Cycles were performed over 1 metre depths, at 1 metre intervals, effectively creating near continuous post-peak and remoulded resistance profiles with depth. The first cycle sounding (after the initial Ball PT sounding) is estimated as the pseudo post-peak value. 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. Figure 11 shows the cyclic degradation of the Ball PT compared to the Electric VST at 6.5 metres depth. Only the last and second last cycles are presented in Figure 10, 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. This increases the confidence in these site-specific N-value calibrations. They can be applied to other Ball PT profiles in this soil unit.

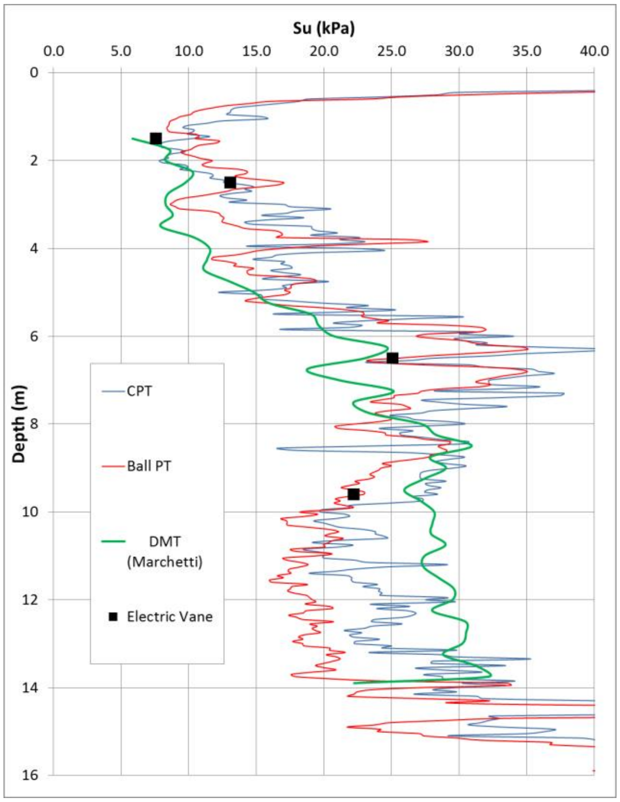


Figure 9. $s_u$ profile from CPTU, Ball PT, DMT and Electric VST

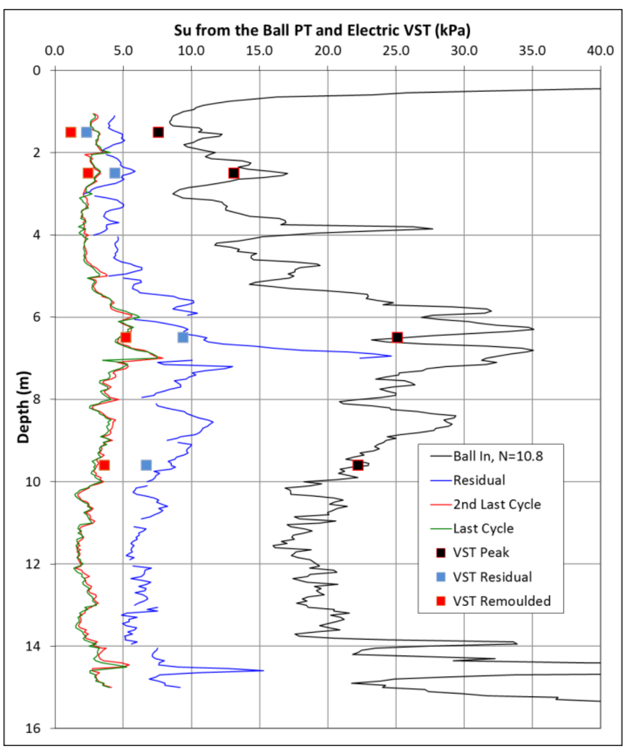


Figure 10. Ball PT and Electric VST results

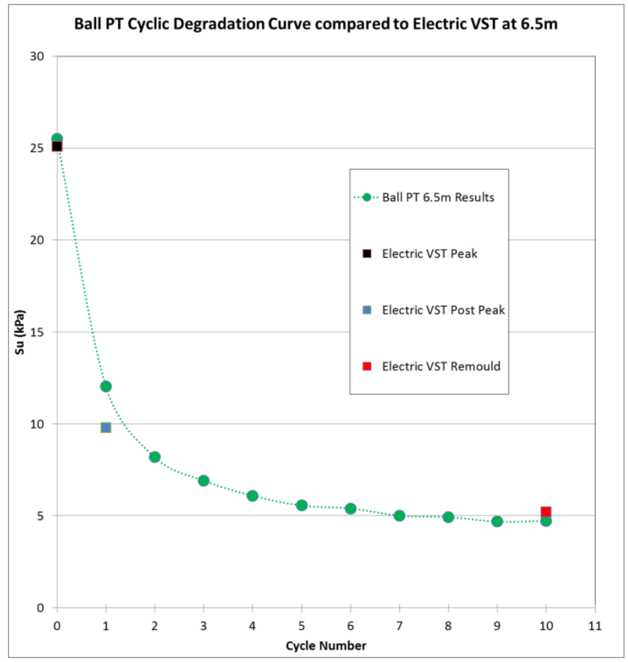


Figure 11. Ball PT Cyclic Degradation curve at 6.5 metres

## 4.4 Remoulded Strengths and Sensitivites

The sensitivity, St, 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 CPTU friction sleeve, fs, is close to the remoulded $s_u$. Therefore St from the CPTU can be estimated as a first approximation using Equation 1 and fs, see Equation 5.

$$S_t = \frac{q_{net}}{f_s N_{kt}} \quad [5]$$

Figure 12 shows the results of the remoulded strengths. Below 7 metres the data from the CPTU, Ball PT and Electric VST appear to provide a similar result, however above 7 metres the fs data appears to underestimate the remoulded strength. This could be a result of the resolution and sensitivity of the fs 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 13. 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 St.

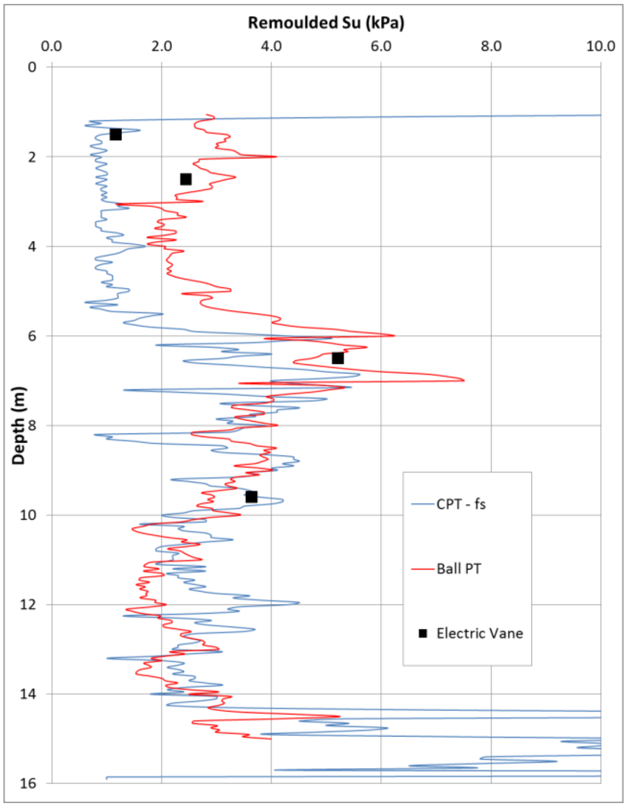

Figure 12. Remoulded shear strength comparison

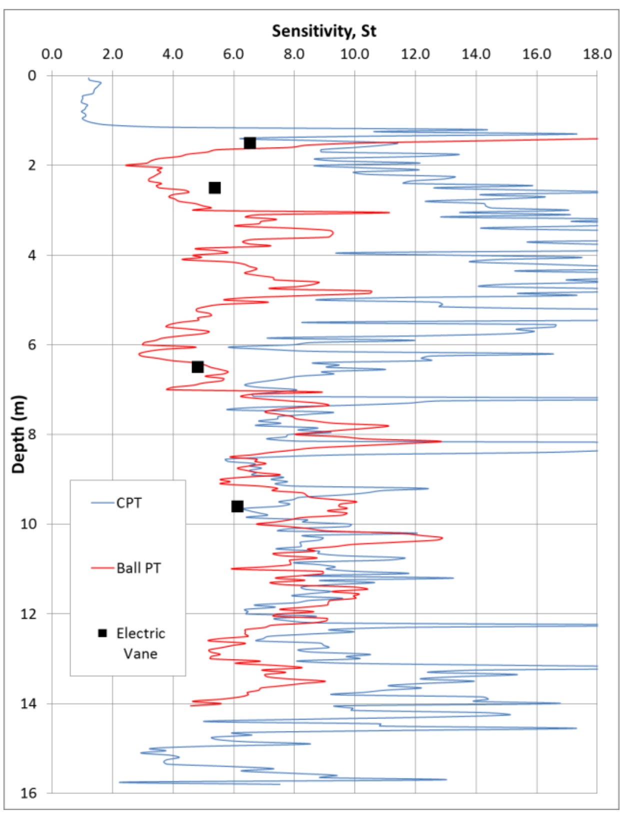

Figure 13. Comparison of sensitivity ($S_t$)

## 5 DISCUSSION AND CONCLUSION

The undrained shear strength is not a unique strength property for the soil. It depends on the effective stress of the soil when it reaches the failure surface. This effective stress depends on the friction angle, initial in-situ effective stress, the applied stress path, and the pore-water pressure generated over the shear stress path. Different failure mechanisms will have different shear stress paths, generate different amounts of pore water pressure, and have different undrained shear strengths. The VST has been in practice since the 1950s and many applications have been developed that use a vane $s_u$. For example, Bjerrum proposed a correction factor based on the plasticity index to relate measured vane results to back-calculated slope failures (Larsson 1980).

The Electric Vane Shear device is an improvement on vane testing to measure $s_u$. 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.

The penetrometer results are correlated to the vane $s_u$ through the N factors in Table 3. Both CPTU and Ball PT methods show good overall agreement in their determination of peak $s_u$. All existing experience and applications with the vane $s_u$ can be directly used with continuous CPTU and Ball PT $s_u$ profiles.

The Ball PT is better than the CPTU for deep, low strength, undrained sediments. This advantage is due to a reduction in the magnitude of the systematic corrections to the net tip resistance. These effects can be observed in Figure 9 below 8 metres, where the CPTU is slightly overestimating $s_u$ compared to the Ball PT. The disadvantage of the Ball PT is the limitations in applicable soil units. CPTU can be performed in soils ranging from fluid mine-tailings through glacial till. The Ball PT, with the larger tip area, will quickly reach refusal in deposits with larger strengths.

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 10 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. A cross section of a slope created with Ball PT soundings may reveal a critical failure layer that could be easily missed with infrequent vane measurements or conventional drilling.

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 any soft soil site investigation, specifically offering the advantage of continuous strength profiling. Full flow penetration testing can also characterize the sensitivity of cohesive soils and aid in assessing the potential risk of clay slopes to failure or flowslides. The Electric Vane can be used to not only measure highly accurate peak, post-peak and remoulded strengths of a cohesive soil, but also to help assess its brittleness.

This paper contains a set of in-situ measurements performed at a site with very soft low strength soil. In summary:

1. The Electric Vane improves conventional vane testing by moving the torque measurement downhole.
2. In soft soil conditions, the Ball PT improves CPTU by reducing the magnitude of the corrections to obtain a net penetration resistance.
3. The full flow penetrometers provide a profile of "vane $s_u$" using site-specific N factor calibrations.
4. The Ball PT can be cycled to obtain profiles of the peak, post-peak, and remoulded "vane $s_u$".
5. A profile of undrained shear strength reduces the risk of missing a weak layer, which may easily occur with discrete vane testing and conventional drilling and sampling.

Therefore, when an objective of a site investigation is to obtain $s_u$ for design calculations, a combination of Ball PT soundings and Electric VST can provide an accurate cross-section. This can be easily achieved by calibrating a site specific N factor and performing multiple Ball PT soundings.

## ACKNOWLEDGEMENTS

The writers would like to acknowledge the assistance of Prestige Fabrication for allowing the use of the test site and Mud Bay Drilling for assistance with the field testing.

## REFERENCES

Armstrong, J.E. (1984). "Environmental and engineering applications of the surficial geology of the Fraser Lowland, British Columbia". Geological Survey of Canada, Paper 83-23.

ASTM D 2573-01 (2001) Standard Test Method for Field Vane Shear Test in Cohesive Soil, ASTM, Philadelphia, Pennsylvania, USA.

Chung, S.F. and Randolph, M.F. Penetration resistance in soft clays for different shaped penetrometers, Proceedings ISC-2 on Geotechnical and Geophysical Site Characterization, pp. 671-677. Viana da Fonseca & Mayne (eds.) © 2004 Millpress, Rotterdam

Crawford, C.B. & Campanella, R.G. 1991. Comparison of Field Consolidation with Laboratory and In Situ Tests. Canadian Geotechnical Journal, 28: 103-112.

DeJong, J.T., Yafrate, N.J., DeGroot, D.J. and Jakubowski, J. (2004) Evaluation of the undrained shear strength profile in soft layered clay using full-flow probes Proceedings ISC-2 on Geotechnical and Geophysical Site Characterization, pp. 679-686. Viana da Fonseca & Mayne (eds.) © 2004 Millpress, Rotterdam

DeJong, J.T., Yafrate, N.J. & Randolph, M.F. 2008. Use of pore pressure measurements in a ball fullflow penetrometer. Proc. 2nd Int. Conf. Geotechnical and Geophysical Site Characterization – ISC'3, Taiwan, London: Millpress, 1269 – 1275.

DeJong, J.T., Yafrate, N.J., DeGroot, D.J., Low, H.E., Randolph, M.F. (2010) Recommended Practice for Full-Flow Penetrometer Testing and Analysis, Geotechnical Testing Journal, Vol. 33, No. 2

Larsson, R. (1980) Undrained shear strength in stability calculation of embankments and foundations on soft clays, Candian Geotechnical Journal, Vol. 17, pp. 591-602.

Long, M. and Gudjohnsson, G.T. (2004) T-bar testing in Irish soils. Proceedings ISC-2 on Geotechnical and Geophysical Site Characterization, pp. 719-726. Viana da Fonseca & Mayne (eds.) © 2004 Millpress, Rotterdam

Lunne,T.,M. F., Randolph, M.F., S. F.,Chung, K.H. Andersen, K.H. and M. Sjursen (2005) Comparison of cone and T-bar factors in two onshore and one offshore clay sediments. Proceedings of International Symposium on Frontiers on Geotechnics;pp. 981-991. Perth, Australia, Sept. 2005.

Lunne, T., Robertson, P.K. & Powell, J.J.M. (1997). Cone Penetration Testing in Geotechnical Engineering, Blackie Academic and Professional, London.

Marchetti S., Monaco P., Totani G. & Calabrese M. "The Flat Dilatometer Test (DMT) in Soil Investigations "A Report by the ISSMGE CommitteeTC16. Proc. IN SITU 2001, Intnl. Conf. On In situ Measurement of Soil Properties, Bali, Indonesia, May 2001, 41 pp.

Mayne, P.W. (2005) "Integrated ground behavior: In-situ and laboratory tests." Deformation Characteristics of Geomaterials (2), Taylor & Francis, UK: 155-177.

Park, C.B., Miller, R.D., and Xia, J., 1999, Multi-channel analysis of surface waves (MASW): Geophysics, v. 64, no. 3, p. 800-808.

Stewart, D.P. & Randolph, M.F. (1991). A new site investigation tool for the centrifuge, Proc. Int. Conf. Centrifuge 1991, Boulder, H.Y. Ko (ed.), Balkema, 531-538.

Stewart, D. P. and Randolph, M. F. 1994. T-bar penetration testing in soft clay. *ASCE Journal of Geotechnical Engineering, 120(12):* 2230-2235.

Weemees, I., Howie, J., Woeller, D.J., Sharp, J., Cargill, E., Greig, J. (2006). Improved Techniques for the In-situ Determination of Undrained Shear Strength in Soft Clays, Proceedings of Canadian Geotechnical Conference, Vancouver, BC