Evaluation of existing CPTu-based correlations for the undrained shear strength of soft Finnish clays

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ABSTRACT: The Tampere University of Technology has been carrying out an extensive research program on soil testing in Finland. The aim of this research project is to collect data from high-quality in situ and laboratory tests and derive correlations for strength and deformation properties specific to Finnish clays. Correlation models for the undrained shear strength of soft clays based on CPTu measurements have been proposed in the literature by several authors. However, such models are often calibrated from a specific site or soil type. Thus, validation of these models is required before applying them to different soil conditions. In this paper, the existing correlations for the undrained shear strength of soft clays based on CPTu data are compared to test the results from different sites in Finland. The validity of the existing models is assessed for Finnish clays by evaluating their bias and uncertainties.

1 INTRODUCTION

The scope of this paper involves assessing the validity of existing correlations for \( s_u \) in Finnish soils based on the piezocone (CPTu) parameters. Data collected by the Tampere University of Technology (TUT) from seven clay sites in Finland are exploited to evaluate the correlations that are commonly used in Sweden and Norway. Specifically, the validity of the CPTu correlations for \( s_u \) from the triaxial compression (TXC; \( s_{u,\text{TXC}} \)) and direct simple shear (DSS; \( s_{u,\text{DSS}} \)) tests is checked against TXC and DSS tests on high-quality samples of soft clays. The CPTu correlations for \( s_{u,\text{DSS}} \) are also compared with down-hole field vane (FV; \( s_{u,\text{corrFV}} \)) test results from the different sites. Finally, the bias and uncertainties of the examined correlations are evaluated with respect to the presented dataset of Finnish clays.

2 SOIL INVESTIGATION

2.1 Test sites

Table 1 summarizes the basic properties of the seven clay sites considered in this study. The investigated clays were slightly overconsolidated (overconsolidation ratio, \( OCR < 3 \)), and they covered a wide range of water contents \( (w = 66–127\%) \) and sensitivities \( (S_t = 16–98) \). The natural water content was above the liquid limit \( (w_L) \) in all the sites, and the remolded undrained shear strength \( (s_u^m) \) was generally lower than 2 kPa. Some of the sites have been presented and discussed in Di Buò et al. (2016) and Selänpää et al. (2017).

The maximum penetration depths reached were 9 m at Lempäälä and Perniö, 23 m at Murro, 15 m at Masku, 11 m at Paimio and Sipoo, and 16 m at Joensuu. The depths for sampling were chosen by observing the most homogenous layers from the CPTu data. The deepest sampling depths were 7 m at Lempäälä, 8 m at Perniö and Masku, 5 m at Murro and Joensuu, and 9 m at Paimio and Sipoo.

<table>
<thead>
<tr>
<th>Site</th>
<th>OCR (–)</th>
<th>( w ) (%)</th>
<th>( w_L ) (%)</th>
<th>( I_p ) (%)</th>
<th>( S_t ) (–)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lempäälä</td>
<td>1.1–1.4</td>
<td>68–127</td>
<td>42–69</td>
<td>16–26</td>
<td>24–54</td>
</tr>
<tr>
<td>Perniö</td>
<td>1.2–2.5</td>
<td>70–110</td>
<td>44–75</td>
<td>19–47</td>
<td>37–72</td>
</tr>
<tr>
<td>Murro</td>
<td>1.2–1.9</td>
<td>66–95</td>
<td>58–97</td>
<td>28–53</td>
<td>20–23</td>
</tr>
<tr>
<td>Masku</td>
<td>1.4–1.8</td>
<td>80–117</td>
<td>66–95</td>
<td>39–59</td>
<td>18–21</td>
</tr>
<tr>
<td>Sipoo</td>
<td>1.2–2.0</td>
<td>79–116</td>
<td>66–89</td>
<td>36–63</td>
<td>16–45</td>
</tr>
<tr>
<td>Joensuu</td>
<td>1.2–2.8</td>
<td>72–109</td>
<td>65–95</td>
<td>39</td>
<td>20–35</td>
</tr>
</tbody>
</table>

Where: \( OCR = \) overconsolidation ratio from oedometer test with constant-rate-of-strain (CRS) of 0.001–0.0025 mm/min depending on clay type; \( w = \) water content; \( w_L = \) liquid limit; \( I_p = \) plasticity index; and \( S_t = \) sensitivity from the fall cone test.
2.2 In situ tests and sampling

Pairs of sampling and in situ tests were performed within 2 meters of each other. The in situ tests performed consisted of the CPTu and FV tests. Seismic and resistivity measurements were also gathered. However, the evaluation of soil properties from such measurements is beyond the scope of this study. Therefore, these data are not presented.

The CPTu tests were carried out using a low-capacity (0.75t) and high-sensitivity probe, which is expected to provide high accuracy in soft, homogenous soils (Sandven, 2010). The tests fulfil the requirements of application class 1 according to ISO (2012). The excess pore pressure during penetration \( u_2 \) was measured right above the cone tip.

To verify the test repeatability and perform resistivity and seismic measurements, a minimum of three tests were conducted at each site. In general, the repeatability was good, as discussed in Di Buò et al. (2016). Therefore, the piezocone data used to evaluate the correlations in this study were based on a single CPTu sounding for each site.

FV measurements were obtained using a down-hole vane device equipped with a casing. This setup has been shown to provide high accuracy in both torque and rotation measurements (Selännpää et al., 2017). However, the pushing of the vane into the soil always causes some disturbance. Thus, repeatability was also checked for the vane tests by performing a minimum of three tests for each depth. It was assumed that differences in the measured torques—and therefore, \( s_u \)—were mainly due to disturbance, and the highest of the measured values was taken as the most representative.

FV measurements must be corrected to account for anisotropy and rate effects (Bjerrum, 1973). In Finland, this is done by means of a reduction factor that depends on the liquid limit (Ratahalointokeskus, 2005). Only corrected FV results are discussed in this study.

2.3 Laboratory tests

Soil sampling was mainly performed using an open-drive tube sampler with a diameter of 132 mm designed at TUT (Di Buò et al., 2016). The sampler is a small-scale reproduction of the SGI-type Laval open-drive block sampler (Larsson, 2011). The main difference with the SGI sampler is that the soil is stored in the sampling steel tube and extruded only before testing. This feature was designed to avoid possible damaging of the sample during handling and lateral stress reduction during storage. The sampler is also equipped with a cutting wire system that separates the sample from the ground prior to sampler withdrawal. An air feeding system was also implemented to prevent suction at the cutting end (Di Buò et al., 2016).

The Perniö test site included some high-quality samples taken by a Sherbrooke-type mini block sampler (Emdal et al., 2016). For two out of eight of these high-quality samples, a considerably higher \( s_{uc} \) was measured, in comparison with the other test results. These two tests are samples that have been prepared and trimmed for testing within 24 h of sampling. The effect of storage time was studied by Amundsen et al. (2017) and the short swelling time resulting in smaller disturbance may partly explain the superior results. In Figures 5–8, the two tests can be easily identified, as they had the highest measured \( s_{uc} \) among the tests (\( s_{uc} > 25 \text{ kPa} \)).

The laboratory tests on the tube samples included consolidated isotropic undrained compression (CIUC) and extension (CIUE) tests, consolidated anisotropic undrained compression (CAUC) tests and extension (CAUE) tests, DSS tests, CRS oedometer and index tests. This study focuses only on the test results from the CIUC, CAUC, and DSS tests. The laboratory tests were conducted in a climatized room with a constant temperature of 20°C.

The cell pressure \( \sigma_{cell} \) in the CIUC tests was chosen as the smallest value between \([0.73 \sigma'_{s}; 0.6 \sigma'_{p}]\), where \( \sigma'_{s} \) is the effective vertical stress and \( \sigma'_{p} \) is the preconsolidation stress. The basic principles for selecting between these values were as follows: a) to consolidate close to the in situ hydrostatic stress level, and b) to ensure that the yield surface did not expand during consolidation. The consolidation pressure was kept constant for 24 h, while the end of consolidation was verified by the measured volumetric strain. The preconsolidation stress \( \sigma'_{p} \) was inferred from the CRS oedometer tests on samples from the same tube as the triaxial specimens.

The CAUC test results seemed in line with those of the CIUC tests, with differences in terms of the measured peak \( s_{uc} \) in the order of ±3%. Therefore, the CAUC and CIUC tests are analyzed and presented together.

In the DSS tests, the samples were first consolidated to a stress level close to the preconsolidation stress. They were then unloaded to the in situ stress state before shearing.

The average failure times in the CIUC and DSS tests were 2.5 h and 1.25 h, respectively. In this study, no strain-rate correction was applied to the test results.

The sample quality of the triaxial specimens was evaluated according to Lunne et al.’s (1997) criteria, which are based on the volume change during reconsolidation to the effective in situ stress. According to the sample quality classification by Lunne et al. (1997), 7 out of 37 triaxial test results...
could be classified as “Good,” while the remaining 30 were “Very good to excellent.”

3 INTERPRETATION OF THE UNDRAINED SHEAR STRENGTH

The net cone resistance \(q_{net} (= q_e - \sigma_v)\) is related to \(s_u\) by means of the cone factor \(N_{kt}\), as

\[
s_u = \frac{q_e - \sigma_v}{N_{kt}} - q_{int},
\]

(1)

where \(q_e\) = corrected cone resistance; \(\sigma_v\) = vertical total stress.

The effective cone resistance \(q_e (= q_T - \Delta u)\) is related to \(s_u\) by means of the cone factor \(N_{ke}\), as

\[
s_u = \frac{q_T - \Delta u}{N_{ke}} = \frac{q_T}{N_{ke}},
\]

(2)

where \(\Delta u\) = measured pore pressure.

The excess pore water pressure \(\Delta u (= u_t - u_0)\) is related to \(s_u\) by means of the cone factor \(N_{kt}\), as

\[
s_u = \frac{u_t - u_0}{N_{kt}} = \frac{\Delta u}{N_{kt}},
\]

(3)

where \(u_0\) = initial pore pressure in situ.

Numerous correlations for cone factors have been presented to evaluate \(s_u\) for local soil conditions. In this study, the cone factors that are generally used in Scandinavia were evaluated for Finnish soil conditions. The correlations of the cone factors evaluated in this study are presented in Table 2.

Correlations 1, 2, and 3 were proposed by Larsson & Åhnberg (2003). This is accounted for in the interpretation. Correlation 2 is only valid for slightly overconsolidated clays. Therefore, it is used in this study only when OCR is lower than 2—which is taken as the upper boundary of the “low” OCR data points.

Correlations 4–9 were established by Karlsrud et al. (2005) for Norwegian clays, including one site from the United Kingdom. These correlations are divided into two groups based on their sensitivity as \(S < 15\) and \(S > 15\). The lowest \(S\) value in the dataset in Table 1 is 16. However, correlations 4, 6, and 8 for \(S < 15\) are also evaluated in this study. The cone factors \(N_{kt}\) and \(N_{ke}\) were observed to be functions of OCR by Karlsrud et al. (2005), while \(N_u\) was observed to depend on the pore pressure ratio \(B_q\). The correlations are based on the high-quality samples taken by the Sherbrooke block sampler. No reduction was applied to the measured peak \(s_u\).

4 EVALUATION OF THE CORRELATIONS

When comparing the CPTu measurements and \(s_u\) values, an average CPTu value taken from a ±5-cm distance from the middle of either the triaxial or DSS samples or FV was used. Index properties were taken within a ±10-cm distance with respect to the comparison level.

In Figures 1 and 2, the undrained shear strength is calculated using the average \(N_{kt}\), \(N_{ke}\), and \(N_u\) values for the dataset. The calculated mean values were \(N_{kt} = 16.8\) and \(N_{ke} = 10.7\) for \(s_{DSS}\), \(N_{kt} = 17.5\) and \(N_{ke} = 9.3\) for \(s_{corrFV}\), and \(N_{kt} = 10.7\), \(N_{ke} = 7.0\), and \(N_u = 5.6\) for \(s_{corr}\). These reference values are used for comparison with the correlations in Table 2. The results generally showed good agree-

![Figure 1. Comparison between the interpreted and measured \(s_{DSS}\) and \(s_{corrFV}\) values using the average \(N_{kt}\) and \(N_{ke}\).](image)
ment between the measured and calculated $s_{uc}$ values using the average $N_{kt}$, $N_{\Delta u}$, and $N_{ke}$.

In Figures 3–8, the $s_u$ values calculated from the cone factor models in Table 2 are compared with the measured $s_u$ values. The goodness of each correlation model was evaluated through the calculation of the bias factor ($b$) and coefficient of variation ($COV$), following Ching and Phoon (2014). The bias factor $b$ is defined as the mean value of the ratio (measured $s_u$)/(calculated $s_u$).
If \( b = 1 \), the prediction is unbiased. The COV is calculated as the ratio of the standard deviation of the (measured \( s_u \)) / (calculated \( s_u \)) ratio and the bias factor. These values are summarized in Tables 3–6.

In Figure 1, the interpretation of \( s_{dSS} \) and \( s_{wUcorrFV} \) using constant cone factors resulted in the following: (i) nearly unbiased predictions, and (ii) lower calculated COVs when using \( N_{kt} \), compared with \( N_{ke} \). However, the COV values relative to \( s_{wUcorrFV} \) were consistently higher than those for \( s_{dSS} \), indicating a higher variability of FV measurements compared with DSS.

In Figure 2, the calculated \( b \) values suggest an almost unbiased prediction (\( b = 1.01–1.05 \)) when using constant \( N_{tr}, N_{tu}, \) and \( N_{wL} \) factors in each site. The lowest variability was observed when using Equation 1, resulting in a COV = 0.13. The higher observable scatter associated with Equations 2 and 3 resulted in higher calculated COV values (>0.18).

As shown in Figure 3, correlations 1 and 2 underestimated the \( s_{dSS} \) of Finnish clays by 9% and 16%, respectively, and gave COVs of 0.12 and 0.17. When comparing the measured \( s_{wUcorrFV} \) and \( s_{dSS} \) from correlation 1 in Figure 4, a similar \( b \) value was obtained as that for the measured \( s_{dSS} \). However, the COV was larger (0.18 vs. 0.12). In contrast, \( s_{dSS} \) from correlation 2 underestimated \( s_{wUcorrFV} \) by 14%. The scatter was also larger compared with correlation 1 (COV = 0.26).

In Figure 5, measured \( s_{uc} \) is compared with \( s_{uc} \) interpreted based on correlations 3 and 4 in Table 2. Correlation 3 underestimates the measured values by 17% (\( b = 1.17 \)) with a COV = 0.20. On the contrary, correlation 4 overestimates \( s_{uc} \) (\( b = 0.79 \)), even though the calculated COV (0.125) is lower than the COV from correlation 3.

According to Figure 6, correlation 5 overestimates by 15% (\( b = 0.85 \)), while correlation 6 provides an almost unbiased prediction. In both cases, relatively low variability around the mean trend is observed (COV = 0.114–0.128).

As shown in Figure 7, correlations 7 and 8 slightly overestimate \( s_{uc} \) by 6–12% with COV of 0.11–0.13. The COV of correlation 8 is notably improved in comparison to the reference value (COV’ = 0.26 vs COV = 0.13).

Correlation 9 in Figure 8 underestimates \( s_{uc} \) by 32% (\( b = 1.324 \)). The COV’ is significantly higher than for correlation 8 (0.26 vs 0.13).

Tables 3–6 summarize the evaluated \( b \) and COV for the correlations in Table 2. Correlations 4, 6, and 8 are for \( S_I < 15 \), while correlations 5, 7, and 9 are for \( S_I > 15 \).

5 DISCUSSION AND CONCLUSIONS

The main challenge in verifying CPTu-based correlations is to gather a reliable dataset of test results for the comparison. For the dataset used in this study, the comparison between the existing correlations and undrained shear strength from FV resulted in the highest variability (Table 4). For the DSS, the variability was slightly lower (Table 3), while the smallest variability (lowest COVs) was found for the triaxial compression test results (Tables 5–6). This may indicate that, for practical applications, the use of triaxial compression data will result in a more reliable estimate of cone factors compared with other test types. This is primarily reflected in Figure 2, and confirmed in Tables 5–6. Particularly, the best correlation was found between the triaxial compression test values and the interpretation based on correlations 6 and 7 for \( N_{ke} \).
The higher variability in the DSS tests compared with the triaxial tests may have been partly due to the lack of experience with DSS testing at TUT. The DSS equipment was taken into use for the first time at TUT during this research project.

Under— or overestimation of $s_u$ observed by the bias factor can result from differences in sample qualities in datasets, even if samples are classified with the same quality. Another reason for this could be the properties of the clays. For instance, Norwegian clays are siltier than clays in Sweden and Finland are, whereas in Finland, the organic content of the clays is often higher than that in Sweden, as summarized by Broms (1974). Clays at the Murro, Joensuu, and upper layer in the Lempälä testing sites consist of higher organic content than 2%; the other sites exhibit lower organic content. It could be reasonable to leave these sites out of the dataset in future analyses.

Another aspect is that even though the accuracy of CPTu probes, especially in terms of the capacity to measure low values, has improved, the results can vary among the different manufacturers (Sandven, 2010); this can affect the correlation results.

Based on the change in the $COV$ values from the reference values (based on mean cone factors), it seems that it may be beneficial to include $OCR$ or $B_u$ in the interpretation of $s_u$. This can be observed in Table 6. In interpretations based on $N_{ku}$, such a benefit is, however, not too clear (Table 5). The $B_u$ parameter was observed to correlate with the $OCR$, as reported by Lunne et al. (1997) and Karlsrud et al. (2005). Moreover, D’Ignazio et al. (2016) discussed, based on a large soil database, how the undrained shear strength of Finnish clays is predominantly dependent on the OCR. In addition, the plasticity index seems also to improve the evaluation, especially when $N_{ku}$ is used to assess $s_{uc}$ (Table 6).

Dividing correlations 4–9 into two groups by sensitivity does not seem appropriate for Finnish clays, although the Finnish dataset did not include samples with $S_u$ lower than 15. As shown in Table 6, the interpretation based on $N_{nu}$ and $N_{su}$ intended for low-sensitive Norwegian soils seems valid for Finnish clays. Even though the Norwegian data consists of high-quality block samples, the evaluation of $s_{uc}$ seems to work well, especially when using $N_{nu}$. The evaluations based on $N_{ju}$ seemed to give too-high values compared to the measurements (Table 5). Interpretations using $N_{ju}$ showed over— and underestimated $s_{uc}$ values, depending on which sensitivity group was considered (Table 6). It must be pointed out that a disadvantage of the $N_{ju}$ method is that it is sensitive to the accuracy of both the measurements of cone resistance, and especially, pore pressure in soft, sensitive soils. Moreover, the use of the $B_u$ parameter is not suitable for heavily overconsolidated clays, as the value could be very small or even negative (Powell et al., 1988).

As shown in Tables 3–5, the interpretation of $s_u$ from average $N_{ku}$ works relatively well. The use of parameters such as liquid limit and $OCR$ (correlations 1–3) gives also satisfactory results. Nevertheless, one of the difficulties in evaluating the goodness of the correlations 1–3 for the Finnish dataset is that there is already high scatter in the original correlation results from the Swedish dataset, as mentioned by Larsson et al. (2007). Furthermore, Larsson et al. (2007) suggested that $s_u$ anisotropy depends on the liquid limit. Therefore, for practical applications the interpretation $s_{uc}$ could be scaled using factors that are functions of $w_G$, in order to use anisotropic strength in calculations.

In Sweden, FV test results are corrected based on the liquid limit and $OCR$ (Larsson et al., 2007). This method was developed to provide a good fit with the DSS strength. A thorough study on the applicability of this method to Finnish clays is recommended in the future, as it could decrease the scatter in the interpreted vane test results. The dataset was relatively narrow in terms of strength and $OCR$ ranges, as the authors’ main interest was to focus on very soft soils. Combining the present database with other databases could increase the reliability of the evaluation of $s_u$.

REFERENCES


