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A comparison between in situ techniques to measure undrained shear strength of oil sands tailings

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Abstract

A comprehensive comparison between undrained shear strength (S_u) measured from piezocone penetration tests (CPTu), piezoball penetration tests (BCPTu), and electronic field vane shear tests (eVST) in soft tailings is presented. To evaluate the comparability of S_u from both penetrometers and eVST, a comparative study was performed using data collected from oil sands tailings storage facilities in northern Alberta, Canada. Two paired datasets of eVST-CPTu and eVST-BCPTu were compiled and the relationships between S_u values from the three strength measurement techniques were explored. Results show that N_{kt} and N_{ball} of 15 and 12.2 are reasonable values to scale net tip resistance and determine the strength in soft tailings from CPTu and BCPTu, respectively. Furthermore, comparing to eVST results, both CPTu and BCPTu penetrometers were found to be effective tools in profiling the strength of soft tailings when S_u is less than 10 kPa. BCPTu was observed to be slightly more accurate than CPTu in very low strength fluid-like tailings.

Keywords: *undrained shear strength, field vane shear test, piezocone penetration test, ball penetration test, soft tailings*

1 Introduction

Characterisation of undrained shear strength (S_u) is commonly required in geotechnical assessment of soils and tailings. Accurate determination of tailings strength along with regular monitoring of strength increase due to consolidation is necessary in soft fines dominated soils and tailings.

A combination of in situ and laboratory tests is generally employed to characterise geomaterials strength. The laboratory analysis is expensive, and results are limited to discrete depths. If sampling is possible, disturbance is likely, and the sample may no longer be representative of in situ conditions. These limitations make laboratory analyses of soft tailings less attractive than in situ techniques.

In situ determination of S_u is commonly performed using either piezocone penetration tests (CPTu), piezoball penetration tests (BCPTu), or electronic field vane shear tests (eVST). CPTu and BCPTu offer the advantage of continuous profiling of soil or tailings properties, including S_u, with depth. The BCPTu has been demonstrated to be advantageous over CPTu for profiling very soft soils and slurries (e.g. Randolph 2004; Yafrate et al. 2009; DeJong et al. 2010; Schaeffers & Weemees 2012). The larger cross-sectional area of the penetrometer tip results in higher penetration forces, improving measurement precision. In addition, due to flow around the ball, a smaller overburden stress correction is required which improves strength determination in soft soils and tailings when the precise unit weight may be unknown.

The field vane shear test (FVST) is generally the reference test to which other tests are compared and is an in situ means for direct measurement of S_u at discrete depths. Digitisation of the FVST created the electronic field vane shear test (eVST) with rate-controlled motors and downhole measurements of torque. Site-specific correlations are generally developed by carrying out adjacent CPTu or BCPTu soundings and eVST boreholes.

This paper examines a large dataset to compare S_u measured from CPTu, BCPTu and eVST in soft clay and fines dominated oil sands tailings in northern Alberta, Canada. Two paired datasets of eVST-CPTu and eVST-BCPTu were compiled and the relationships between the three strength measurement techniques were explored. The impact of ball penetrometer area and shaft size on the strength measurements was also investigated.

2 Background

2.1 Piezocone penetration testing (CPTu)

The piezocone penetrometer or CPTu is a direct push probe frequently used in geotechnical site investigations (Figure 1a). The CPTu measures various parameters including tip resistance (q_c), sleeve friction (f_s), and pore pressure (u_2). The CPTu is typically advanced at a constant rate of 2 cm/s (ASTM 2012), continuously recording these measurements as it progresses through the soil. In soils, the pore pressure measurements allow the cone to monitor the dynamic pore pressures during penetration, the dissipation of pore pressure when the probe is stopped, and the in situ pore pressures when the dissipation test is allowed to reach equilibrium during pauses in penetration. The rate of pore pressure dissipation is a function of the permeability of the soil. In fluids such as water or a suspension, the pore pressure sensor provides a continuous measure of the fluid pressure.

To interpret CPTu data, systematic correction using Equation 1 is required to calculate corrected tip resistance (q_t):

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

where:

q_c = measured resistance.

u_2 = porewater pressure at the shoulder.

A = net area ratio for the piezocone.

During undrained penetration, the scaled net tip resistance is approximately equal to the undrained shear strength (S_u). The net tip resistance (q_{net}) for CPTu is calculated using Equation 2:

$$q_{net}(CPTu) = q_t - \sigma_{vo} \tag{2}$$

where:

q_t = corrected tip resistance.

σ_{vo} = total vertical stress which depends on the unit weight of the material.

The undrained shear strength (S_u) is then calculated using the following equation:

$$S_u = \frac{q_{net}(CPTu)}{N_{kt}} \tag{3}$$

where N_{kt} is a strength factor.

Various theoretical and numerical solutions have been proposed to establish the appropriate N_{kt}, including those based on limit plasticity, cavity expansion theory, strain path method, as well as numerical finite element simulations (e.g. Konrad & Law 1987; Mayne 2016; Teh & Houlsby 1991; Lu et al. 2004). However, these approaches require additional input parameters, such as the rigidity index, cone roughness, lateral stress state, friction angle, and other variables, which must be determined prior to their application. Consequently, site-specific calibrations against laboratory results or FVSTs are generally used to determine the strength factor. It should be mentioned that shear strength is not a unique value for a given soil or tailings, but rather depends on various factors such as the mode of shearing, rate of loading, failure mode and other variables (Mayne 2008). Therefore, when determining N_{kt} through site-specific calibrations, the choice of reference test for measuring the undrained shear strength, such as triaxial or vane shear impacts the N_{kt}

value. Numerous investigations have been conducted to quantify N_{kt}, resulting in a broad range of values. However, many of the studies have reported N_{kt} values in the range of 15–20 (Lunne et al. 1997).

2.2 Piezoball penetration testing (BCPTu)

The piezoball penetrometer or BCPTu is now used as a standard test tool for profiling soft soil and tailings, determining the undrained shear strength and sensitivity (Figure 1a). The BCPTu consists of a standard cone penetrometer body and a large spherical attachment that replaces the standard conical tip.

For BCPTu, the net penetration resistance is calculated using the following relationship (Randolph 2004):

$$q_{net}(\text{BCPTu}) = q_b - [\sigma_{v0} - (1-a)u_2]\left(\frac{A_s}{A_p}\right) \tag{4}$$

where:

q_b = measured resistance.

σ_{vo} = total vertical stress.

a = net end area ratio.

u_2 = porewater pressure behind the shoulder.

A_s = area of the shaft.

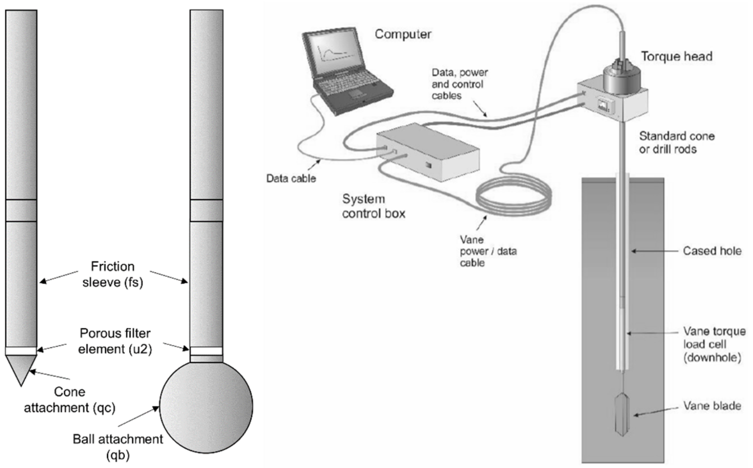
A_p = area of the projected penetrometer.

In order to minimise overburden corrections, a penetrometer with an area ratio (A_s:A_p) of 1:10 is recommended (DeJong et al. 2010), but other practical considerations may impact the ball size choice. The undrained shear strength is related to the net penetration resistance using the following relationship:

$$S_u = \frac{q_{net}(BCPTu)}{N_{ball}} \tag{5}$$

where N_{ball} is a strength factor.

Determination of N_{ball} using theoretical solutions has a more robust basis than CPT due to the simple geometry of the ball. However, site-specific correlations using laboratory or field vane results are preferred because theoretical methods do not account for all factors influencing the in situ measurements. Several studies have demonstrated that the range of N_{ball} is slightly narrower compared to N_{kt} (e.g. Low et al. 2010; DeJong et al. 2011). Yafrate & DeJong (2006) indicated that for soils with low to moderate sensitivity, N_{ball} values range from 11.6–13.2 using the vane shear test as the reference.



(a) (b)

Figure 1 Components of a) CPTu and BCPTu and b) eVST (downhole configuration, casing not generally utilised in fluid tailings)

2.3 Digital field vane shear testing (eVST)

The eVST is performed to directly measure peak and remoulded undrained shear strength. The test is carried out by inserting a four-bladed vane into soil or tailings at discrete depths and applying torque at a constant rate, which is adjustable by the operator, to rotate the vane creating a cylindrical failure surface in the geomaterial (Figure 1b). The produced measurements of stress versus strain may be useful to practitioners and researchers. The downhole configuration was used for all data in this study, the torque load cell was positioned immediately above the vane blade, eliminating the influence of rod friction in the measured torque. Although eVST is an accurate and direct measurement of undrained shear strength, it is more time consuming than CPTu and BCPTu, and results are limited to discrete depth intervals.

3 Dataset description

3.1 Study region

To evaluate S_u from cone, ball, and eVST, a comparative study was performed using data collected from oil sands tailings storage facilities in northern Alberta, Canada. The oil sands mining region typically builds upstream cyclone sand tailings dams, with tailings composition ranging from medium quartz sand to clay. The fines are dominated by clay minerals, resulting in large volumes of fluid clay slurry tailings within the containment structures. The tailings storage facilities in the region have been extensively investigated using CPTu, BCPTu, and eVST, along with sampling.

ConeTec's geospatial database was used to query all CPTu, BCPTu, and eVST soundings from 2009 to 2022 in the region. The resulting paired dataset was limited to soundings collected within a 5 m radius and within one month of the reference eVST location. These criteria were put in place to minimise the temporal and spatial variation between eVST and CPTu/BCPTu results. Ultimately, the query resulted in 266 paired eVST-CPTu and 144 paired eVST-BCPTu locations.

3.2 Calculating qnet from CPTu and BCPTu

To calculate q_{net} and thus the peak undrained shear strength from CPTu and BCPTu profiles, an estimate of total vertical stress (σ_{vo}) is required which depends on the total unit weight of the tailings. As proposed by Styler et al. (2018), unit weights for CPTu profiles in fluid-behaving tailings were determined using equilibrium pore pressure dissipation (PPD) data and/or solids contents from adjacent samples.

For soundings without equilibrium PPD or adjacent solids content data, the slope of the dynamic pore pressure profile (u_2) was used as the total unit weight in fluid-behaving tailings (Entezari et al. 2020). The slope of the dynamic pore pressure was calculated over a moving depth window of 1 m. Within the depth window, the data points with an effective tip resistance (q_t-u_2) greater than 100 kPa are excluded from the calculation of the slope. This effective tip resistance criterion was imposed to exclude soil-like tailings. The calculated slope of the dynamic pore pressure was constrained between 9.8 and 18 kN/m^3. A default unit weight of 18.21 kN/m^3 was assumed for tailings with an effective tip resistance exceeding 100 kPa, based on prior experience.

Unit weight profiles for BCPTu soundings were available from PPD or sample result interpretation for all soundings in the study. S_u measurement from the BCPTu is less sensitive to potential errors in unit weight and overburden stress estimates than the CPTu. Vertical overburden stress acts on both the top and bottom of the ball, with only the area of the shaft not cancelling out. Hence, in the case of $A_s/A_p = 0.1$, only 1/10th the overburden correction is required for the BCPTu compared to CPTu.

Figures 2 and 3 depict example profiles from different paired CPTu-eVST and BCPTu-eVST locations, respectively. Assumed values of $N_{kt} = 15$ and $N_{ball} = 11$ were used to scale q_{net} and derive S_u from CPTu and BCPTu profiles.

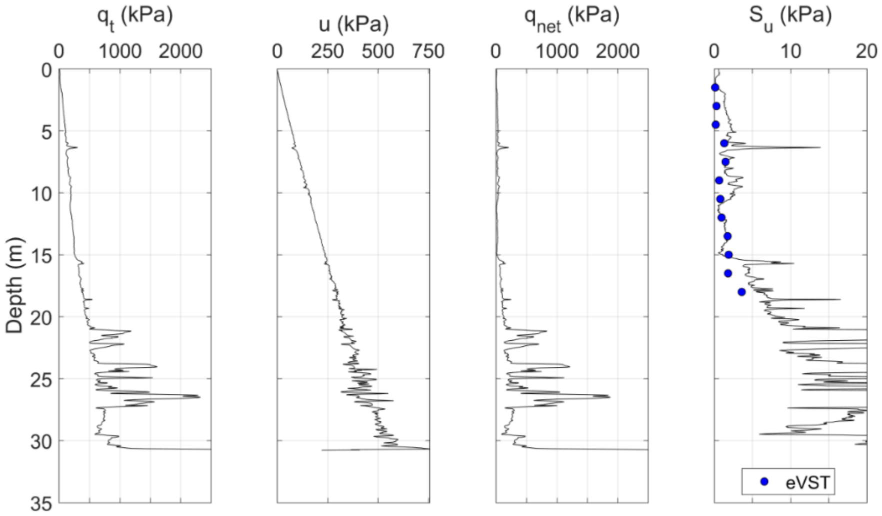


Figure 2 Example location tested with CPTu and eVST. Horizontal distance between CPTu and eVST location is 2.94 m

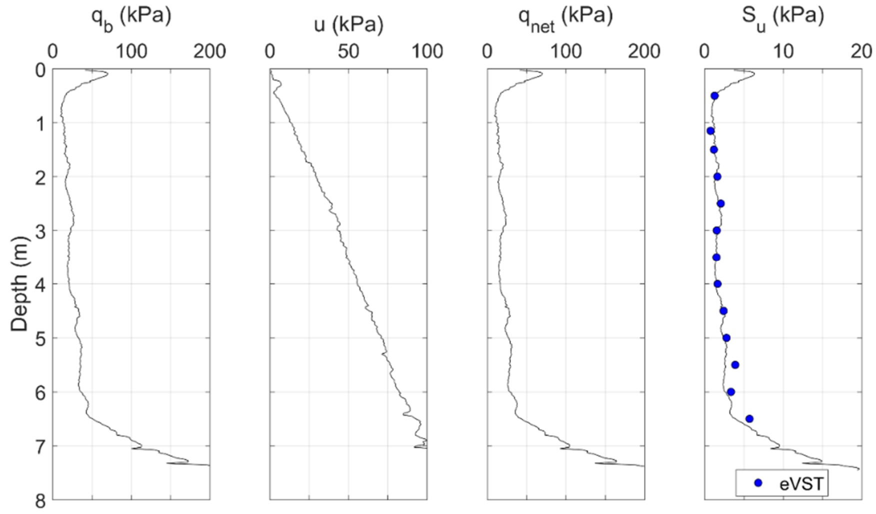


Figure 3 Example location tested with BCPTu and eVST. Horizontal distance between BCPTu and eVST location is 3.93 m

3.3 Pairing q_{net} from CPTu and BCPTu with S_u from eVST

To pair q_{net} values obtained from CPTu and BCPTu to S_u values measured at discrete depths using eVST, the average of q_{net} values from CPTu and BCPTu were calculated over a 50 cm depth window centered at the elevation of the eVST. The pairing process ultimately resulted in 888 and 652 paired data points from eVST-CPTu and eVST-BCPTu, respectively.

Since the primary interest of this study was to compare in situ techniques to measure the undrained strength of soft tailings, the dataset was screened to retain fines dominated fluid-behaving and soft tailings with less than 10 kPa strength, as well as being uniform (homogenous) over the 50 cm depth window. This screening process successfully eliminated data potentially in loose sandy deposits.

After the screening process, the final dataset included 206 data pairs from eVST-CPTu and 318 data pairs from eVST-BCPTu. Among the 318 data pairs from eVST-BCPTu, 144 pairs were obtained from BCPTu soundings with a projected area (A_p) of of 100 cm^2 and a shaft area (A_s) of 10 cm^2, 164 pairs were from BCPTu soundings with A_p of 150 cm^2 A_s of 15 cm^2, and 10 pairs were from BCPTu soundings with A_p of 100 cm^2 A_s of 15 cm^2.

4 Results

4.1 Comparison between CPTu and eVST

4.1.1 Determining N_{kt}

Figure 4 illustrates the correlation between the measured S_u from eVST and q_{net} from CPTu. The slope of the fitted line to the data points, which was forced to have a zero intercept, was calculated to be 15. This slope is the N_{kt} used to scale q_{net} to estimate S_u from CPTu. This indicates that the commonly used N_{kt} of 15 is an excellent approximation for the estimation of S_u in soft tailings from CPTu.

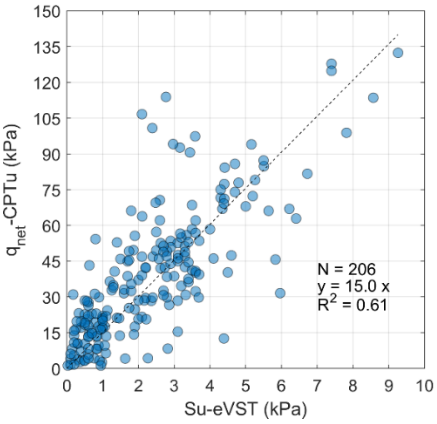
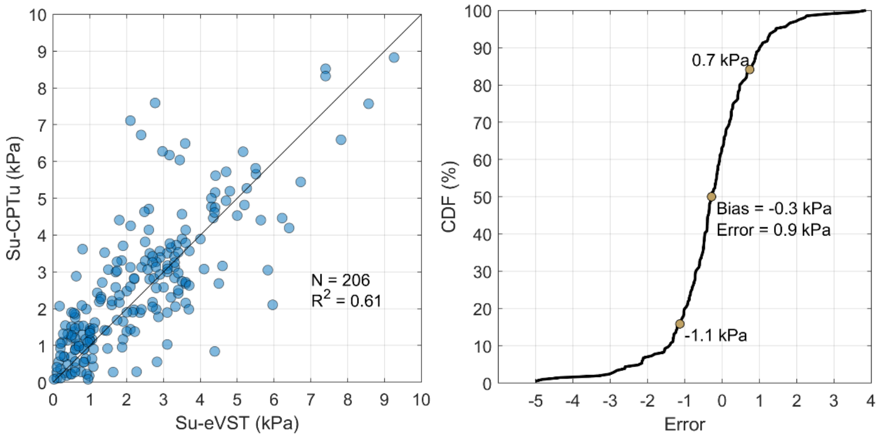


Figure 4 Relationship between measured S_u from eVST and calculated q_{net} from CPTu

4.1.2 S_u from CPTu versus eVST

Figure 5a presents a comparison between measured S_u from eVST and estimated S_u from CPTu. The q_{net} values from CPTu were scaled using the N_{kt} of 15 to calculate S_u from CPTu. An error analysis was performed using the properties of the cumulative distribution function (CDF) of errors on the dataset. Because the eVST is the reference test method to obtain S_u, the error was calculated as the difference between the measured S_u from eVST and estimated S_u from the CPTu (error = S_u eVST - S_u CPTu). The 50th percentile in the CDF can be taken as the bias of the CPTu method in obtaining S_u. Assuming the errors follow a normal distribution, the CDF values at 15.9 and 84.1% correspond to ±1 standard deviation. The average of the two CDF values at 15.9 and 84.1% is considered as the overall error of the CPTu method in determining S_u. The CDF of errors is shown in Figure 5b. The bias is observed to be immaterial at -0.3 kPa. The overall error is calculated to be 0.9 kPa. This means that 68.2% of the derived S_u values from CPTu fall within ±0.9 kPa of the measured S_u from eVST.



(a) (b)

Figure 5 a) Relationship between measured and estimated S_u from eVST and CPTu; b) CDF of errors

4.2 Comparison between BCPTu and eVST

4.2.1 *Determining N_{ball}*

Figure 6 shows the relationship between measured S_u from eVST and q_{net} from BCPTu. The slope of the fitted line (forced to have a zero intercept), which is considered the N_{ball} value, was calculated to be 12.2. This is slightly higher than the N_{ball} of 11–11.5 obtained from earlier site-specific observations in oil sands tailings.

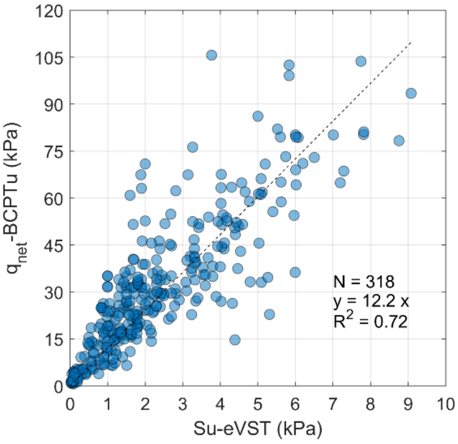
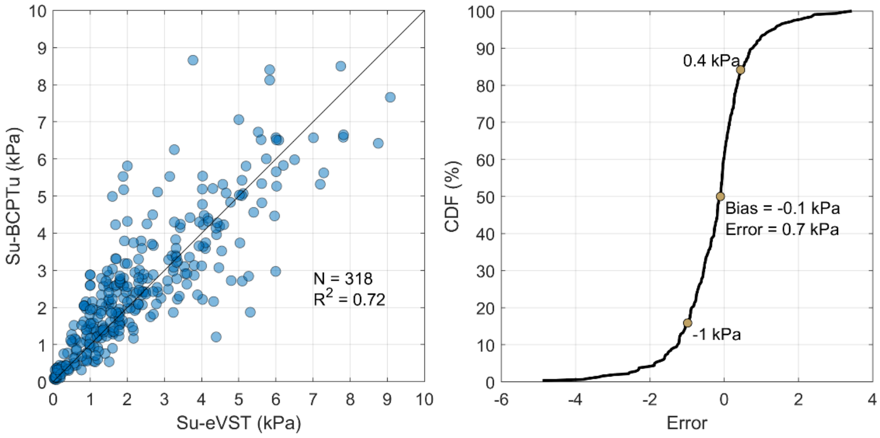


Figure 6 Relationship between measured S_u from eVST and calculated q_{net} from BCPTu

4.2.2 *S_u from BCPTu versus eVST*

The relationship between the measured S_u from eVST and estimated S_u from BCPTu is shown in Figure 7a. To scale q_{net} from BCPTu and calculate S_u, N_{ball} of 12.2 was used. The CDF of error was calculated by subtracting BCPTu shear strength values from the eVST values (error = S_u eVST - S_u BCPTu). As shown in Figure 7b, the bias and error were found to be -0.1 and ±0.7 kPa, respectively.

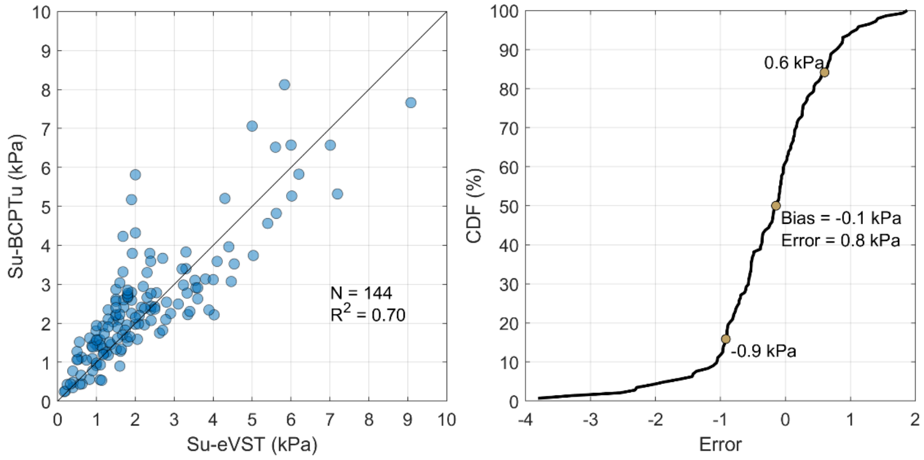


(a) (b)

Figure 7 a) Relationship between measured and estimated S_u from eVST and BCPTu; b) CDF of errors

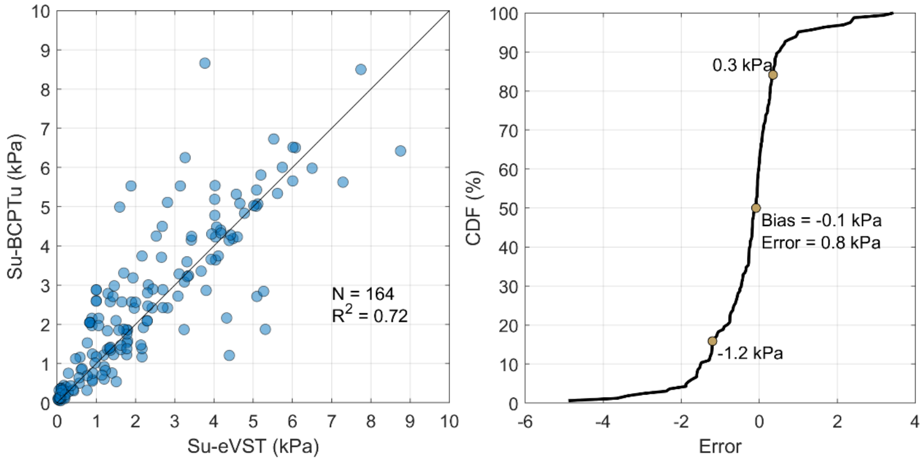
4.2.3 *Impact of ball penetrometer area and shaft size*

A performance assessment was done to analyse the impact of ball penetrometer projected area and shaft size on the strength measurement. The analysis excluded data points from BCPTu soundings with A_s:A_p of 15:100, because only 10 data pairs were obtained from such soundings which were statistically insufficient for error assessment. Figures 8a and 9a show the relationship between measured and estimated S_u from eVST and BCPTu for the fraction of the dataset with A_p:A_s = 10:100 and 15:150, respectively. The CDFs of errors (Figures 8b and 9b) depict that in general, both penetrometers are equally effective in estimating undrained shear strength in soft tailings with less than 10 kPa strength (bias of -0.1 kPa and error of ±0.8 kPa).



(a) (b)

Figure 8 a) Relationship between measured and estimated S_u from eVST and BCPTu soundings with A_s:A_p = 10:100; b) CDF of errors



(a) (b)

Figure 9 a) Relationship between measured and estimated S_u from eVST and BCPTu soundings with A_s:A_p = 15:150; b) CDF of errors

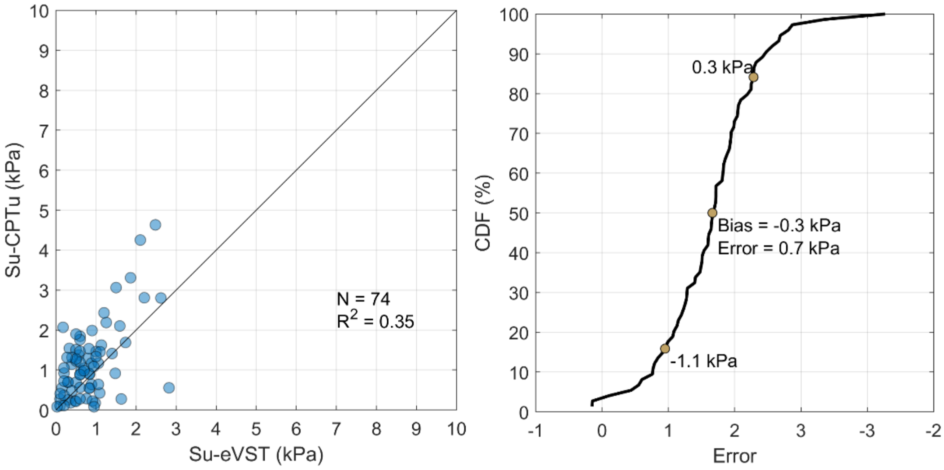
4.3 Performance comparison in fluid-like and non-fluid-like tailings

Comparing BCPTu and CPTu, it appears that they both are effective tools for the estimation of undrained shear strength in tailings with less than 10 kPa strength. The results showed that the estimated strength from both probes demonstrate similar error distributions when compared to eVST results, with BCPTu being only slightly more accurate and precise.

An analysis was performed to assess the performance of both probes in fluid-like tailings with very low strengths. Tailings with less than 3 kPa strength and exhibiting dynamic pore pressure linearity greater than 0.95 were considered fluid-like tailings. The linearity of dynamic pore pressure was used as an index to identify fluid-like tailings as fluid pressure will increase linearly with depth. The linearity was calculated using the R^2 of porewater pressure data over the same 1 m window depth used for the calculation of the slope, described in Section 3.2. Figures 10a and 11a show the relationship between the measured and estimated strength from eVST-CPTu and eVST-BCPTu datasets for fluid-like tailings. Comparing the CDF of errors

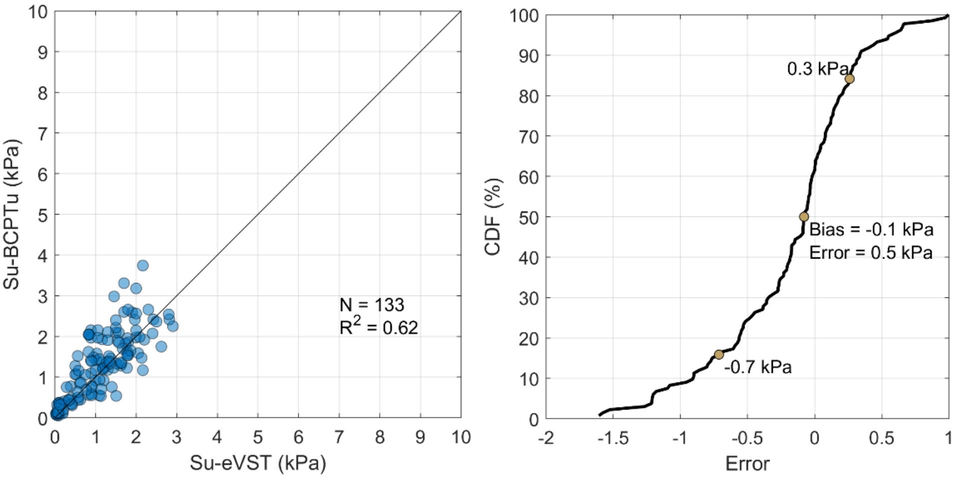
(Figures 10b and 11b) and R^2 values revealed that BCPTu is a better tool for strength measurement in fluid-like tailings. A comparison of BCPTu to CPTu resulted in lower error (-0.1±0.5 kPa compared to -0.3±0.7 kPa) and higher R^2 (0.62 compared to 0.35).

For tailings with non-fluid-like behaviour (i.e. greater than 3 kPa strength), the results showed that both probes exhibit similar CDF with no significant difference (Figures 12 and 13). Overall, BCPTu appears to be a more effective tool for measuring strength in fluid-like tailings, whereas both BCPTu and CPTu are equally effective in non-fluid soft tailings. However, the advantage of CPTu is that it can penetrate stiffer layers and provide more engineering properties of the tailings, while BCPTu is used for undrained strength and tailings behaviour type (Entezari et al. 2022) only. A performance assessment of strength measurements using CPTu and BCPTu compared to eVST is summarised in Table 1.



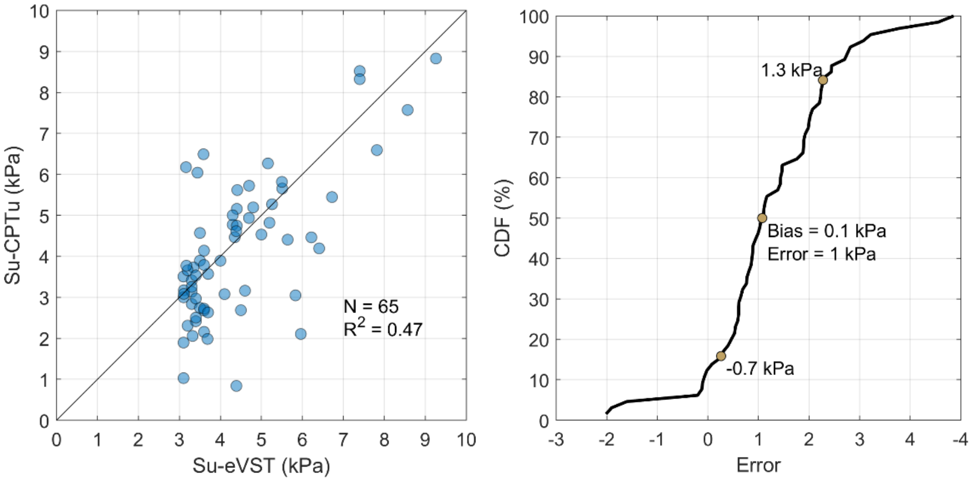
(a) (b)

Figure 10 a) Relationship between measured and estimated S_u from eVST and CPTu soundings in fluid-like tailings; b) CDF of errors



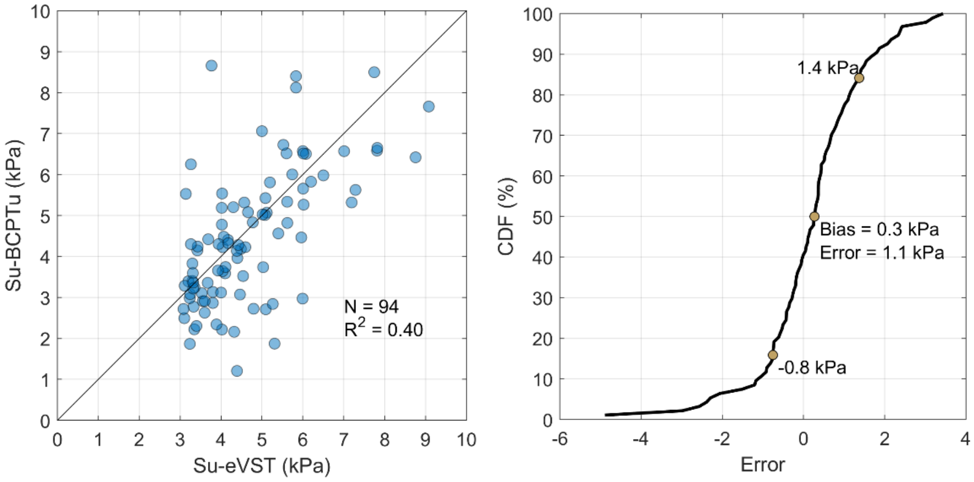
(a) (b)

Figure 11 a) Relationship between measured and estimated S_u from eVST and BCPTu soundings in fluid-like tailings; b) CDF of errors



(a) (b)

Figure 12 **a) Relationship between measured and estimated S_u from eVST and CPTu soundings in non-fluid tailings; b) CDF of errors**



(a) (b)

Figure 13 **a) Relationship between measured and estimated S_u from eVST and BCPTu soundings in non-fluid tailings; b) CDF of errors**

Table 1 **Summary of performance assessment in S_u measurement for CPTu and BCPTu compared to eVST**

	CPTu			BCPTu		
	N	R^2	bias±error (kPa)	N	R^2	bias±error (kPa)
Soft tailings (S_u < 10 kPa)	206	0.61	-0.3±0.9	318	0.72	-0.1±0.7
Fluid-like tailings (S_u < 3 kPa & pore pressure linearity > 0.95)	74	0.35	-0.3±0.7	133	0.62	-0.1±0.5
Non-fluid tailings (S_u > 3 kPa)	65	0.47	0.1±1.1	94	0.40	0.3±1.1

5 Conclusion

This study investigated the effectiveness of CPTu and BCPTu testing for estimation of the undrained shear strength of soft tailings. Using two paired datasets of eVST-CPTu and eVST-BCPTu from oil sands tailings, both

CPTu and BCPTu were found to be effective tools for determining the strength of soft tailings, with BCPTu being more accurate and precise in fluid-like tailings with an undrained shear strength less than 3 kPa.

Overall, it was observed that for tailings up to 10 kPa in strength, CPTu and BCPTu estimate S_u with ±0.9 kPa and ±0.7 kPa, respectively. It should be noted that the reported errors include spatial variability as eVST and CPTu/BCPTu soundings are performed at as much as a 5 m radial offset. Furthermore, ball penetrometers with A_s:A_p of 10:100 and 15:150 were found to be equally effective in estimating undrained shear strength in soft tailings with less than 10 kPa strength.

The study also determined that N_{kt} and N_{ball} of 15 and 12.2 are reasonable values for scaling net tip resistance and determining strength in soft tailings using CPTu and BCPTu, respectively. It should be noted that the study was limited to fine grained clay dominated tailings less than 10 kPa in shear strength, and from a single geological region. The tailings are expected to be normally or under-consolidated, and of similar plasticity and sensitivity, and hence these results may not necessarily be repeatable in other regions. Site-specific calibration of penetrometer derived shear strengths is always recommended.

Penetration tests are significantly more efficient while providing continuous data and hence have an advantage over the eVST and laboratory methods to measure shear strength on a production basis. The continuous nature of the CPTu and BCPTu allows for the identification of tailings strata that may not be detected through drilling or vane shear testing.

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