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

J. Selänpää, B. Di Buò, M. Haikola & T. Länsivaara
Tampere University of Technology, Tampere, Finland

M. D'Ignazio
Norwegian Geotechnical Institute, Oslo, Norway

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_{uC}) and direct simple shear (DSS; s_{uDSS}) tests is checked against TXC and DSS tests on high-quality samples of soft clays. The CPTu correlations for s_{uDSS} are also compared with down-hole field vane (FV; $s_{ucorrFV}$) 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^{re}) 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).

Table 1. Basic Soil Properties of the Investigated Sites.

Site	OCR (–)	w (%)	w_L (%)	I_P (%)	S_t (–)
Lempäälä	1.1–1.4	68–127	42–69	16–26	24–54
Perniö	1.2–2.5	70–110	44–75	19–47	37–72
Murro	1.2–1.9	66–95	58–97	28–53	20–23
Masku	1.4–1.8	80–117	66–95	39–59	18–21
Paimio	1.3–1.9	67–109	40–66	16–36	66–98
Sipoo	1.2–2.0	79–116	66–89	36–63	16–45
Joensuu	1.2–2.8	72–109	65–95	39	20–35

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

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.

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 (Selänpää 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 (Ratahallintokeskus, 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 ($s_{uC} > 25$ 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 (σ'_{cell}) in the CIUC tests was chosen as the smallest value between [$0.73 \cdot \sigma'_1$; $0.6 \cdot \sigma'_p$], where σ'_1 is the effective vertical stress and σ'_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 σ'_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} (= $q_T - \sigma_{v0}$) is related to s_u by means of the cone factor N_{kt}, as

$$s_u = \frac{q_T - \sigma_{v0}}{N_{kt}} = \frac{q_{net}}{N_{kt}}, \tag{1}$$

where q_T = corrected cone resistance; σ_{v0} = vertical total stress.

The effective cone resistance q_e (= $q_T - u_2$) is related to s_u by means of the cone factor N_{ke}, as

$$s_u = \frac{q_T - u_2}{N_{ke}} = \frac{q_e}{N_{ke}}, \tag{2}$$

where u_2 = measured pore pressure.

The excess pore water pressure Δu (= $u_2 - u_0$) is related to s_u by means of the cone factor $N_{\Delta u}$, as

$$s_u = \frac{u_2 - u_0}{N_{\Delta u}} = \frac{\Delta u}{N_{\Delta u}}, \tag{3}$$

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 and Mulabdic (1991) for Swedish clays. Larsson and Mulabdic (1991) suggested that N_{kt} and $N_{\Delta u}$ depend on the liquid limit (w_L). Correlations 1 and 3 can be used in soils with *OCR* values higher than 1.3 by multiplying the equation by $(OCR/1.3)^{b-1}$, where *b* can be taken as equal to 0.8 (Larsson & Åhnberg, 2003). This is accounted for in the interpretation.

Table 2. Correlations for cone factors for s_{uC} and $s_{uDSS.}$

n.	s_u	Correlation	Note
1	s_{uDSS}	$N_{kt} = 13.4 + 6.65 \cdot w_L$	OCR ≈ 1.3
2	s_{uDSS}	$N_{\Delta u} = 14.1 – 2.8 \cdot w_L$	*OCR ≈ 1.3
3	s_{uC}	$N_{kt} = 3.6 + 13.2 \cdot w_L$	OCR ≈ 1.3
4	s_{uC}	$N_{kt} = 7.8 + 2.5 \cdot \log(OCR) + 0.082 \cdot I_p$	$S_t < 15$
5	s_{uC}	$N_{kt} = 8.5 + 2.5 \cdot \log(OCR)$	$S_t > 15$
6	s_{uC}	$N_{ke} = 11.5 - 9.05 \cdot B_q$	$S_t < 15$
7	s_{uC}	$N_{ke} = 12.5 - 11.0 \cdot B_q$	$S_t > 15$
8	s_{uC}	$N_{\Delta u} = 6.9 - 4.0 \cdot \log(OCR) + 0.07 \cdot I_p$	S_t 15
9	s_{uC}	$N_{\Delta u} = 9.8 - 4.5 \cdot \log(OCR)$	$S_t > 15$

Where: B_q = pore pressure ratio = $(u_2 - u_0)/(q_T - \sigma_{v0})$;
*Valid only for slightly overconsolidated clayey soils.

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 $S_t < 15$ and $S_t > 15$. The lowest S_t value in the dataset in Table 1 is 16. However, correlations 4, 6, and 8 for $S_t < 15$ are also evaluated in this study. The cone factors N_{kt} and $N_{\Delta u}$ were observed to be functions of *OCR* by Karlsrud et al. (2005), while N_{ke} 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_{uC}.

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}, $N_{\Delta u}$, and N_{ke} values for the dataset. The calculated mean values were N_{kt} = 16.8 and $N_{\Delta u}$ = 10.7 for s_{uDSS}; N_{kt} = 17.5 and $N_{\Delta u}$ = 9.3 for $s_{ucorrFV}$; and N_{kt} = 10.7, $N_{\Delta u}$ = 7.0, and N_{ke} = 5.6 for s_{uC}. These reference values are used for comparison with the correlations in Table 2. The results generally showed good agree-

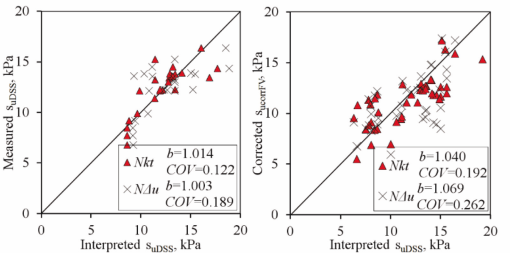

Figure 1. Comparison between the interpreted and measured s_{uDSS} and $s_{ucorrFV}$ values using the average N_{kt} and $N_{\Delta u}$.

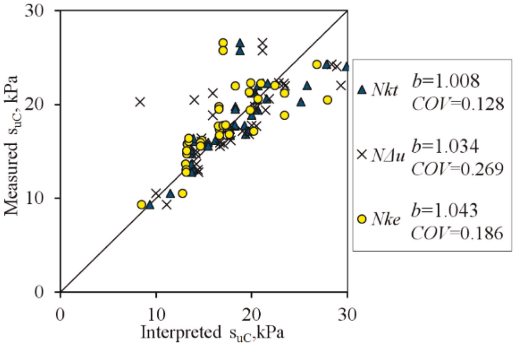

Figure 2. Comparison between the interpreted and measured s_{uC} values using the average N_{kt}, $N_{\Delta u}$, and N_{ke}.

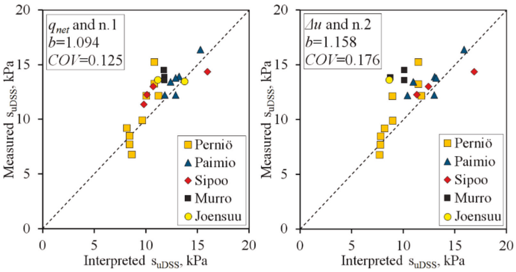

Figure 3. Interpretation of s_{uDSS} using correlations 1 and 2.

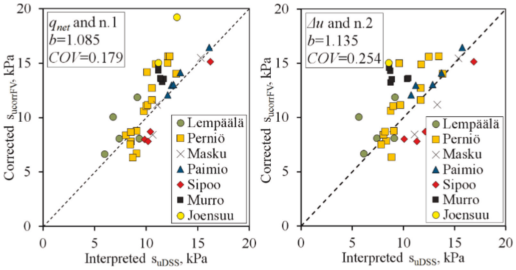

Figure 4. Interpretation of s_{uDSS} using correlations 1 and 2.

ment between the measured and calculated s_{uC} and s_{uDSS}, especially when using Equation 1. Higher scatter could be observed when using Equations 2 and 3, and in general, for $s_{ucorrFV}$.

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).

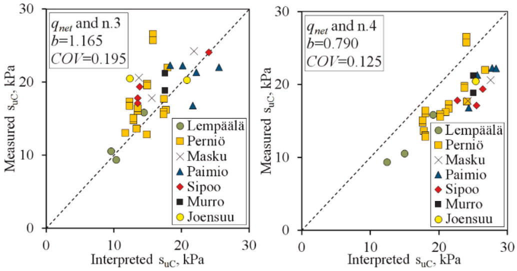

Figure 5. Interpretation of s_{uC} using correlations 3 and 4.

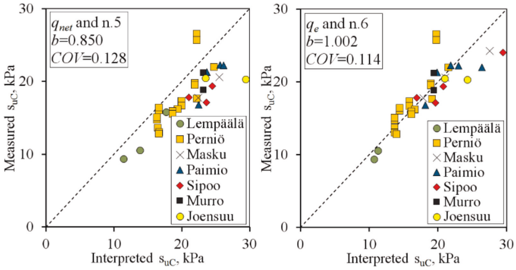

Figure 6. Interpretation of s_{uC} using correlation 5 for q_{net} and correlation 6 for q_e.

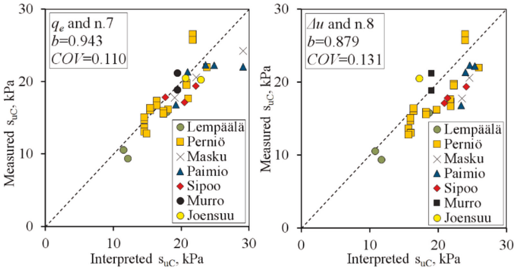

Figure 7. Interpretation of s_{uC} using correlation 7 for q_e and correlation 8 for Δu.

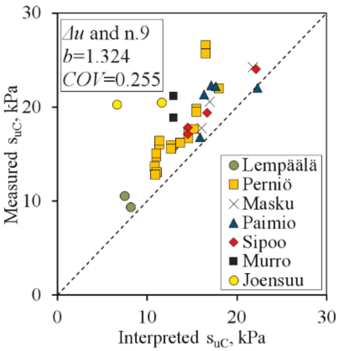

Figure 8. Interpretation of s_{uC} using correlation 9 for Δu.

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_{uDSS} and $s_{ucorrFV}$ using constant cone factors resulted in the following: *i)* nearly unbiased predictions, and *ii)* lower calculated *COVs* when using N_{kt} compared with $N_{\Delta u}$. However, the *COV* values relative to $s_{ucorrFV}$ were consistently higher than those for s_{uDSS}, 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_{kt}, N_{ke}, and $N_{\Delta u}$ 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).

Table 3. Summarized Results of the Interpreted s_{uDSS}.

	N_{kt} aver.	n.1 $(w_L \cdot OCR)$	$N_{\Delta u}$ aver.	n.2 $(w_L \cdot OCR)$
b	1.014	1.094	1.003	1.158
COV	0.122	0.125	0.189	0.176

Table 4. Summarized Results of the Interpreted $s_{ucorrFV}$.

	N_{kt} aver.	n.1 $(w_L \cdot OCR)$	$N_{\Delta u}$ aver.	n.2 $(w_L \cdot OCR)$
b	1.040	1.085	1.069	1.135
COV	0.192	0.179	0.262	0.254

Table 5. Summarized Results of the Interpreted s_{uC} with N_{kt}.

	N_{kt} aver.	n.3 $(w_L \cdot OCR)$	n.4 $(I_P\ OCR)$	n.5 (OCR)
b	1.008	1.165	0.790	0.850
COV	0.128	0.195	0.125	0.128

Table 6. Summarized Results of the Interpreted s_{uC} with $N_{\Delta u}$ and N_{ke}.

	N_{ke} aver.	n.6 (B_q)	n.7 (B_q)	$N_{\Delta u}$ aver.	n.8 $(I_P\ OCR)$	n.9 (OCR)
b	1.043	1.002	0.943	1.034	0.879	1.324
COV	0.186	0.114	0.110	0.269	0.131	0.255

As shown in Figure 3, correlations 1 and 2 underestimated the s_{uDSS} of Finnish clays by 9% and 16%, respectively, and gave *COVs* of 0.12 and 0.17.

When comparing the measured $s_{ucorrFV}$ and s_{uDSS} from correlation 1 in Figure 4, a similar b value was obtained as that for the measured s_{uDSS}. However, the *COV* was larger (0.18 vs. 0.12). In contrast, s_{uDSS} from correlation 2 underestimated $s_{ucorrFV}$ 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 $S_t < 15$, while correlations 5, 7, and 9 are for $S_t > 15$.

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 Lempäälä 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_q in the interpretation of s_{uC}. This can be observed in Table 6. In interpretations based on N_{kt}, such a benefit is, however, not too clear (Table 5). The B_q 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 $N_{\Delta u}$ 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_t lower than 15. As shown in Table 6, the interpretation based on N_{ke} and $N_{\Delta u}$ 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_{ke}. The evaluations based on N_{kt} seemed to give too-high values compared to the measurements (Table 5). Interpretations using $N_{\Delta u}$ 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_{ke} 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_q 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_{kt} 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 interpreted s_{uC} could be scaled using factors that are functions of w_L, 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

Amundsen, H.A., Jønland, J., Emdal, A., & Thakur, V. 2017. An attempt to monitor pore pressure changes in a block sample during and after sampling. *Geotechnique Letters.* vol. 7 (2).

Ching, J., and Phoon, K.-K. 2014. Transformations and correlations among some clay parameters—the global database. *Canadian Geotechnical Journal*, 51(6), 663–685.

Bjerrum, L. 1973. Problems of Soil Mechanics and Construction on Soft Clays. *State-of-the-art report. Proceedings of the 8th ICSMFE,* Moscow, 3, pp 111–159

Broms, B.B., 1974. Scandinavia. *General report. European symposium on penetration testing, ESOPT,* Stockholm, June 5–7 1974. Proceedings. Vol. 2. pp 14–23.

Di Buò, B., D'Ignazio, M., Selänpää, J. & Länsivaara, T. 2016. Preliminary results from a study aiming to improve ground investigation data. *Proceedings of the 17th Nordic Geotechnical Meeting,* Reykjavik, 25–28 May 2016, 1, pp 187–197

D'Ignazio, M., Phoon, K.K., Tan, S.A., & Länsivaara, T.T. 2016. Correlations for undrained shear strength of Finnish soft clays. *Canadian Geotechnical Journal*, *53*(10), 1628–1645.

Emdal, A., Gylland, A., Amundsen, H.A., Kåsin, K. & Long, M. 2016. Mini-block sampler. *Canadian Geotechnical Journal,* 53(8), 1235–1245.

ISO. 2012. Geotechnical investigation and testing—Field testing—Part 1: Electrical cone and piezocone penetration tests, *International Standard ISO 22476–1:2012*

Karslrud, K., Lunne, T., Kort, D.A. & Strandvik S. 2005. CPTU correlations for clays. *Proc. of the XVI-th International Conference on Soil Mechanics and Geotechnical Engineering.* Osaka 2005, 693–702

Larsson, R. & Mulabdic, M. 1991. Piezocone Tests in Clay. *Swedish Geotechnical Institute, SGI,* Linköping, Report 42, 240 pp.

Larsson, R. & Åhnberg, H., 2003. Long-term effects of excavations at crests of slopes. *Swedish geotechnical institute.* Linköping 2003. Report 61. 130p

Larsson, R., Sällfors, G., Bengtsson, P.-E., Alén, C., Bergdahl, U. & Eriksson, L. 2007. Skjuvhållfasthet: utvärdering i kohesionsjord. *Swedish geotechnical institute.* Linköping 2007, Information 3.

Larsson, R. 2011. Metodbeskrivning för SGI:s 200 mm diameter 'blockprovtagare'-Ostörd provtagning i finkornig jord (In Swedish) *Swedish Geotechnical Institute, SGI.* Göta River Commission. GÄU. Subreport 33. Linköping.

Lunne, T., Berre, T. & Strandvik, S. 1997. Sample disturbance effects in soft low plasticity Norwegian clay. *Proc. of Conference on Recent Developments in Soil and Pavement Mechanics,* Rio de Janeiro, 1997, 81–102

Lunne, T., Robertson, P.K. & Powell, J.J.M. 1997. Cone penetration testing in geotechnical practice. London, Spon Press. 312p

Powell, J.J.M., Quarterman, R.S.T. & Lunne, T. 1988. Interpretation and use of the piezocone test in UK clays. *Penetration Testing in the UK:* 151–156. London: Thomas Telford.

Ratahallintokeskus 2005. Radan stabiliteetin laskenta, olemassa olevat penkereet. *Ratahallintokeskuksen julkaisuja B15,* Ratahallintokeskus, Helsinki. (In Finnish. In English: Guidelines for embankments stability calculation by the Finnish Transport Agency, publication B15).

Sandven, R. 2010. Influence of test equipment and procedures on obtained accuracy in CPTU. *In Proceedings of the 2nd International Symposium on Cone Penetration Testing (CPT'10),* Huntington Beach, Calif. Edited by Mitchell et al.

Selänpää, J., Di Buò, B., Länsivaara, T. & D'Ignazio, M. 2017. Problems related to field vane testing in soft soil conditions and improved reliability of measurements using an innovative field vane device. *In Landslides in Sensitive Clays.* pp. 109–119. Springer International Publishing.