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ARTICLE

Correlations for undrained shear strength of Finnish soft clays

Marco D'Ignazio, Kok-Kwang Phoon, Siew Ann Tan, and Tim Tapani Länsivaara

Abstract: The study focuses on the derivation of transformation models for undrained shear strength (s_u) of Finnish soft sensitive clays. Specific correlation equations for s_u of Finnish clays are presented in this work for the first time. Field and laboratory measurements from 24 test sites in Finland are exploited for this purpose and a multivariate database is constructed. The multivariate data consist of s_u from the field vane test, preconsolidation stress, vertical effective stress, liquid limit, plastic limit, natural water content, and sensitivity. The main objective is to evaluate the interdependence of s_u, consolidation stresses, and index parameters and provide a consistent framework for practical use. The new correlations are established through regression analyses. The constructed framework is further validated by another independent multivariate database of clays from Sweden and Norway as well as by empirical equations for Swedish and Norwegian clays. Existing correlations are evaluated for Finnish and Scandinavian clays. Finally, bias and uncertainties of the new correlations are presented.

Key words: global transformation models, soft clays, multivariate database, undrained shear strength.

Résumé : L'étude porte sur la dérivation de modèles de transformation pour la résistance non drainée au cisaillement (s_u) des argiles douces sensibles finlandaises. Des équations de corrélation spécifiques pour la s_u des argiles finlandaises sont présentées dans cette œuvre pour la première fois. Des mesures sur-le-champ et en laboratoire de 24 sites d'essai en Finlande sont exploitées à cette fin et une base de données multivariée est construite. Les données multivariées se composent de s_u à partir de l'essais d'un scissomètre, de la contrainte de préconsolidation, de la contrainte efficace verticale, de la limite de liquide, de la limite plastique, de la teneur naturelle en eau et de la sensibilité. L'objectif principal est d'évaluer l'interdépendance de la s_u, des contraintes de consolidation et les paramètres d'index et à fournir un cadre cohérent pour une utilisation pratique. Les nouvelles corrélations sont établies par analyse de régression. Le cadre construit est en outre validé par une autre base de données multivariée indépendante des argiles de Suède et de la Norvège, ainsi que par des équations empiriques pour les argiles suédoises et norvégiennes. Les corrélations existantes sont évaluées pour les argiles finlandaises et scandinaves. Enfin, les biais et les incertitudes des nouvelles corrélations sont présentés. [Traduit par la Rédaction]

Mots-clés : modèles de transformation globale, argiles molles, base de données multidimensionnelle, résistance au cisaillement.

Introduction

Soft sensitive clays are widespread in Scandinavia, especially on coastal areas. The high compressibility of these soils, along with their low undrained shear strength (s_u) (even lower than 10 kPa near the ground surface), makes geotechnical design often rather challenging. Therefore, s_u needs to be carefully evaluated for a reliable assessment of the safety level.

Scandinavian soft clays are typically slightly over consolidated. The overconsolidation is normally the result of the aging process (e.g., Bjerrum 1972). For quick clays, the remolded undrained shear strength (s_u^{re}) can be even less than 0.5 kPa and 50–100 times lower than the initially "intact" s_u (e.g., Rankka et al. 2004; Karlsrud and Hernandez-Martinez 2013).

s_u can be evaluated from in situ as well as laboratory tests. In Scandinavia, the field vane (FV) test and piezocone cone penetration (CPTU) test are the most commonly used in situ tests. Laboratory tests include undrained triaxial compression (TXC) and direct simple shear (DSS) tests. For some special cases where s_u anisotropy needs to be assessed, triaxial extension (TXE) tests are also performed.

In situations where s_u is not directly measured or measurements are considered to be unreliable, s_u is commonly evaluated from transformation models based on clay properties, such as vertical preconsolidation pressure (σ'_p) (e.g., Mesri 1975; Jamiolkowski et al. 1985) or plasticity (e.g., Hansbo 1957; Chandler 1988). Such transformation models are typically empirical or semi-empirical, obtained by data fitting through regression analyses (e.g., Kulhawy and Mayne 1990). However, such models must be carefully applied and their limitations be recognized, as soil properties, soil behavior, and site geology may differ from the data source from where the transformation models are calibrated. As a direct consequence, predictions from these models may result in biases with respect to the actual property (s_u) values.

According to Phoon and Kulhawy (1999), uncertainty coming from transformation models can be customarily categorized as epistemic, meaning that it can be reduced by collecting a greater number of data or improving the available models. Therefore, "global" models, calibrated from data sets covering several sites and soil types, are preferred to "site-specific" models, which are restricted to a specific soil type or a specific site. Ching and Phoon (2012*a*, 2012*b*, 2014*a*, 2014*b*) presented global models based on soil

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Table 1. Summary of multivariate clay databases.

Database	Reference	Parameters of interest	No. of data points	No. of sites or studies	Range of properties		
					OCR	PI	S_t
CLAY/5/345	Ching and Phoon (2012*a*)	LI, s_u, s_u^{re}, σ'_p, σ'_v	345	37 sites	1~4	—	Sensitive to quick clays
CLAY/7/6310	Ching and Phoon (2013)	s_u^{CIUC}, $s_u^{CK_0UC}$, $s_u^{CK_0UE}$, s_u^{DSS}, s_u^{FV}, s_u^{UU}, s_u^{UC}	6310	164 studies	1~10	Low to very high plasticity	Insensitive to quick clays
CLAY/6/535	Ching et al. (2014)	s_u/σ'_p, OCR, $(q_t - \sigma_v)/\sigma'_v$, $(q_t - u_2)/\sigma'_v$, $(u_2 - u_0)/\sigma'_v$, B_q	535	40 sites	1~6	Low to very high plasticity	Insensitive to quick clays
CLAY/10/7490	Ching and Phoon (2014*a*)	LL, PI, LI, σ'_v/P_a, σ'_p/P_a, s_u/σ'_v, S_t, $(q_t - \sigma_v)/\sigma'_v$, $(q_t - u_2)/\sigma'_v$, B_q	7490	251 studies	1~10	Low to very high plasticity	Insensitive to quick clays

data covering a large number of test sites from several countries. Ching and Phoon (2012*b*) pointed out how site-specific models are more accurate (or less uncertain) than global models, although bias can be significant when applied to another site. Instead, global models are less biased, although less precise (or more uncertain).

Global transformation models for s_u of Swedish and Norwegian clays are available in the literature (Larsson and Mulabdic 1991; Larsson et al. 2007; Karlsrud and Hernandez-Martinez 2013). However, a comparable model calibrated using a sufficiently large soil database containing Finnish soft clay data is still missing. Therefore, the main objectives of the present paper are (*i*) to test existing transformation models for s_u for Finnish soft clays and (*ii*) to derive, for the first time, transformation models for s_u specific to Finnish soft clays using a large multivariate database consisting of FV data points from Finland. Another independent multivariate database of FV data points from Sweden and Norway is compiled and used for comparison and validation.

The value of multivariate soil databases has been demonstrated by Ching and Phoon (2012*a*, 2012*b*, 2013, 2014*a*, 2014*b*) and Ching et al. (2014). Müller (2013), Müller et al. (2014, 2016), and Prästings et al. (2016) have demonstrated how uncertainties related to s_u can be reduced when multivariate soil data are available, showing the benefits of using multivariate analyses (e.g., Ching et al. 2010) in geotechnical engineering applications. Multivariate soil databases are, however, limited in the literature. A summary is given in Table 1. Ching and Phoon (2014*a*) proposed labeling a multivariate database as "soil type"/"number of parameters of interest"/ "number of data points". Based on this nomenclature, the two databases presented in this paper are (*i*) F-CLAY/7/216 for Finnish clays (where "F" stands for Finland) and (*ii*) S-CLAY/7/168 for Scandinavian clays (where "S" stands for Scandinavia). The seven parameters in these databases consisted of s_u from the FV test (s_u^{FV}), effective vertical stress (σ'_v), vertical preconsolidation pressure (σ'_p), natural water content (w), liquid limit (LL), plastic limit (PL), and sensitivity ($S_t = s_u/s_u^{re}$).

The paper is organized as follows. Firstly, after a brief overview on existing transformation models for s_u, the compilation of F-CLAY/7/216 and S-CLAY/7/168 databases is presented. Secondly, 10 dimensionless parameters are derived from the seven basic parameters, resulting in two dimensionless databases. These dimensionless databases (labelled as F-CLAY/10/216 and S-CLAY/10/168) are compared to existing correlations in the literature. To develop more refined correlations for Finnish clays, outliers are removed from F-CLAY/10/216 according to systematic criteria based on soil nature, mechanical characteristics, and statistical considerations. New transformation models for s_u specific to Finnish clays are derived through regression analyses from the resulting F-CLAY/10/173 database. These new transformation models are compared with existing correlations for Scandinavian clays from the literature. Finally, the performance of the new models derived from F-CLAY/10/173 is evaluated by calculating the biases and uncertainties associated with S-CLAY/10/168.

Overview on existing transformation models for undrained shear strength

The dependency of s_u on σ'_p and plasticity has been the object of research over the last decades, because of its practical usefulness. Skempton (1954) suggested a linear correlation between the normalized s_u determined from FV test (s_u^{FV}/σ'_v) and plasticity index (PI) for normally consolidated clays. Subsequently, Chandler (1988) indicated that the same correlation could be valid also for overconsolidated clays as shown in eq. (1), although attention must be paid when dealing with fissured, organic, sensitive or other special clays.

$$\frac{s_u^{FV}}{\sigma'_p} \approx 0.11 + 0.0037\text{PI} \tag{1}$$

Hansbo (1957) suggested, for Scandinavian clays, that s_u^{FV}/σ'_p is directly proportional to LL. Larsson (1980), collected strength data points from FV test in Scandinavian clays and proposed a transformation model similar to eq. (1), as described by eq. (2)

$$\frac{s_u^{FV}}{\sigma'_p} \approx 0.08 + 0.0055\text{PI} \tag{2}$$

According to Bjerrum (1972), s_u^{FV} needs to be converted into mobilized s_u(s_u(mob) ≈ $s_u^{FV}\lambda$). The parameter λ is a correction multiplier that accounts for rate effects as well as anisotropy, and it is thought to be dependent on the plasticity of the clay.

Mesri (1975, 1989) suggested a unique relationship for s_u(mob) of clays and silts, corresponding approximately to DSS condition (eq. (3)), regardless of the plasticity of the clay.

$$\frac{s_u(\text{mob})}{\sigma'_p} \approx 0.22 \tag{3}$$

However, according to Larsson (1980), eq. (3) tends to overestimate s_u in very low–plastic clays, while it underestimates s_u in high-plastic clays. For low overconsolidated clays with low to moderate PI, Jamiolkowski et al. (1985) recommended (eq. (4))

$$\frac{s_u(\text{mob})}{\sigma'_v} \approx (0.23 \pm 0.04)\text{OCR}^{0.8} \tag{4}$$

The transformation model suggested by Jamiolkowski et al. (1985) is based on the stress history and normalized soil engineering properties (SHANSEP) framework (eq. (5)) proposed by Ladd and Foott (1974). The SHANSEP framework is normally adopted to describe the variation of s_u with the overconsolidation ratio, OCR ($= \sigma'_p/\sigma'_v$).

$$(5) \qquad \frac{s_u}{\sigma'_v} = S(\mathrm{OCR}^m)$$

where S and m are constants dependent on material and test type. S represents the normalized s_u for normally consolidated state. The exponent m varies between 0.75 and 0.95 (Jamiolkowski et al. 1985). A value of m equal to 0.8 is often assumed in practice. Note that $m = 1$ would reduce eq. (5) to eq. (3) with $S = 0.22$.

Larsson et al. (2007) studied the SHANSEP relation between s_u/σ'_v and OCR for inorganic Scandinavian clays. Data from undrained TXC, DSS, and TXE tests were collected to assess s_u anisotropy. By assuming an average m value equal to 0.8, it was shown how the normally consolidated undrained shear strength ratio (S) is material dependent for DSS (eq. (6)) and TXE, as it increases with increasing liquid limit; while it seems fairly constant for TXC.

Karlsrud and Hernandez-Martinez (2013) studied the (s_u/σ'_v)–OCR relation for Norwegian soft clays from laboratory tests on high-quality block samples. Outcomes from this study indicate that s_u strongly correlates with natural water content (w) combined with OCR (eq. (7) for DSS strength). More specifically, peak strengths from TXC, DSS, and TXE test were observed to increase with increasing w. Possible reasons to explain this might be e.g., (*i*) the open structure typical of Norwegian clays (Rosenqvist 1953, 1966), which allows the soil to retain a quantity of pore water, typically above the liquid limit of the soil or (*ii*) the increasing rate effects with plasticity.

$$(6) \qquad \frac{s_u^{\mathrm{DSS}}}{\sigma'_v} \approx (0.125 + 0.205\mathrm{LL}/1.17)\mathrm{OCR}^{0.8}$$

$$(7) \qquad \frac{s_u^{\mathrm{DSS}}}{\sigma'_v} \approx (0.14 + 0.18w)\mathrm{OCR}^{(0.35+0.77w)}$$

Ching and Phoon (2012*a*) proposed a global transformation model for s_u(mob) from FV and unconfined compression (UC) tests as a function of OCR and S_t. The model was built based on a large database of structured clays (CLAY/5/345) consisting of 345 clay data points from several locations all over the world (eq. (8)).

$$(8) \qquad \frac{s_u(\mathrm{mob})}{\sigma'_v} \approx 0.229\mathrm{OCR}^{0.823}S_t^{0.121}$$

Analysis of multivariate clay databases

F-CLAY/7/216 and S-CLAY/7/168

The first clay database compiled in this study consists of 216 FV data points from 24 different test sites from Finland. Each data "point" contains multivariate information, i.e., information from different tests conducted in close proximity is available. The collected data points contain information on seven basic parameters measured at comparable depths and sampling locations: s_u^{FV}, σ'_v, σ'_p, w, LL, PL, and S_t.

The standard FV test is normally carried out at high speed of rotation, inducing strain rates in the soil that are much higher than in conventional laboratory tests (e.g., triaxial tests, DSS tests). The main consequence is that s_u^{FV} is overestimated and, therefore, a correction is needed to convert s_u^{FV} into s_u(mob) (e.g., Bjerrum 1972). The parameter s_u(mob) is defined as the undrained shear strength that is mobilized in a full-scale failure of an embankment or slope in the field (Bjerrum 1972; Mesri and Huvaj 2007). s_u(mob) cannot be uniquely defined, as it is a function of failure mode, stress state, and strain rate, among others. In this study, the s_u^{FV} values are converted into s_u(mob) values through a correction factor λ, as reported in the Finnish Guidelines for stability analysis (Ratahallintokeskus 2005). In this way, rate effects and anisotropy are implicitly accounted for. The strength correction factor used is expressed by eq. (9)

$$(9) \qquad \lambda = \frac{1.5}{1 + \mathrm{LL}}$$

According to Jamiolkowski et al. (1985) and Chandler (1988), s_u obtained from FV is somewhat comparable to s_u from DSS test results. It is common practice in Sweden to consider s_u from DSS tests as a reference value (e.g., Westerberg et al. 2015). DSS tests may, however, be affected by some disturbance effects resulting from sampling as well as specimen preparation. In Finland, DSS tests are not in use and the FV test is normally assumed to provide reliable s_u values, despite some issues related to test equipment. As suggested by Mansikkamäki (2015), when casing is used to protect the vane during penetration into the ground, rod friction is minimized and, therefore, measured torque values are assumed to be less biased than when slip-coupling is used. FV data points from Finland collected in this study are mostly obtained using FV test equipment that includes casing. As a consequence, the results presented later will likely be representative of the best possible estimate of s_u^{FV} in Finnish current practice.

The database is compiled from data given in Gardemeister (1973), Lehtonen et al. (2015), together with data from recent soil investigations performed by Tampere University of Technology, Finland (J. Selänpää, personal communication, 2015). Gardemeister (1973) collected FV and oedometer tests performed at different construction sites in Finland. For the purpose of the present study, sites characterized by organic (organic content higher than 2%) and (or) silty soils have been discarded, because the focus of this study is on the strength of inorganic clays. Some low organic clays may, however, be present in the database.

This database is labeled as F-CLAY/7/216 following the nomenclature proposed by Ching and Phoon (2014*a*). F-CLAY/7/216 is a new database that would contribute to the list of multivariate soil databases shown in Table 1. The basic statistics of the seven clay parameters in F-CLAY/7/216 are listed in Table 2. The parameters σ'_v and σ'_p are normalized to the atmospheric pressure, P_a ($P_a = 101.3$ kPa). The numbers of available data points (n) are reported in the second column. The statistics shown are the mean value, coefficient of variation (COV), minimum value (Min) and maximum value (Max). Clay properties cover a wide range of S_t values varying from 2 (insensitive clays) to 64 (quick clays), and a wide range of PI values (2~95) and w values (25~150).

A second independent database consisting of 168 FV data points from Sweden and Norway is extracted from the existing global CLAY/10/7490 database (Ching and Phoon 2014*a*). This database is labelled as S-CLAY/7/168 and it contains multivariate information on the same soil parameters as in F-CLAY/7/216. The purpose of S-CLAY/7/168 is to act as an independent set of data to be used for comparison with F-CLAY/7/216 in subsequent analyses. The geographical coverage of S-CLAY/7/168 is restricted to Sweden (12 sites) and Norway (seven sites). Full information on all seven parameters is available for only 59 data points. Fortunately, for the remaining 109 data points, information on all six parameters with the exception of S_t is known. The practical implication here is that the effect of S_t on s_u correlations is more difficult to discern in the case of S-CLAY/7/168. Basic statistics of the seven clay parameters in S-CLAY/7/168 are reported in Table 3. The multivariate clay data contained in F-CLAY/7/216 and S-CLAY/7/168 are listed in Appendix A.

Table 2. Basic statistics of the seven basic parameters in F-CLAY/7/216.

Variable	n	Mean	COV	Min	Max
s_u^{FV} (kPa)	216	21.443	0.501	5	75
σ'_v/P_a	216	0.464	0.485	0.074	1.609
σ'_p/P_a	216	0.948	0.515	0.251	2.884
LL	216	66.284	0.298	22.0	125.0
PL	216	27.740	0.204	10.0	50.0
w	216	76.340	0.268	25.0	150.0
S_t	216	17.447	0.789	2.0	64.0

Table 3. Basic statistics of the seven basic parameters in S-CLAY/7/168.

Variable	n	Mean	COV	Min	Max
s_u^{FV} (kPa)	168	16.346	0.505	5.62	48.75
σ'_v/P_a	168	0.503	0.632	0.068	2.101
σ'_p/P_a	168	0.786	0.726	0.150	3.116
LL	168	71.055	0.396	22.77	201.81
PL	168	29.448	0.344	2.73	73.92
w	168	76.631	0.347	17.27	180.11
S_t	59	12.068	0.779	3.0	42.5

Fig. 1. Plasticity chart.

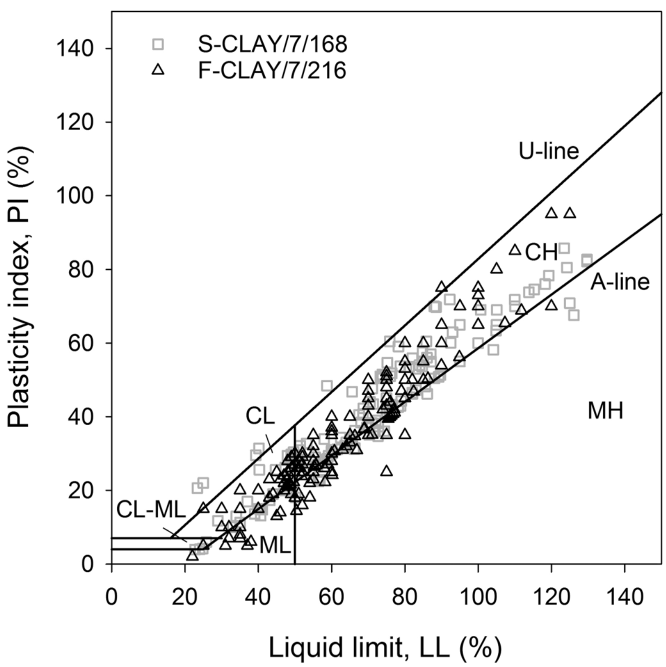


Figure 1 shows how the data points are positioned in the plasticity chart to provide a broad physical overview of the databases. Figure 2 suggests that w tends to increase for increasing LL, and that w is higher than LL for the majority of the data points.

Dimensionless databases: F-CLAY/10/216 and S-CLAY/10/168

Ten dimensionless soil parameters are of primary interest in this study. They are derived from the seven basic clay parameters appearing in F-CLAY/7/216 and S-CLAY/7/168 and they can be categorized into two groups:

1. Index properties, including natural water content (w), liquid limit (LL), plasticity index (PI), and liquidity index (LI).
2. Stresses and strengths, including OCR, normalized s_u(mob) against vertical effective stress [$s_u(\mathrm{mob})/\sigma'_v$] and preconsolidation pressure [$s_u(\mathrm{mob})/\sigma'_p$], normalized s_u^{FV} against vertical effective stress (s_u^{FV}/σ'_v) and preconsolidation pressure (s_u^{FV}/σ'_p), and sensitivity ($S_t = s_u/s_u^{re}$).

Fig. 2. Water content (w) versus liquid limit (LL) for F-CLAY/7/216 and S-CLAY/7/168.

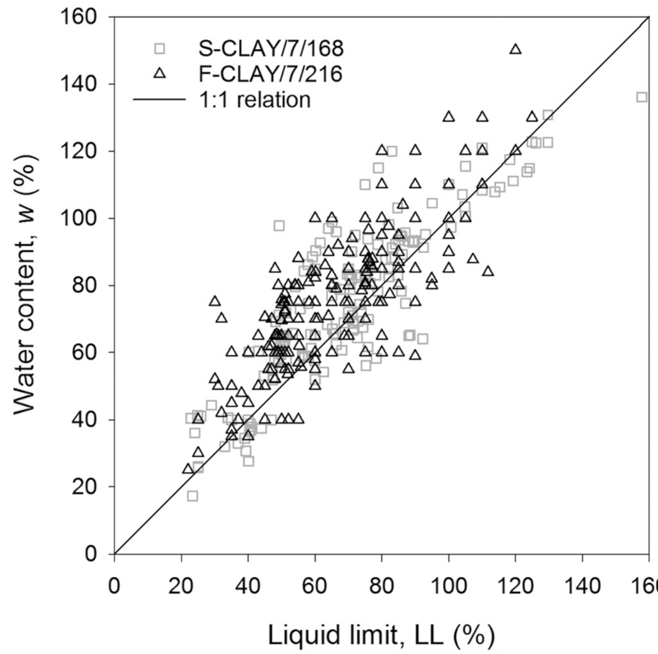
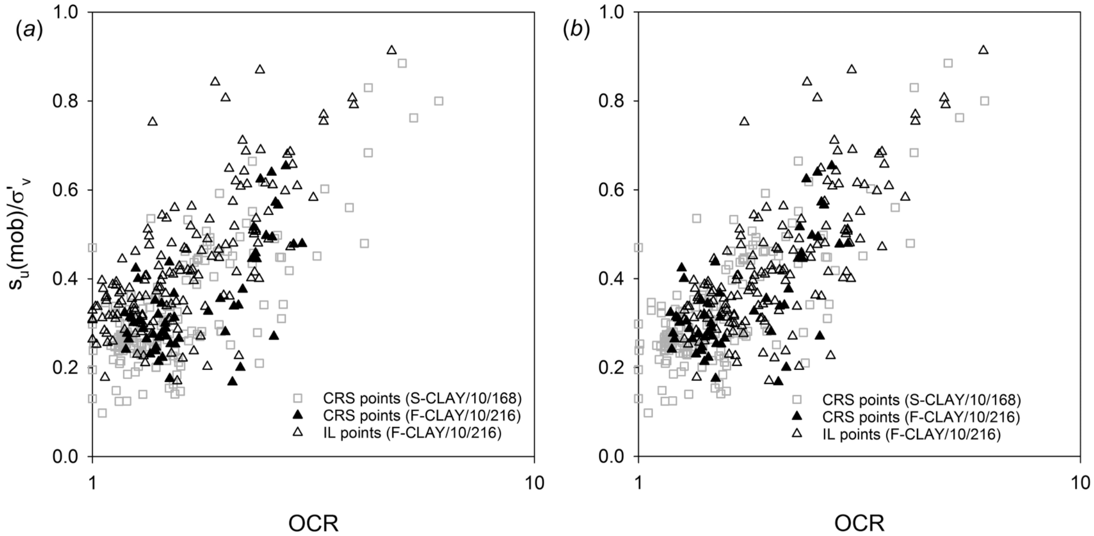


Figure 3a shows the $s_u(\mathrm{mob})/\sigma'_v$ values plotted against OCR for F-CLAY/10/216 and S-CLAY/10/168. The trend described by the $s_u(\mathrm{mob})/\sigma'_v$ points vs. OCR seem on average higher for Finnish clays than for Scandinavian clays. The reason for such a discrepancy could lie in the definition of σ'_p used to estimate OCR. Indeed, σ'_p is normally determined through an oedometer test and it is strongly affected by the strain rate used in the test (e.g., Leroueil et al. 1983, 1985). As suggested by Leroueil et al. (1985) and Leroueil (1988, 1996), constant rate of strain (CRS) oedometer tests provide stress–strain curves that normally differ from those provided by conventional 24 h incrementally loaded (IL) oedometer tests. The main reason for such differences can be found in the different rate of loading (or rate of straining) applied during the test. According to Leroueil and Soares Marques (1996), the strain rate in IL test after 24 h is between 1×10^{-7} s^{-1} for highly compressible clays and 5×10^{-8} s^{-1} for low compressible clays. The strain rate in CRS tests is normally between 1×10^{-6}–4×10^{-6} s^{-1}. As a consequence, σ'_p is larger in CRS than in the 24 h IL test (Leroueil 1996). More specifically, Leroueil (1996) suggests that σ'_p obtained from the CRS oedometer test is typically 25% larger than that deduced from the IL test. For Finnish clays, Kolisoja et al. (1989) reported, for one site in Finland, the ratio $\sigma'_{pCRS}/\sigma'_{pIL}$ to be equal to 1.16. Hoikkala (1991) observed the same ratio to be equal to 1.3 for three different sites in Finland. Länsivaara (1999), based on the data collected by Leroueil (1996) on several types of clays, suggested $\sigma'_{pCRS}/\sigma'_{pIL} = 1.27$. Karlsrud and Hernandez-Martinez (2013) observed, for oedometer tests conducted on block samples of Norwegian clays, that σ'_p values derived from the IL tests were 10%–18% lower than for the CRS tests.

Upon examination of the original sources (listed in Table A1 of Ching and Phoon (2014a)) from where data contained in S-CLAY/7/168 have been collected, it seems that σ'_p points were mostly measured from CRS oedometer tests. F-CLAY/7/216 contains only 56 σ'_{pCRS} points, while the remaining 162 points are from 24 h IL tests (σ'_{pIL}) (Fig. 3a). Therefore, to make data suitable for comparison, σ'_{pIL} is increased by 27% for all data points as a first-order correction following the proposal by Länsivaara (1999) (Fig. 3b). By applying $\sigma'_{pCRS}/\sigma'_{pIL} = 1.27$ to all 162 σ'_{pIL} values from Finland, the strength points from F-CLAY/10/216 seem to better adapt to the $s_u(\mathrm{mob})/\sigma'_v$ – OCR trend shown by those contained in S-CLAY/10/168

Fig. 3. s_u(mob)/σ'_v against OCR for (*a*) raw data points and (*b*) data points corrected to σ'_p from CRS oedometer test using $\sigma'_{pCRS}/\sigma'_{pIL}$ = 1.27.



(Fig. 3*b*). It is plausible that the difference between F-CLAY/10/216 and S-CLAY/10/168 in the s_u(mob)/σ'_v versus OCR plot is primarily caused by the difference between the CRS and IL test, rather than the difference between clay types, as also indicated by Fig. 1 and Fig. 2.

The basic statistics of the 10 dimensionless parameters are listed in Table 4 and Table 5 for the dimensionless databases, labeled as F-CLAY/10/216 and S-CLAY/10/168, respectively.

Table 4. Basic statistics of 10 dimensionless soil parameters in F-CLAY/10/216, derived from the seven basic parameters in F-CLAY/7/216.

Variable	n	Mean	COV	Min	Max
$s_u(\text{mob})/\sigma'_v$	216	0.458	0.715	0.167	2.754
$s_u(\text{mob})/\sigma'_p$	216	0.209	0.281	0.081	0.469
s_u^{FV}/σ'_v	216	0.513	0.712	0.176	2.938
s_u^{FV}/σ'_p	216	0.234	0.293	0.083	0.594
OCR	216	2.170	0.467	1.18	7.50
LL	216	66.284	0.298	22.0	125.0
PI	216	38.545	0.482	2.0	95.0
w	216	76.340	0.268	25.0	150.0
LI	216	1.443	0.459	0.425	4.800
S_t	216	17.447	0.789	2.0	64.0

Table 5. Basic statistics of 10 dimensionless soil parameters in S-CLAY/10/168, derived from the seven basic parameters in S-CLAY/7/168.

Variable	n	Mean	COV	Min	Max
$s_u(\text{mob})/\sigma'_v$	168	0.329	0.417	0.098	0.885
$s_u(\text{mob})/\sigma'_p$	168	0.210	0.269	0.088	0.470
s_u^{FV}/σ'_v	168	0.386	0.469	0.098	0.974
s_u^{FV}/σ'_p	168	0.244	0.311	0.088	0.490
OCR	168	1.664	0.476	1.00	6.07
LL	168	71.06	0.396	22.77	201.81
PI	168	41.61	0.496	3.91	127.89
w	168	76.63	0.347	17.27	180.11
LI	168	1.267	0.507	0.60	5.50
S_t	59	12.068	0.779	3.00	42.50

Comparison with existing transformation models

The 384 clay data points constituting F-CLAY/10/216 and S-CLAY/10/168 databases are compared with transformation models proposed in the literature to check their consistency. It is worth pointing out that transformation models are generally derived based on certain types of clays and geographical locations. The basis for these models is usually empirical. Very often, for such models we do not know the basic statistics (such as those reported in Table 4 and Table 5).

The 10 transformation models analyzed are labeled using the following template: "primary input parameter"–"target parameter"–"secondary input parameter". They are categorized into four types (see e.g., Table 6):

Type A — Models for S_t, including two LI–(s_u^{re}/P_a) models and two LI–(S_t) models.

Type B — Models for effective stress, including one LI–(σ'_p/P_a)–S_t model. Basic statistics of σ'_p/P_a are reported in Table 2 and Table 3 and not included in the dimensionless databases, as s_u^{FV} and s_u(mob) are the parameters of primary interest for this study.

Type C — Models for shear strength, including one PI–[s_u(mob)/σ'_p] model, one OCR–[s_u(mob)/σ'_v] model, and one OCR–[s_u(mob)/σ'_v]–S_t model.

Type D — Models for shear strength, including two PI–(s_u^{FV}/σ'_p), one LL–(s_u^{FV}/σ'_p). These three models are compared to uncorrected s_u^{FV} (λ correction factor is not applied), being originally derived from uncorrected measurements.

Many of the transformation models are derived empirically using regression analyses. Only the LI–(s_u^{re}/P_a) model by Wroth and Wood (1978) represents an exception. It is derived theoretically from the modified Cam clay model. The LI–(σ'_p/P_a)–S_t and OCR–[s_u(mob)/σ'_v]–S_t models proposed by Ching and Phoon (2012*a*) are derived from sensitive structured clay data. The LI–S_t model by Bjerrum (1954) is based on Norwegian marine clay data.

Figures 4–11 show the comparison between databases and transformation models. For the LI–(σ'_p/P_a)–S_t and OCR–[s_u(mob)/σ'_v]–S_t models by Ching and Phoon (2012*a*), data points are divided into two groups according to S_t values. The two groups are based on the distinction between "low to medium sensitive" (S_t < 15) and "highly sensitive" (S_t > 15) clays suggested by Karlsrud and Hernandez-Martinez (2013) for Norwegian clays.

The OCR–[s_u(mob)/σ'_v] transformation model by Jamiolkowski et al. (1985) provides a reasonable average fit to the data. For OCR < 8, s_u(mob)/σ'_v seems to be strongly dependent on OCR (Fig. 4). A deviation from the trend line in Fig. 4 is visible at OCR values greater than 5. However, data points with OCR > 5 belong to layers located in proximity of the ground surface (above 1.50 m)

Table 6. Transformation models in literature and their calibration results for F-CLAY/10/216.

					Comparison to F-CLAY/10/216 database		Calibration results	
Type	Relationship	Literature	n	Transformation model	Figure	Fit to the trend?	Bias factor, b	COV of $\varepsilon = \delta$
A	LI–(s_u^{re}/P_a)	Wroth and Wood (1978)	216	$s_u^{re}/P_a \approx 1.7^{-4.6\mathrm{LI}}$	9	No	—	—
		Locat and Demers (1988)	216	$s_u^{re}/P_a \approx 0.0144\mathrm{LI}^{-2.44}$	9	Yes	4.05	3.02
	LI–(S_t)	Bjerrum (1954)	216	$S_t \approx 10^{0.8\mathrm{LI}}$	11	Yes	1.56	1.40
		Ching and Phoon (2012*a*)	216	$S_t \approx 20.726\mathrm{LI}^{1.910}$	11	No	0.57	1.94
B	LI–(σ'_p/P_a)–S_t (for $S_t < 15$)	Ching and Phoon (2012*a*)	216	$\sigma'_p/P_a \approx 0.235\mathrm{LI}^{-1.319}S_t^{0.536}$	12a	Yes	2.02	0.94
	LI–(σ'_p/P_a)–S_t (for $S_t > 15$)	Ching and Phoon (2012*a*)	216	$\sigma'_p/P_a \approx 0.235\mathrm{LI}^{-1.319}S_t^{0.536}$	12a	Yes	0.95	0.47
C	PI–(s_u(mob)/σ'_p)	Mesri (1975, 1989)	216	$s_u(\mathrm{mob})/\sigma'_p \approx 0.22$	5	Yes	0.95	0.28
	OCR–[s_u(mob)/σ'_v]	Jamiolkowski et al. (1985)	216	$s_u(\mathrm{mob})/\sigma'_v \approx 0.23\mathrm{OCR}^{0.8}$	4	Yes	1.06	0.30
	OCR–[s_u(mob)/σ'_v]–S_t	Ching and Phoon (2012*a*)	216	$s_u(\mathrm{mob})/\sigma'_v \approx 0.229\mathrm{OCR}^{0.823}S_t^{0.121}$	6a	Yes	0.77	0.32
D	LL–(s_u^{FV}/σ'_p)	Hansbo (1957)	216	$s_u^{FV}/\sigma'_p \approx 0.45\mathrm{LL}$	7	Yes	0.84	0.38
	PI–(s_u^{FV}/σ'_p)	Larsson (1980)	216	$s_u^{FV}/\sigma'_p \approx 0.08 + 0.0055\mathrm{PI}$	8	Yes	0.89	0.43
		Chandler (1988)	216	$s_u^{FV}/\sigma'_p \approx 0.11 + 0.0037\mathrm{PI}$	8	Yes	0.97	0.35

Fig. 4. OCR–[s_u(mob)/σ'_v] model proposed by Jamiolkowski et al. (1985).

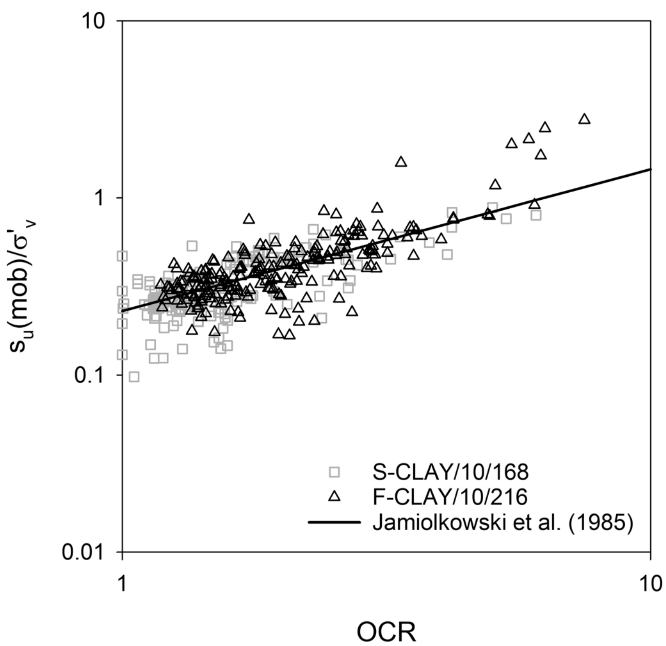
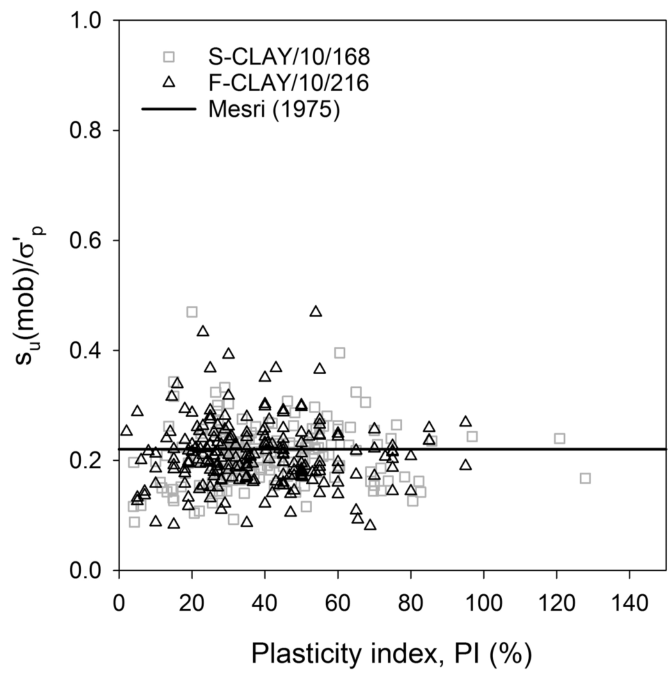


Fig. 5. PI–[s_u(mob)/σ'_p] model proposed by Mesri (1975, 1989).



where the clay might be fissured and (or) partially saturated. Therefore, the interest for those points is limited, because the focus of this study is on intact clays.

The PI–[s_u(mob)/σ'_p] model by Mesri (1975, 1989) takes out the dependency of s_u(mob) on PI, stating that $s_u(\mathrm{mob})/\sigma'_p$ is constant and equal to 0.22. From Fig. 5, $s_u(\mathrm{mob})/\sigma'_p$ seems independent of PI, thus confirming the suggestion given by Mesri.

The dependency of s_u on S_t predicted by the OCR–[s_u(mob)/σ'_v]–S_t model by Ching and Phoon (2012*a*), is not visible from the collected data points (Fig. 6). However, the majority of the F-CLAY/10/216 data points for $S_t < 15$ are located between the $s_u(\mathrm{mob})/\sigma'_v$–OCR trend lines for $S_t = 1$ and $S_t = 15$ (Fig. 6*a*).

It is quite difficult to observe a well-defined trend for the data points to the LL–(s_u^{FV}/σ'_p) model by Hansbo (1957) (Fig. 7). Both databases seem to better adapt to the mean trend suggested by the PI–(s_u^{FV}/σ'_p) models (Fig. 8), although high scatter can be observed along the trend lines suggested by Larsson (1980) and Chandler (1988, after Skempton 1954).

Data points seem to depart from the LI–(s_u^{re}/P_a) model by Wroth and Wood (1978) for LI values greater than 1 (Fig. 9). However, the transformation model by Locat and Demers (1988) seems able to reproduce the trend observed for LI < 2 (Fig. 9). For LI > 2, the data points deviate from the existing transformation models. The authors believe that S_t was determined from the FV test for some of the Finnish data points (from Gardemeister 1973). The FV test is known to produce higher s_u^{re} values than the conventional fall cone (FC) test. Tanaka et al. (2012) demonstrated how s_u^{re} determined from the FV test and the laboratory vane test (LVT) is as much as tenfold larger than s_u^{re} determined using the FC test (Fig. 10*b*). This was attributed to the different remolding methods, as the turning of the vane is not equivalent to the remolded state for the FC test, which is obtained by kneading by hand. Hence, the actual s_u^{re} may be lower than that shown in Fig. 9, which consequently produces a higher S_t. However, there are only 29 points with LI > 2. The conclusions of this study will be largely unaffected, because 29 points only constitute 13.4% of the total num-

Fig. 6. OCR–[s_u(mob)/σ'_v]–S_t model by Ching and Phoon (2012*a*) for (*a*) F-CLAY/10/216 and (*b*) S-CLAY/10/168.

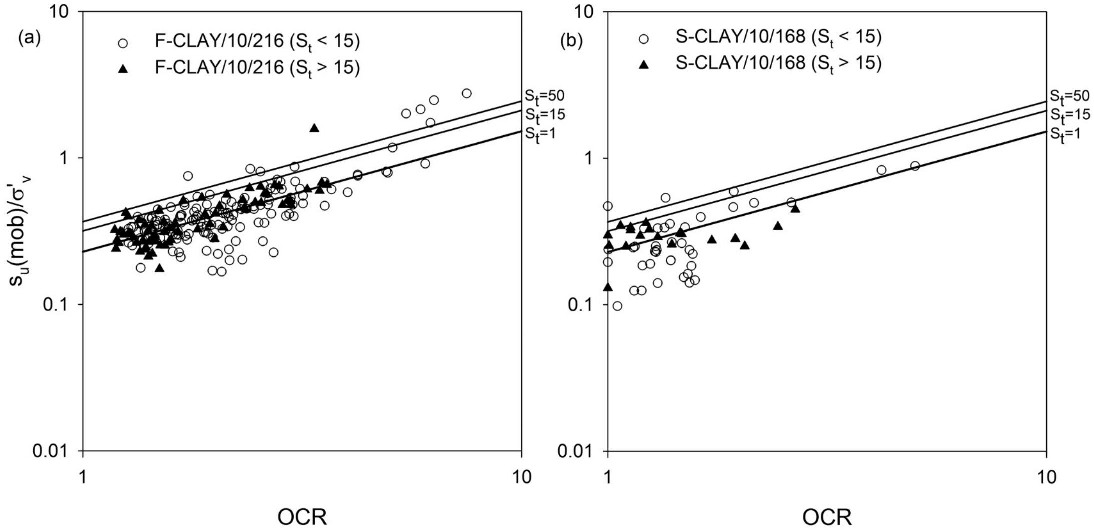


Fig. 7. LL–(s_u^{FV}/σ'_p) model proposed by Hansbo (1957).

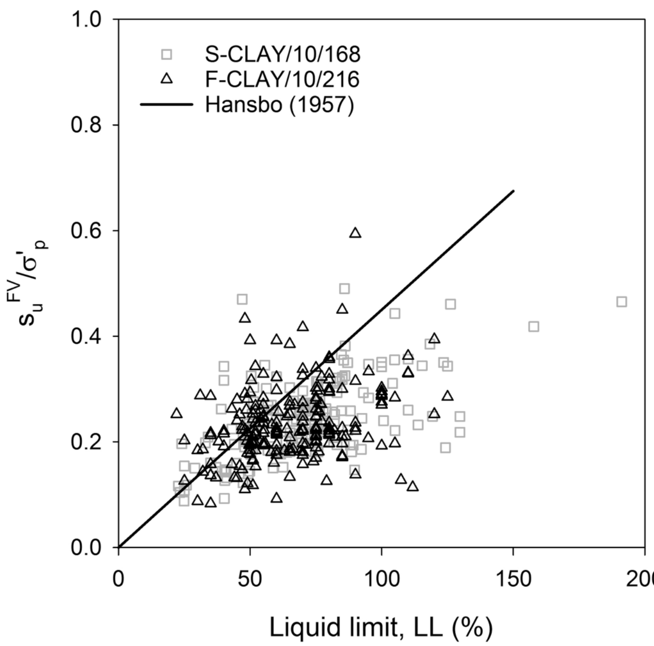
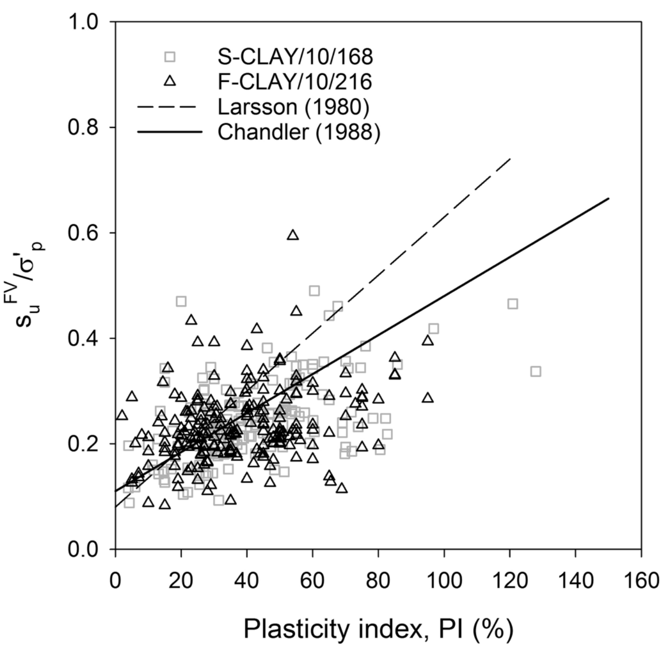


Fig. 8. PI–(s_u^{FV}/σ'_p) models proposed by Larsson (1980) and Chandler (1988).



ber of points. Based on the experimental results presented by Tanaka et al. (2012), the authors would like to further suggest that while undisturbed s_u values from FV and FC can be mixed (as shown in Fig. 10*a*), s_u^{re} or derived parameters (S_t) between FV and FC should be treated separately (as suggested by Fig. 10*b*).

The LI–(S_t) model by Bjerrum (1954) can reasonably describe the data points for LI < 2, despite the high scatter observed (Fig. 11). In contrast, the global model by Ching and Phoon (2012*a*) seems to provide an upper bound rather than an average fit to the databases (Fig. 11).

The LI–(σ'_p/P_a)–S_t model by Ching and Phoon (2012*a*) does not seem to fit the data points in F-CLAY/10/216 for $S_t < 15$ (Fig. 12*a*). The LI–(σ'_p/P_a)–S_t transformation model appears to provide a better description of the highly sensitive clays ($S_t > 15$) in F-CLAY/10/216, as the majority of the points are contained in the interval between the LI–(σ'_p/P_a)–S_t lines for $S_t = 15$ and $S_t = 50$ (Fig. 12a). In contrast, for the low to medium sensitive clays ($S_t < 15$) in S-CLAY/10/168, most of the data points are comprised between the LI–(σ'_p/P_a)–S_t boundary lines for S_t = 1 and S_t = 15 (Fig. 12*b*), while for the highly sensitive clays, the models cannot satisfactorily describe the observed values.

Bias and uncertainties of the existing transformation models

Bias factor (denoted by *b*), and COV (denoted by δ) are evaluated and discussed for the transformation models described in the previous section, based on the F-CLAY/10/216 and S-CLAY/10/168 databases. The parameters *b* and δ represent the sample mean and the COV, respectively, of the ratio (actual target value)/(predicted target value). If *b* = 1, the model prediction is unbiased. For instance, for the OCR–[s_u(mob)/σ'_v] transformation model by Jamiolkowski et al. (1985), the actual target value is s_u(mob)/σ'_v and the predicted target value is $0.23OCR^{0.8}$. For the data points where s_u(mob)/σ'_v and OCR are simultaneously known, (actual target value)/(predicted target value) = [s_u(mob)/σ'_v]/($0.23OCR^{0.8}$).

Fig. 9. LI–(s_u^{re}/P_a) models.

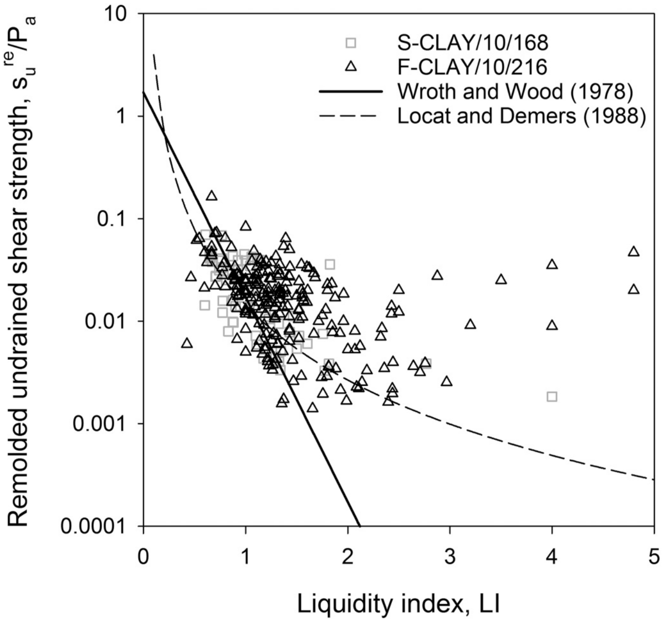


Fig. 10. Comparison of strengths measured by FC, FV, and LVT at (*a*) undisturbed and (*b*) remolded conditions (Tanaka et al. 2012).

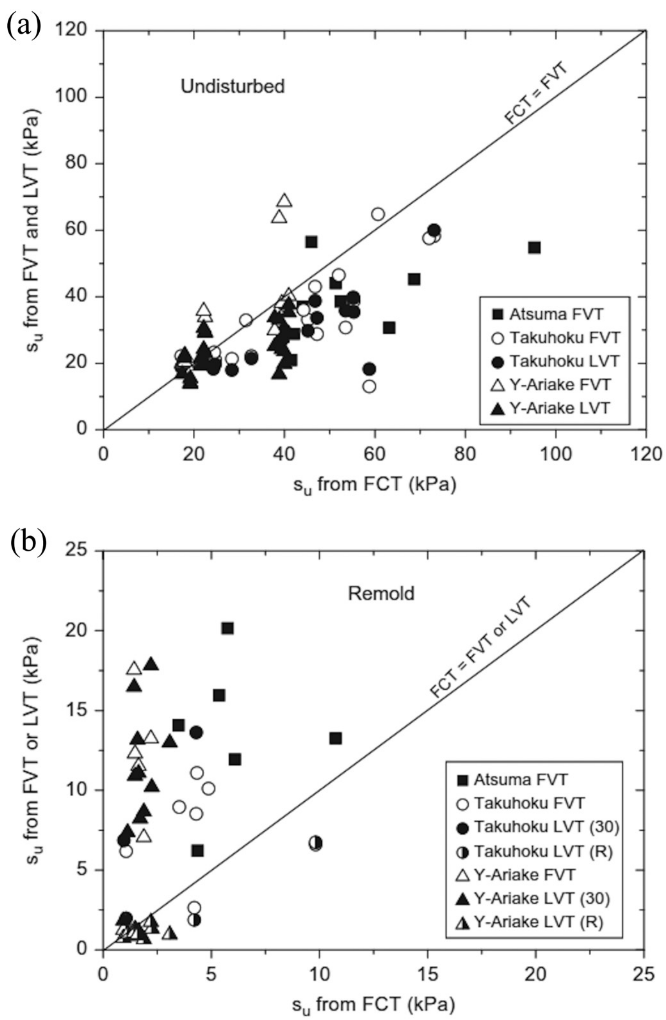
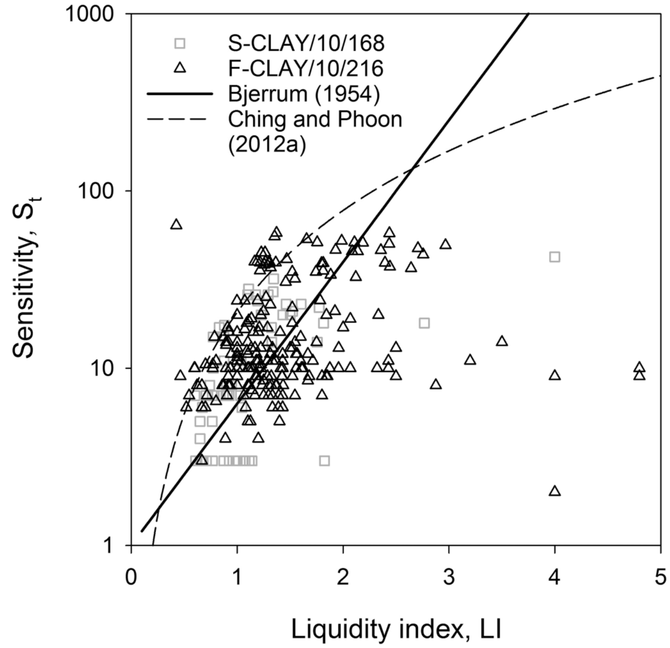


Fig. 11. LI–S_t models.



According to Ching and Phoon (2014*a*):

$$\begin{aligned}\varepsilon &= (\text{actual target value})/(b \times \text{predicted target value})\\ &= (\text{actual target value})/(\text{unbiased prediction})\end{aligned}$$

where ε is the variability term with mean = 1 and COV = δ. If $\delta = 0$, there is no data scatter about the transformation model, indicating that the prediction is deterministic, rather than uncertain.

Bias factors and COVs for the different transformation models analyzed are reported in Table 6 for F-CLAY/10/216 and Table 7 for S-CLAY/10/168, respectively. Bias factor, COV of ε, and number of data points used for each calibration are denoted, respectively, by b, δ, and n.

The LI–(s_u^{re}/P_a) model by Locat and Demers (1988) seems quite conservative, as it underpredicts the actual value by a factor of 4.05 for Finnish clays (Table 6) and 1.60 for Scandinavian clays (Table 7). Bjerrum's (1954) transformation model underestimates the actual S_t values for both Finnish and Scandinavian clays. Nevertheless, the uncertainty underlying these predictions still remains considerable, as the COV for type A models ranges between 61% and 302%. A similar analysis can be carried out for the LI–(σ'_p/P_a)–S_t model by Ching and Phoon (2012*a*). The deviation of about 50%–60% from the mean trend lines of both F-CLAY/10/216 and S-CLAY/10/168, combined with a COV greater than 1 and equal to 0.61 for Finnish and Scandinavian clays, respectively, would result in predicted values characterized by a high degree of uncertainty. Therefore, models of type A and B are "biased" models with respect to both databases.

In contrast, different outcomes are obtained for the transformation models of type C and D (models for shear strength). Models of type C (s_u(mob)/σ'_v is the target parameter) show bias factors (b) close to 1 and COV (δ) lower than 0.30. Exception is found for the OCR–[s_u(mob)/σ'_v]–S_t model (Ching and Phoon 2012*a*), which shows a bias factor of 0.71–0.77 with a COV of 0.32–0.36. These results would thus suggest that s_u(mob) of Scandinavian clays can be described by different well established transformation models with relatively low uncertainty. For instance, the equation by Mesri (1975, 1989) can be adapted to Finnish soft clays by including the bias factor (b) calibrated from F-CLAY/10/216 database as

Fig. 12. LI–(σ'_p/P_a)–S_t model by Ching and Phoon (2012*a*) for (*a*) F-CLAY/10/216 and (*b*) S-CLAY/10/168.

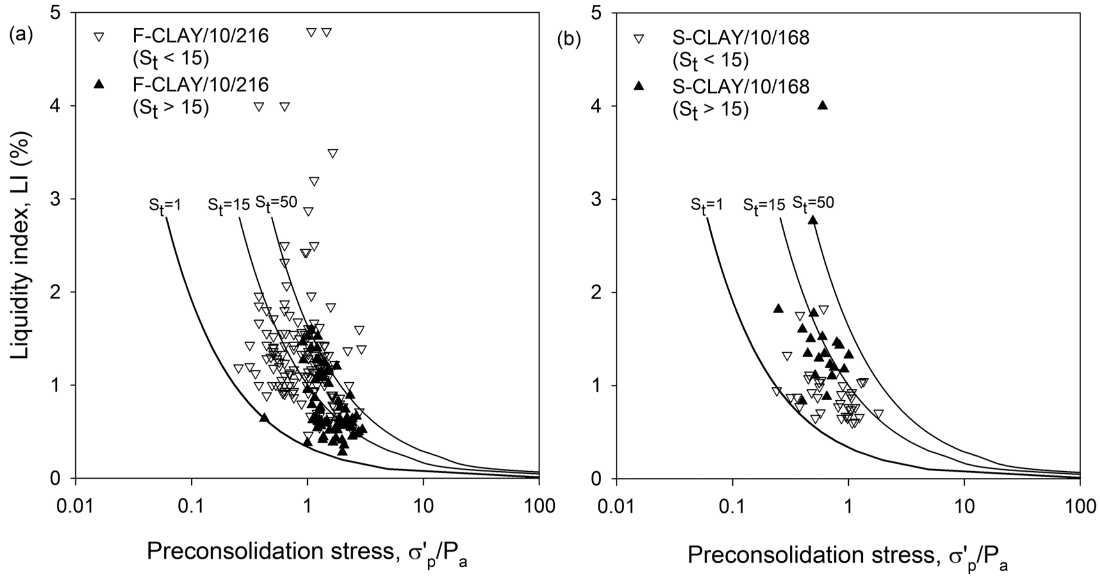


Table 7. Transformation models in literature and their calibration results for S-CLAY/10/168.

					Comparison to S-CLAY/10/168 database		Calibration results	
Type	Relationship	Literature	n	Transformation modelmodelmodel	Figure	Fit to the trend?	Bias factor, b	COV of $\varepsilon = \delta$
A	LI–(s_u^{re}/P_a)	Wroth and Wood (1978)	59	$s_u^{re}/P_a \approx 1.7^{-4.6\mathrm{LI}}$	9	No	—	—
		Locat and Demers (1988)	59	$s_u^{re}/P_a \approx 0.0144\mathrm{LI}^{-2.44}$	9	Yes	1.60	0.96
	LI–(S_t)	Bjerrum (1954)	59	$S_t \approx 10^{0.8\mathrm{LI}}$	11	Yes	1.48	0.65
		Ching and Phoon (2012*a*)	59	$S_t \approx 20.726\mathrm{LI}^{1.910}$	11	No	0.49	0.61
B	LI–(σ'_p/P_a)–S_t (for S_t < 15)	Ching and Phoon (2012*a*)	59	$\sigma'_p/P_a \approx 0.235\mathrm{LI}^{-1.319}S_t^{0.536}$	12b	Yes	1.23	0.51
	LI–(σ'_p/P_a)–S_t (for S_t > 15)	Ching and Phoon (2012*a*)	59	$\sigma'_p/P_a \approx 0.235\mathrm{LI}^{-1.319}S_t^{0.536}$	12b	Yes	0.84	0.54
C	PI–[s_u(mob)/σ'_p]	Mesri (1975, 1989)	168	$s_u(\mathrm{mob})/\sigma'_p \approx 0.22$	5	Yes	0.96	0.27
	OCR–[s_u(mob)/σ'_v]	Jamiolkowski et al. (1985)	168	$s_u(\mathrm{mob})/\sigma'_v \approx 0.23\mathrm{OCR}^{0.8}$	4	Yes	0.97	0.25
	OCR–[s_u(mob)/σ'_v]–S_t	Ching and Phoon (2012*a*)	168	$s_u(\mathrm{mob})/\sigma'_v \approx 0.229\mathrm{OCR}^{0.823}S_t^{0.121}$	6b	Yes	0.71	0.36
D	LL–(s_u^{FV}/σ'_p)	Hansbo (1957)	168	$s_u^{FV}/\sigma'_p \approx 0.45\mathrm{LL}$	7	Yes	0.82	0.34
	PI–(s_u^{FV}/σ'_p)	Larsson (1980)	168	$s_u^{FV}/\sigma'_p \approx 0.08 + 0.0055\mathrm{PI}$	8	Yes	0.85	0.37
		Chandler (1988)	168	$s_u^{FV}/\sigma'_p \approx 0.11 + 0.0037\mathrm{PI}$	8	Yes	0.96	0.31

$s_u(\mathrm{mob})/\sigma'_p = b(0.22) = 0.95(0.22) = 0.209$, with a COV ($\delta$) = 0.28 (low variability).

Type D models (s_u^{FV}/σ'_p is the target parameter, see Tables 6–7) show a bias factor b varying between 0.82 and 0.97 with COV between 0.31 and 0.43, suggesting reasonably low variability for these models. In particular, the PI–(s_u^{FV}/σ'_p) model proposed by Chandler (1988) results almost "unbiased" with respect to both F-CLAY/10/216 and S-CLAY/10/168, suggesting b comprised between 0.96–0.97 and δ varying between 0.31 and 0.35.

s_u/σ'_v transformation models for F-CLAY/10/173

Removal of outliers in F-CLAY/10/216

As the scope of this study is to derive transformation models for s_u of Finnish soft clays that are more refined than the existing models in the literature, the data points collected in F-CLAY/10/216 are analyzed with the purpose of improving the quality of the database by removing outliers. The quality of data points is assessed through criteria based on the physical nature of the soil, mechanical characteristics, and statistical considerations. The adopted criteria are listed below:

1. Points located near the ground surface that may belong to fissured upper layers (dry crust), as the study focuses on intact and saturated clays. Dry crust layers are generally unsaturated and contain cracks and fissures. s_u of such soils may be highly overestimated when measured with the FV test (La Rochelle 1974; Lefebvre et al. 1987; D'Ignazio et al. 2015). Dry crust layers in Finland are normally 1–2 m thick. Therefore, points near the ground surface, at depths lower than 1.50 m, are left out.
2. Points with $s_u(\mathrm{mob})/\sigma'_p$ lower than an initial shear stress mobilization (τ_0/σ'_p where τ_0 is the initially mobilized shear stress) in the soil $\tau_0/\sigma'_p = 0.5(1 - K_0)$ equal to 0.15 for normally consolidated state. K_0 is the earth pressure coefficient at rest calculated from Jaky's (1944) formula ($K_0 = 1 - \sin\phi'$, where ϕ' is the effective friction angle of the soil). $\tau_0 = 0.15$ implies $\phi' = 18°$, which could represent, according to the authors' experience, the lowest boundary value for friction angle of Scandinavian clays.
3. Outliers identified through the "2σ" (95% confidence interval of $s_u(\mathrm{mob})/\sigma'_v$) statistical criteria. "σ" is the standard deviation of the variable $s_u(\mathrm{mob})/\sigma'_v$. Data points where, for a given "i"

value $|[s_u(\text{mob})/\sigma'_v]_i - \text{mean}[s_u(\text{mob})/\sigma'_v]| > 2\sigma$, are removed. Normally, outliers for a given data set are identified using the 3σ (three sigma) rule, representing the 99% confidence interval of the data. The reason why in this study the 95% confidence interval criteria is used, has to do with the inherent soil variability. s_u profiles obtained from the FV test are likely to show clear fluctuations against a mean trend. Strength variability with depth may depend not only on the consolidation stresses (initial or mechanically induced), but also on the inherent variability of the soil layers (variation of grain size, index properties). Furthermore, sample disturbance can affect the preconsolidation pressure (σ'_p) trend with depth and consequently the ratio $s_u(\text{mob})/\sigma'_p$. To remove these points, a statistical criterion stronger than the "3σ" was preferred to a "visual" one.

The number of data points left out is 43 out of 216, corresponding to 20% of the database. To be more specific, 10, 24, and 9 points are removed based on criteria 1, 2 and 3, respectively. The outcomes of this study will then be based on 173 higher quality multivariate clay data points. The updated dimensionless database is hereinafter called F-CLAY/10/173. Updated basic statistics of F-CLAY/10/173 database are listed in Table 8. One major outcome of this procedure is the reduction of the COV for all the analyzed dimensionless variables (see Table 8). Index parameters and sensitivity are not significantly affected by the removal of data points. However, OCR range drops considerably from 1~7.50 to 1~3.70. Such low OCR values are expected to be found in shallow clay deposits in Finland. Therefore, s_u of Finnish clays for OCR > 4 will not be discussed in this study. Moreover, the average $s_u(\text{mob})/\sigma'_p$ in Table 8 is slightly higher than in Table 4, resulting from the removal of the unreliable data points.

Table 8. Basic statistics of the data points after removal of outliers (database F-CLAY/10/173).

Variable	n	Mean	COV	Min	Max
$s_u(\text{mob})/\sigma'_v$	173	0.399	0.284	0.213	0.690
$s_u(\text{mob})/\sigma'_p$	173	0.213	0.183	0.148	0.338
s_u^{FV}/σ'_v	173	0.447	0.306	0.226	0.920
s_u^{FV}/σ'_p	173	0.239	0.203	0.148	0.394
OCR	173	1.91	0.31	1.18	3.69
LL	173	66.4	0.29	22	125.0
PI	173	38	0.47	2	95.0
w	173	78.3	0.25	25.00	150.0
LI	173	1.48	0.43	0.46	4.80
S_t	173	18.80	0.76	2.00	58.0

Table 9. Linear regression coefficients for multivariable function F.

Transformation model	Secondary input parameter, Y_j	α	β	γ	r^2
OCR–$s_u(\text{mob})/\sigma'_v$–$Y_j$	Y_1 (PI)	0.242	0.763	−0.013	0.67
	Y_2 (LL)	0.245	0.760	−0.005	0.67
	Y_3 (w)	0.246	0.760	0.027	0.67
	Y_4 (LI)	0.241	0.770	0.045	0.67
	Y_5 (S_t)	0.242	0.762	0.006	0.67
OCR–s_u^{FV}/σ'_v–Y_j	Y_1 (PI)	0.328	0.756	0.165	0.68
	Y_2 (LL)	0.319	0.757	0.333	0.70
	Y_3 (w)	0.296	0.788	0.337	0.69
	Y_4 (LI)	0.281	0.770	−0.088	0.63
	Y_5 (S_t)	0.280	0.786	−0.013	0.62

Derivation of new transformation models

Regression analyses are carried out to derive new transformation models for s_u of Finnish soft clays. The F-CLAY/10/173 database is used for this purpose. The SHANSEP framework (eq. (5)) proposed by Ladd and Foott (1974) is adopted to describe the variation of $s_u(\text{mob})$ and s_u^{FV} with OCR and index parameters.

Larsson et al. (2007) and Karlsrud and Hernandez-Martinez (2013) studied the anisotropic s_u of Scandinavian and Norwegian clays, respectively, from TXC, DSS, and TXE tests. Larsson et al. (2007) reported S and m (see eq. (5)) to be dependent on LL (eq. (6) for DSS), while Karlsrud and Hernandez-Martinez (2013) found w, combined with the OCR, to be the best index parameter for correlating their test results (eq. (7) for DSS). A direct comparison between s_u^{DSS} and s_u^{FV} would, however, be misleading, if rate effects are not accounted for. Nevertheless, eqs. (6) and (7) will be still used for qualitative comparison.

Linear regression analyses are performed using the "fminsearch" algorithm implemented in the mathematical software MATLAB (Mathworks 1995). The "fminsearch" function (see Mathworks 1995) finds the minimum of an unconstrained multivariable function through a derivative free method (unconstrained linear optimization). The multivariable function $F = f(s_{u,i}/\sigma'_v, \text{OCR}, Y_j)$ is defined by eq. (10)

$$F = \frac{s_{u,i}}{\sigma'_v} = \alpha \text{OCR}^{\beta} Y_j^{\gamma} \tag{10}$$

where $s_{u,i} = \{s_{u,1} = s_u(\text{mob}), s_{u,2} = s_u^{FV}\}$, $Y_j = \{Y_1 = \text{PI}, Y_2 = \text{LL}, Y_3 = w, Y_4 = \text{LI}, Y_5 = S_t\}$. The scalar coefficients α, β, and γ and the coefficient of determination (r^2) for the two newly constructed OCR–$(s_{u,i}/\sigma'_v)$–Y_j transformation models are given in Table 9. The r^2 of the new correlations ranges from 0.62 to 0.70.

The results of the regression analyses suggest that for the OCR–(s_u^{FV}/σ'_v)–Y_j transformation model, s_u^{FV}/σ'_v is directly proportional to PI, LL, w and inversely proportional to LI, while it is not markedly dependent on S_t. In contrast, a similar conclusion cannot be drawn for the OCR–$[s_u(\text{mob})/\sigma'_v]$–$Y_j$ model, as $s_u(\text{mob})/\sigma'_v$ seems to be only lightly correlating with index parameters. This concept can be well understood by looking at the scalar coefficient γ for the OCR–$[s_u(\text{mob})/\sigma'_v]$–$Y_j$ models from Table 9. For $\gamma > 0$, $s_u(\text{mob})/\sigma'_v$ increases with increasing Y_j; on the contrary, for $\gamma < 0$ it reduces by increasing Y_j. Although γ values indicate that $s_u(\text{mob})/\sigma'_v$ decreases with increasing PI or LL and, in contrast, increases with increasing w, LI or S_t, it should be emphasized how γ tends to zero for the OCR–$[s_u(\text{mob})/\sigma'_v]$–$Y_j$ transformation model. As a result, $s_u(\text{mob})/\sigma'_v$ of Finnish soft clays results (*i*) slightly dependent or nearly independent of the secondary input variable Y_j, and (*ii*) strongly dependent on the consolidation stresses (increasing with increasing OCR). This result agrees with the findings of Mesri (1975, 1989) and Jamiolkowski et al. (1985). However, Mesri (1975, 1989) suggests $m = 1$, which is not consistent with the results presented in Table 9, as for Finnish clays m results lower than 1. To validate such observation, it is worth to mention that the modified Cam clay model (Schofield and Wroth 1968) predicts $m = 1 - C_s/C_c$, where C_c and C_s are the compression and swelling indices, respectively, of a clay. This result indicates that m is generally less than 1 for normally consolidated to lightly overconsolidated clays, which are typically known to be adequately modeled by the modified Cam clay model. Moreover, by averaging α and β from the five OCR–$[s_u(\text{mob})/\sigma'_v]$–$Y_j$ correlation equations of Table 9, and assuming $\gamma = 0$, for Finnish clays, eq. (11)

$$\frac{s_u(\text{mob})}{\sigma'_v} \approx 0.244\text{OCR}^{0.763} \tag{11}$$

which nearly corresponds to the unbiased transformation model presented by Jamiolkowski et al. (1985), as described earlier in this paper. The calibrated bias factor (b) from F-CLAY/10/216 database for the OCR–$[s_u(\text{mob})/\sigma'_v]$ model by Jamiolkowski et al. (1985) is equal to 1.06. This means $s_u(\text{mob})/\sigma'_v = b(0.23)\text{OCR}^{0.8} = 0.244\text{OCR}^{0.8}$ with a coefficient of variation (COV = δ) equal to 0.30.

Fig. 13. Comparison between OCR–(s_u^{FV}/σ_v')–LL for Finnish clays and OCR–(s_u^{DSS}/σ_v')–LL model by Larsson et al. (2007) for Swedish clays.

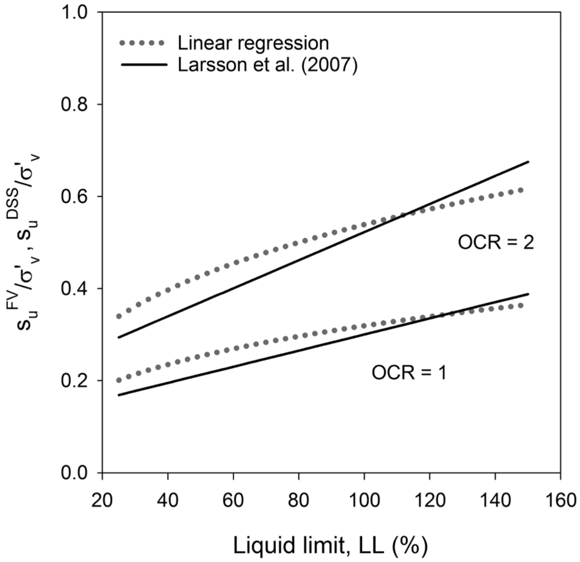
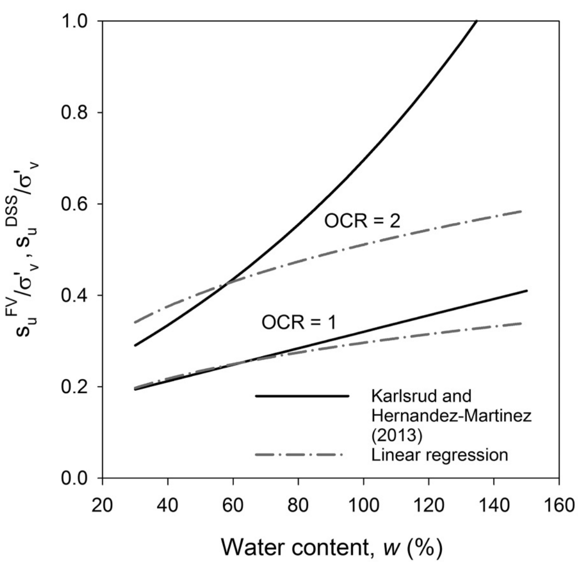


Fig. 14. Comparison between OCR–(s_u^{FV}/σ_v')–w for Finnish clays and OCR–(s_u^{DSS}/σ_v')–w model by Karlsrud and Hernandez-Martinez (2013) for Norwegian clays.



Validation of the new transformation models

It is apparent from Table 9 that the OCR–(s_u^{FV}/σ_v')–Y_j transformation model is strongly dependent on index parameters. As earlier explained in this section, s_u^{DSS} of Scandinavian clays exhibits a marked dependency on LL (eq. (6)) and w (eq. (7)). These results may be explained by the fact that both tests at laboratory scale and FV test are performed at considerably high strain rate in relatively short time frames, if compared with the time scale needed for causing failure in situ. It is known that undrained failure of e.g., embankments may take several days (La Rochelle et al. 1974), while DSS and FV tests are performed on time scales in the order of hours or minutes, respectively. While TXC, TXE, DSS tests are normally performed at a strain rate of about 1%·h^{-1}, FV test is executed at strain rates typically 50–60 times larger (i.e., 60%·h^{-1}, Ching et al. 2013). This is well reflected in Fig. 13 and Fig. 14, where the OCR–(s_u^{FV}/σ_v')–Y_j transformation model is compared to eq. (6) and eq. (7). From Fig. 13, it can be noticed how s_u^{FV}/σ_v' is generally greater than s_u^{DSS}/σ_v', except for LL > 100% at OCR = 1. This is possibly due to the limited amount of LL > 100% data points used to derive the correlations.

However, more uncertainty comes when w is taken as secondary input parameter. The transformation model given by Karlsrud and Hernandez-Martinez (2013) for DSS strength tends to deviate from the mean trend suggested by F-CLAY/10/173 database (Fig. 14), intersecting the regression line and suggesting that for a certain number of combinations of OCR and w, s_u^{DSS} of Norwegian clays would result higher than s_u^{FV} of Finnish clays. One possible reason that could justify the differences between the two models could be that (*i*) eq. (6) is based only on a limited number of DSS tests (as reported by Karlsrud and Hernandez-Martinez 2013) and (*ii*) w of the tested specimens was about 25%~80%, while the new OCR–(s_u^{FV}/σ_v')–w model is calibrated from a wider range of w (w = 25%–150%). Hence, attention must be paid when using eq. (7), as, based on this study, consistency was found only for w < 60%.

Figure 15 compares the variation of s_u^{FV}/σ_v' with OCR for various LL ranges. It is noticeable that for Finnish sensitive clays, the trend

Fig. 15. Comparison between measured (calibration and validation) data and OCR–(s_u^{FV}/σ_v')–LL model for Finnish clays for various LL ranges: (*a*) LL ≤ 50%; (*b*) 50% < LL ≤ 75%; (*c*) 75% < LL ≤ 100%; (*d*) LL > 100%.

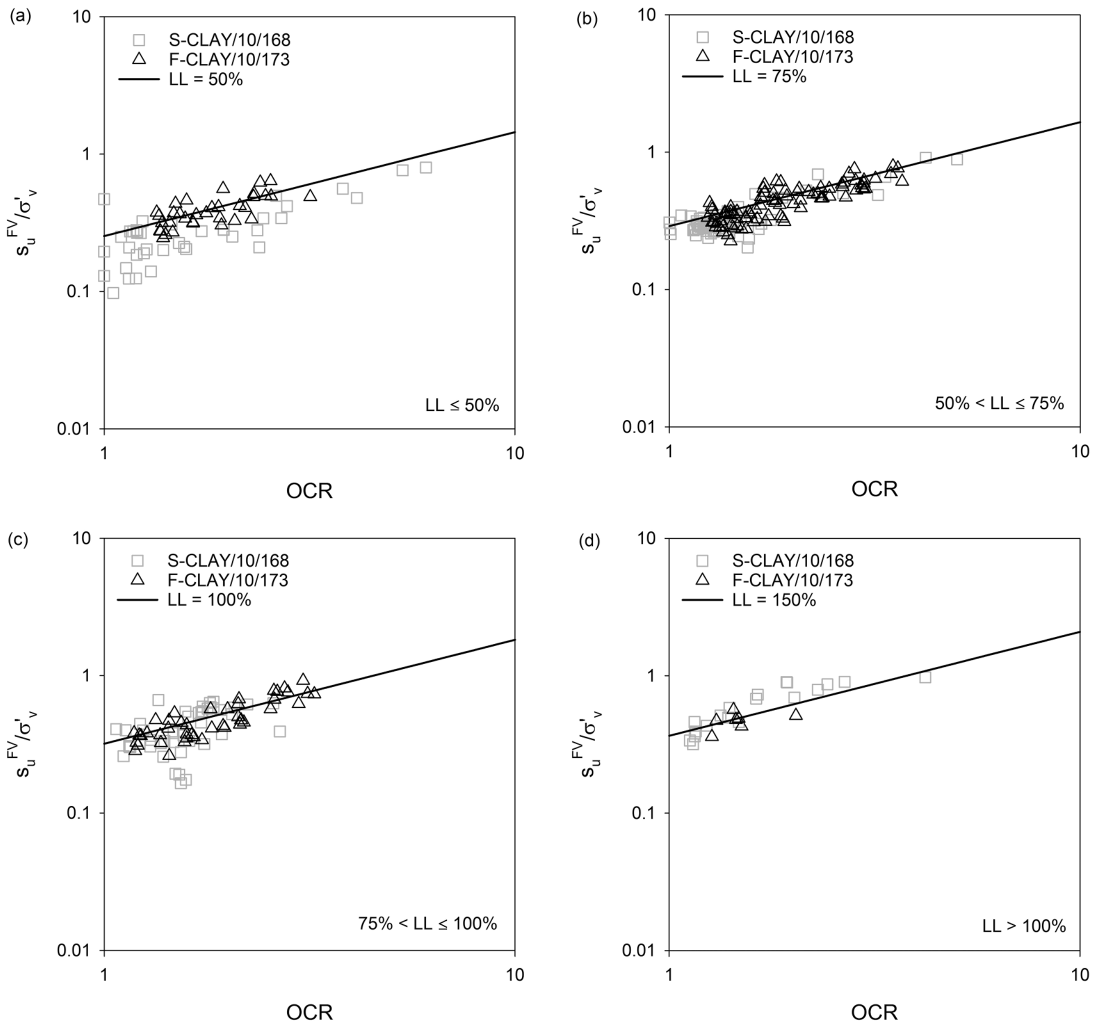


Table 10. Transformation models for Finnish clays and their calibration results for S-CLAY/10/168.

			Calibration results	
Relationship	*n*	Transformation model	Bias factor, *b*	COV of $\varepsilon = \delta$
OCR–[s_u(mob)/σ_v']–PI	168	$s_u(\text{mob})/\sigma_v' \approx 0.242\text{OCR}^{0.763}\text{PI}^{-0.013}$	0.94	0.26
OCR–[s_u(mob)/σ_v']–LL	168	$s_u(\text{mob})/\sigma_v' \approx 0.245\text{OCR}^{0.760}\text{LL}^{-0.005}$	0.94	0.25
OCR–[s_u(mob)/σ_v']–w	168	$s_u(\text{mob})/\sigma_v' \approx 0.246\text{OCR}^{0.760}w^{0.027}$	0.94	0.25
OCR–[s_u(mob)/σ_v']–LI	168	$s_u(\text{mob})/\sigma_v' \approx 0.241\text{OCR}^{0.770}\text{LI}^{0.045}$	0.95	0.26
OCR–[s_u(mob)/σ_v']–S_t	59	$s_u(\text{mob})/\sigma_v' \approx 0.242\text{OCR}^{0.762}S_t^{0.006}$	0.90	0.34
OCR–(s_u^{FV}/σ_v')–PI	168	$s_u^{FV}/\sigma_v' \approx 0.328\text{OCR}^{0.756}\text{PI}^{0.165}$	0.95	0.29
OCR–(s_u^{FV}/σ_v')–LL	168	$s_u^{FV}/\sigma_v' \approx 0.319\text{OCR}^{0.757}\text{LL}^{0.333}$	0.94	0.26
OCR–(s_u^{FV}/σ_v')–w	168	$s_u^{FV}/\sigma_v' \approx 0.296\text{OCR}^{0.788}w^{0.337}$	0.97	0.27
OCR–(s_u^{FV}/σ_v')–LI	168	$s_u^{FV}/\sigma_v' \approx 0.281\text{OCR}^{0.770}\text{LI}^{-0.088}$	0.95	0.33
OCR–(s_u^{FV}/σ_v')–S_t	59	$s_u^{FV}/\sigma_v' \approx 0.280\text{OCR}^{0.786}S_t^{-0.013}S_t$	0.91	0.44

lines (solid lines) for given values of LL move gently upwards for increasing LL. The suggested trends appear to agree with the points from the S-CLAY/10/168 database, grouped following the LL ranges adopted.

Bias and uncertainties of the new transformation models

Bias factor (b) and coefficient of variation of ε (δ) are evaluated for the newly derived transformation models for s_u of Finnish soft clays, through the independent S-CLAY/10/168 database of Scandinavian clays. b and δ of the new correlations are summarized in Table 10. Calculated b values range between 0.94 and 0.97 when the effect of PI, LL, w, and LI is considered, with COV values lower than 0.30. Exception is only made for the OCR–(s_u^{FV}/σ_v')–LI model which shows COV = 0.33. Therefore, the proposed correlations can be considered almost "unbiased" with respect to S-CLAY/10/168 database. The OCR–(s_u^{FV}/σ_v')–S_t and OCR–[s_u(mob)/σ_v']–S_t models are characterized by the lowest bias factors (0.91 and 0.90, respectively) and by the highest coefficients of variation δ (0.44 and 0.34, respectively). One possible reason could be that b and δ of the models where S_t is the secondary input parameter are calculated from a lower number of data points (n = 59) than for the other models (n = 168).

The new correlation equations appear to be less "biased" than the existing type C and type D transformation models presented in Table 6. In particular, s_u^{FV} evaluated using the new equations would result less "biased" ($b \sim 1$) than from type D models of Table 6, with δ values lower than 0.3 (Table 10) versus δ = 0.35–0.43 (Table 6). In addition, equations for s_u(mob) from Table 10 provide an almost unbiased prediction with coefficient of variation (δ) as low as 0.25.

Discussion

Based on the results presented in Table 9, a correct evaluation of σ'_p would be of great importance for assessing s_u of Finnish soft clays when direct measurements are not available. The transformation models derived in this study can predict s_u with relatively low uncertainty, provided that OCR (primary input parameter) and a secondary input parameter (e.g., index parameter) are carefully chosen. The usability of the new models is straightforward, as only little information is required. For instance, simple tests such as oedometer and index tests would provide sufficient information for using the new models specific to Finnish clays. Moreover, the evaluation of a secondary input parameter may not be required, as s_u(mob) was observed to mainly depend on OCR (eq. (11)).

The transformation models presented in this study may also serve as a practical engineering tool for preliminary short-term analyses and (or) as a framework for validation of site-specific measurements that are suspected to be unreliable.

Conclusions

In this study, a calibration database of multivariate clay data points from Finland is compiled for the first time, for the scope of providing correlations for undrained shear strength (s_u) of Finnish clays and evaluating the dependency of s_u on the overconsolidation ratio (OCR), natural water content (w), liquid limit (LL), plasticity index (PI), liquidity index (LI), and sensitivity (S_t). The new transformation models are derived through linear regression analyses.

According to the results presented in this paper, a mutual dependence between the uncorrected s_u from FV test (s_u^{FV}), OCR, and index parameters (PI, LL, w, and LI) exists. The only exception is observed for S_t, which seems to have a negligible influence on s_u^{FV}. On the contrary, the mobilized undrained shear strength s_u(mob) seems to be mainly dependent on OCR and not significantly affected by index parameters.

Another independent clay database of Scandinavian clays is compiled to validate the new equations. Consistency of the new transformation models is checked by (*i*) evaluating bias factors and coefficients of variation associated with the validation database and (*ii*) comparison with existing transformation models for undrained shear strength of Swedish and Norwegian clays. Consistency is clearly revealed by the validation process. In particular, the new transformation models result in overall less biased than the existing ones, showing coefficients of variation lower than 0.30.

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List of symbols

B_q	pore pressure ratio [= $(u_2 - u_0)/(q_t - \sigma_v)$]
b	bias factor
C_c	compression index of clay
C_s	swelling index of clay
COV	coefficient of variation
F	multivariable function
K_0	earth pressure coefficient at rest from Jaky's formula
LI	liquidity index [= (w – PL)/(LL – PL)]
LL	liquid limit
m	SHANSEP exponent
OCR	overconsolidation ratio (= σ'_p/σ'_v)
P_a	atmospheric pressure (= 101.3 kPa)
PI	plasticity index (= LL – PL)
PL	plastic limit
q_t	cone tip resistance
$(q_t - \sigma_v)/\sigma'_v$	normalized cone tip resistance
$(q_t - u_2)/\sigma'_v$	effective cone tip resistance
S	normalized s_u for normally consolidated state
S_t	sensitivity (= s_u/s_u^{re})
s_u	undrained shear strength
s_u(mob)	mobilized undrained shear strength (= λs_u^{FV})
s_u^{CIUC}	s_u from isotropically consolidated undrained compression test
$s_u^{CK_0UC}$	s_u from K_0-consolidated undrained compression test
$s_u^{CK_0UE}$	s_u from K_0-consolidated undrained extension test
s_u^{DSS}	undrained shear strength from direct simple shear test
s_u^{FV}	undrained shear strength measured from field vane test
s_u^{re}	remolded undrained shear strength
s_u^{UC}	s_u from unconfined compression test
s_u^{UU}	s_u from unconsolidated undrained compression test
u_0	hydrostatic pore pressure
u_2	pore pressure acting behind the cone
Y_j	secondary input parameter
w	natural water content
α	scalar coefficient in the multivariable function F
β	scalar coefficient in the multivariable function F
γ	scalar coefficient in the multivariable function F
δ	coefficient of variation of ε
ε	variability term
λ	correction factor for s_u^{FV} based on plasticity
σ	standard deviation of s_u(mob)/σ'_v
σ_v	vertical stress
σ'_v	effective vertical stress
σ'_p	vertical preconsolidation pressure
σ'_{pCRS}	vertical preconsolidation pressure from CRS test
σ'_{pIL}	vertical preconsolidation pressure from IL test
τ_0	initially mobilized shear stress
ϕ'	effective friction angle of soil

Appendix A. Multivariate clay databases

Appendix Tables A1–A2 appear on the following pages.

Table A1. Basic information of the F-CLAY/7/216 database: σ'_p data points from IL oedometer test.

Location	Depth (m)	s_u^{FV} (kPa)	σ'_v (kPa)	σ'_p (kPa)	LL (%)	PL (%)	*w* (%)	S_t
Espoo, Kaukalahti	3.2	13.0	30.2	43.0	70.0	25.0	85.0	11.0
	4.6	7.0	38.6	60.0	60.0	25.0	75.0	11.0
	5.2	7.5	42.2	45.0	45.0	20.0	50.0	10.0
Espoo, Martinkylä	5.5	7.0	24.5	25.0	70.0	20.0	80.0	4.0
	6.0	7.0	27.0	30.0	30.0	15.0	75.0	2.0
	7.0	12.0	32.0	40.0	80.0	20.0	100.0	6.0
	8.0	12.0	37.0	40.0	90.0	15.0	120.0	5.0
Helsinki, Malmi	3.0	9.0	18.0	30.0	80.0	35.0	110.0	12.0
	4.0	11.0	23.0	35.0	75.0	30.0	100.0	10.0
	5.0	10.0	28.0	30.0	43.0	20.0	65.0	10.0
	6.0	11.0	33.0	40.0	55.0	20.0	80.0	11.0
	7.0	8.0	38.0	50.0	25.0	20.0	40.0	9.0
	8.0	16.0	43.0	50.0	22.0	20.0	25.0	13.0
Kouvola	1.5	42.0	24.2	150.0	45.0	20.0	40.0	6.5
	3.0	15.0	33.0	40.0	80.0	25.0	100.0	11.0
	5.0	21.0	43.0	50.0	110.0	25.0	130.0	8.0
	6.0	23.0	48.0	55.0	110.0	25.0	120.0	8.0
	7.0	25.0	53.0	60.0	80.0	25.0	110.0	7.0
Kurkela*	2.2	19.1	35.4	105.4	69.0	32.3	75.0	40.0
	2.7	20.0	37.8	107.8	66.3	31.6	79.0	39.5
	3.2	28.2	40.3	110.3	60.8	30.2	70.0	39.0
	3.7	25.0	42.7	112.4	55.2	28.8	62.0	38.5
	4.2	22.3	45.2	115.2	49.7	27.4	56.7	37.0
	4.7	23.7	47.6	117.6	48.8	27.2	60.0	35.0
	5.2	31.3	50.1	120.1	48.5	27.1	65.3	24.1
	6.2	28.4	55.0	127.3	48.0	27.0	52.1	24.2
	7.2	27.8	59.9	140.0	51.8	28.0	53.5	24.0
	8.2	29.9	64.8	152.3	55.8	28.9	55.7	24.0
	9.2	34.9	69.7	160.0	68.8	32.2	65.0	13.5
	10.2	34.1	74.6	163.0	82.4	35.6	77.4	10.0
	11.2	35.1	79.5	170.0	94.9	38.7	82.0	10.5
	12.2	23.3	84.4	182.3	107.3	41.8	87.7	10.5
	13.2	21.1	89.3	185.0	111.8	42.9	83.9	10.0
Loimaa	3.0	20.0	24.0	48.0	55.0	25.0	65.0	11.0
	4.0	19.0	31.0	90.0	51.0	23.0	60.0	9.0
	5.0	18.0	38.0	50.0	75.0	23.0	70.0	7.0
	7.0	24.0	52.0	65.0	48.0	23.0	65.0	9.0
	8.0	24.0	59.0	85.0	47.0	23.0	70.0	13.0
	9.0	23.0	66.0	67.0	55.0	25.0	70.0	13.0
	10.0	25.0	73.0	110.0	49.0	23.0	60.0	9.0
	11.0	25.0	80.0	120.0	51.0	23.0	60.0	8.0
	12.0	27.0	87.0	110.0	55.0	23.0	57.0	7.0
	13.0	27.0	94.0	100.0	52.0	22.0	65.0	8.0
Lokalahti	5.0	9.0	16.5	22.0	60.0	20.0	100.0	17.0
	7.0	10.0	26.5	28.0	49.0	20.0	80.0	19.0
Nurmijarvi	2.4	8.0	15.6	25.0	120.0	50.0	150.0	10.0
	3.6	7.0	20.4	30.0	52.0	25.0	75.0	9.0
	6.0	16.0	30.0	35.0	80.0	30.0	120.0	7.0
	7.0	17.0	34.0	48.0	75.0	30.0	100.0	10.0
	8.0	22.0	38.0	51.0	75.0	30.0	100.0	12.0
	9.0	24.0	42.0	60.0	90.0	30.0	100.0	13.0
	10.0	25.0	46.0	75.0	75.0	30.0	90.0	13.0
	11.0	28.0	53.0	80.0	65.0	30.0	75.0	14.0
	13.0	34.0	67.0	90.0	60.0	25.0	58.0	12.0
	14.0	22.0	74.0	130.0	65.0	25.0	60.0	8.0
	16.0	28.0	88.0	100.0	40.0	25.0	35.0	6.0
	17.0	30.0	95.0	100.0	52.0	25.0	60.0	7.0
	18.0	35.0	102.0	140.0	70.0	25.0	55.0	8.0
Otaniemi	2.7	5.0	10.1	20.0	105.0	25.0	120.0	9.0
	5.5	12.0	19.5	28.0	70.0	30.0	75.0	5.0
	6.5	11.0	24.5	35.0	70.0	25.0	65.0	4.0
	7.5	14.0	29.5	50.0	80.0	30.0	85.0	5.0
	8.5	19.0	34.5	80.0	65.0	30.0	80.0	7.0
	9.5	12.0	39.5	60.0	43.0	25.0	50.0	6.0
	10.5	15.0	44.5	80.0	47.0	25.0	55.0	8.0
Perniö (location 1)*	2.2	9.30	28.9	74.3	79.0	32.0	75.0	14.0
	2.7	10.20	31.4	62.6	74.0	32.0	78.5	18.6
	2.6	12.20	31.0	64.7	75.0	32.0	80.8	19.1
	2.7	13.60	31.6	61.5	82.0	32.0	97.6	22.9
	2.1	19.10	28.5	73.8	76.0	32.0	88.0	25.2
	5.1	12.80	43.5	61.5	65.0	32.0	80.1	30.7
	3.1	9.30	33.5	51.5	65.0	32.0	83.0	32.0
	2.2	18.60	29.1	73.9	46.0	32.0	61.7	32.7
	5.7	11.60	46.4	64.4	58.0	32.0	80.9	33.7
	3.6	9.90	36.0	54.0	63.0	32.0	86.0	35.0
	4.2	12.80	39.1	57.1	64.0	32.0	90.0	35.5
	5.2	15.40	44.1	62.1	64.0	32.0	70.9	35.6
	6.1	13.30	48.5	66.5	38.0	32.0	47.9	36.7
	4.7	14.80	41.6	59.6	55.0	32.0	88.2	37.4
	3.2	11.30	33.9	51.9	60.0	32.0	82.3	39.1
	3.7	6.40	36.4	54.4	51.0	32.0	77.5	39.4
	4.6	10.70	41.0	59.0	76.0	32.0	96.6	41.3
	4.7	11.60	41.4	59.4	51.0	32.0	72.6	45.7
	4.1	10.40	38.5	56.5	50.0	32.0	69.6	45.7
	3.7	16.00	36.6	54.6	50.0	32.0	74.4	46.3
	5.2	9.90	43.9	61.9	59.0	32.0	84.1	46.5
	3.2	12.50	34.1	52.1	45.0	32.0	70.6	49.4
	5.7	16.80	46.6	64.6	54.0	32.0	80.1	51.1
	4.2	11.30	38.9	56.9	51.0	32.0	72.0	51.3
	5.6	11.30	46.0	64.0	50.0	32.0	75.9	57.7
Perniö (location 2)*	1.5	38.0	19.0	64.0	89.9	36.0	58.9	64.0
	2.5	10.0	24.2	44.2	89.9	36.0	110.0	58.0
	3.0	8.7	26.4	41.4	86.3	36.0	104.0	55.5
	3.5	7.5	28.6	38.6	71.1	36.0	94.0	53.5
	4.0	8.7	30.8	40.8	60.2	36.0	84.0	52.3
	4.5	10.0	33.0	43.0	58.2	36.0	75.0	51.4
	5.0	11.0	35.2	45.2	54.1	36.0	80.0	50.4
	5.5	15.0	37.4	47.4	50.4	36.0	75.0	47.5
	6.0	17.0	39.6	49.6	52.0	36.0	80.0	43.8
	6.5	14.0	41.8	51.8	66.9	36.0	92.0	39.2
	7.0	16.0	44.0	54.0	75.5	36.0	84.0	39.5
	7.5	17.0	46.2	56.2	75.9	36.0	88.0	40.0
	8.0	15.0	48.4	58.4	76.3	36.0	87.0	40.0
	8.5	16.5	50.6	60.6	76.7	36.0	86.0	45.0
	9.0	15.0	52.8	62.8	77.2	36.0	88.0	45.0
	9.5	21.0	55.0	65.0	77.2	36.0	85.0	40.0
	2.0	13.0	21.5	45.0	75.0	25.0	75.0	11.0
	3.0	10.0	27.0	30.0	75.0	30.0	75.0	20.0
	5.0	16.0	38.0	60.0	51.0	25.0	75.0	21.0
	6.0	18.0	43.5	65.0	49.0	30.0	65.0	20.0
Raisio, Autolava	0.8	49.0	19.8	125.0	50.0	20.0	40.0	3.0
	1.5	13.0	18.5	39.0	70.0	20.0	70.0	10.0
	2.5	10.0	24.5	50.0	70.0	23.0	90.0	9.0
	3.0	12.0	27.0	38.0	75.0	25.0	90.0	8.0
	4.0	14.0	32.0	40.0	100.0	27.0	130.0	10.0
Raisio, Krookila	2.5	13.0	26.3	60.0	85.0	25.0	87.0	11.0
	3.5	11.0	30.8	40.0	80.0	25.0	90.0	12.0
	4.5	12.0	35.3	48.0	85.0	25.0	80.0	9.0
	5.5	17.0	39.8	47.0	125.0	30.0	130.0	10.0
	6.5	25.0	44.3	50.0	120.0	25.0	120.0	10.0
	7.5	23.0	48.8	50.0	110.0	25.0	110.0	9.0
	8.5	22.0	53.3	60.0	100.0	25.0	95.0	10.0
	9.5	22.0	57.8	90.0	100.0	25.0	95.0	8.0
	10.5	23.0	62.3	80.0	85.0	25.0	80.0	8.0
Raisio, Ristimaki	0.5	10.0	7.5	30.0	70.0	30.0	70.0	12.0
	1.5	10.0	12.5	35.0	75.0	40.0	85.0	9.0
	2.5	10.0	17.5	35.0	80.0	45.0	95.0	12.0
	3.5	17.0	22.5	50.0	65.0	25.0	100.0	10.0
	5.5	15.0	32.5	43.0	70.0	35.0	80.0	11.0
	8.0	18.0	45.0	50.0	55.0	30.0	75.0	9.0

Table A1 (*continued*).

Location	Depth (m)	s_u^{FV} (kPa)	σ'_v (kPa)	σ'_p (kPa)	LL (%)	PL (%)	w (%)	S_t
Raisio, Siirinpelto	3.5	7.0	29.5	50.0	48.0	20.0	85.0	10.0
	4.5	8.0	34.5	52.0	49.0	20.0	80.0	10.0
	6.0	9.5	42.0	90.0	35.0	20.0	37.0	10.0
	7.5	10.0	49.5	90.0	30.0	20.0	52.0	11.0
Saimaan kanava	3.0	30.0	31.0	120.0	80.0	27.0	60.0	8.0
	4.0	30.0	37.0	80.0	100.0	30.0	110.0	7.5
	5.0	20.0	43.0	80.0	55.0	25.0	65.0	7.0
	6.0	20.0	49.0	85.0	32.0	22.0	70.0	10.0
	7.0	18.0	55.0	90.0	35.0	25.0	50.0	9.0
	8.0	25.0	61.0	80.0	55.0	25.0	65.0	7.0
	9.0	30.0	67.0	110.0	60.0	25.0	75.0	6.0
Salo, Salonkyla	10.0	18.0	50.0	50.0	105.0	25.0	100.0	10.0
	16.0	28.0	80.0	100.0	90.0	25.0	85.0	16.0
	20.0	28.0	100.0	160.0	90.0	25.0	75.0	10.0
Sipoo	1.0	47.0	16.0	120.0	60.0	35.0	50.0	10.0
	1.5	20.0	20.5	80.0	85.0	25.0	80.0	9.0
	3.5	24.0	32.5	80.0	80.0	25.0	85.0	12.5
	4.5	21.0	37.5	78.0	75.0	25.0	75.0	11.5
	5.5	20.0	42.5	90.0	70.0	25.0	80.0	10.5
	6.5	20.0	47.5	80.0	49.9	25.0	65.0	10.0
	7.5	21.0	52.5	125.0	44.0	25.0	60.0	9.0
	10.0	16.0	42.0	42.0	85.0	25.0	85.0	8.0
	12.0	17.0	52.0	67.0	75.0	25.0	80.0	10.0
	14.6	24.0	65.0	70.0	100.0	25.0	85.0	11.0
Somero, Joenssu	1.0	45.0	17.0	100.0	85.0	30.0	60.0	7.0
	2.0	23.0	25.0	60.0	100.0	25.0	90.0	15.0
	4.0	20.0	35.0	55.0	100.0	25.0	110.0	13.0
	6.0	28.0	45.0	75.0	80.0	25.0	110.0	14.0
	8.0	23.0	55.0	85.0	80.0	30.0	110.0	15.0
	10.0	27.0	65.0	95.0	70.0	25.0	80.0	13.0
	12.0	28.0	79.0	98.0	60.0	23.0	75.0	16.0
	14.0	33.0	93.0	100.0	52.0	23.0	70.0	10.0
	18.0	40.0	121.0	180.0	60.0	23.0	60.0	13.0
	20.0	43.0	135.0	175.0	50.0	23.0	60.0	8.0
	24.0	51.0	163.0	220.0	60.0	25.0	50.0	7.0
Somero, Kirkonkyla	4.0	35.0	39.0	130.0	75.0	27.0	70.0	14.0
	5.0	33.0	45.0	115.0	80.0	25.0	75.0	17.0
	6.0	31.0	51.0	75.0	70.0	25.0	70.0	16.0
	7.0	31.0	57.0	110.0	75.0	24.0	75.0	13.0
	8.0	33.0	64.0	110.0	55.0	23.0	65.0	12.0
	11.0	42.0	85.0	150.0	60.0	24.0	55.0	8.0
	12.0	45.0	92.0	230.0	46.0	23.0	55.0	7.0
Somero, Pajulanjoki	4.0	19.0	21.0	70.0	80.0	27.0	110.0	12.0
	5.0	17.0	25.0	79.0	75.0	27.0	100.0	13.0
	6.0	23.0	29.0	80.0	75.0	27.0	100.0	22.0
	7.0	23.0	33.0	90.0	75.0	27.0	100.0	18.0
	8.0	25.0	37.0	62.0	80.0	25.0	85.0	18.0
	9.0	27.0	42.0	105.0	75.0	25.0	80.0	12.0
	10.0	28.0	47.0	110.0	75.0	27.0	85.0	17.0
	11.0	30.0	52.0	120.0	70.0	25.0	80.0	20.0
	12.0	31.0	57.0	135.0	70.0	25.0	80.0	10.0
	13.0	32.0	62.0	100.0	65.0	25.0	75.0	21.0
Tampere	1.5	75.0	33.0	180.0	70.0	27.0	70.0	9.0
	2.5	37.0	40.0	190.0	52.0	27.0	40.0	6.0
	3.0	24.0	43.5	80.0	55.0	27.0	40.0	9.0
	3.5	18.0	47.0	60.0	60.0	25.0	70.0	17.0
	4.0	16.0	50.5	55.0	47.0	27.0	62.0	14.0
	4.5	17.0	54.0	70.0	40.0	25.0	60.0	20.0
	5.0	13.0	57.5	75.0	35.0	28.0	45.0	11.0
	5.5	14.0	61.0	77.0	32.0	25.0	42.0	10.0
	6.0	22.0	64.5	80.0	35.0	27.0	50.0	8.0
	6.5	21.0	68.0	68.0	51.0	25.0	55.0	16.0
	7.0	35.0	71.5	130.0	35.0	25.0	60.0	14.0
	7.5	42.0	75.0	115.0	31.0	26.0	50.0	9.0
	8.0	37.0	78.5	220.0	37.0	32.0	40.0	11.0

Table A1 (*concluded*).

Location	Depth (m)	s_u^{FV} (kPa)	σ'_v (kPa)	σ'_p (kPa)	LL (%)	PL (%)	w (%)	S_t
Vihti	3.0	20.0	23.0	55.0	35.0	15.0	35.0	10.0
	4.0	23.0	30.0	85.0	75.0	50.0	80.0	16.0
	6.0	21.0	44.0	85.0	60.0	30.0	65.0	7.0
	9.0	18.0	65.0	70.0	25.0	10.0	30.0	11.0
	10.0	26.0	72.0	95.0	40.0	20.0	45.0	7.0
	11.0	29.0	79.0	97.0	55.0	30.0	57.0	6.0
	12.0	32.0	86.0	120.0	48.0	25.0	52.0	9.0
	13.0	34.0	93.0	100.0	52.0	25.0	55.0	10.0
	14.0	37.0	100.0	115.0	51.0	25.0	55.0	10.0
Viiala	3.0	22.0	23.8	45.0	65.0	25.0	75.0	8.5
	4.0	22.0	29.3	40.0	48.0	25.0	60.0	9.0
	4.5	20.0	32.0	75.0	75.0	25.0	80.0	8.0
	6.0	25.0	40.3	90.0	52.0	25.0	70.0	8.5
	6.5	22.0	43.0	100.0	85.0	30.0	95.0	11.0
	7.0	35.0	45.8	95.0	100.0	35.0	100.0	14.0
	8.0	32.0	51.3	120.0	85.0	35.0	90.0	14.0
	8.5	42.0	54.0	110.0	80.0	30.0	90.0	11.0
	9.0	43.0	56.8	125.0	77.0	35.0	80.0	16.6
	9.5	55.0	59.5	130.0	95.0	25.0	80.0	15.0
	15.0	43.0	90.5	95.0	80.0	30.0	65.0	6.0
	14.0	32.0	83.5	83.5	75.0	30.0	60.0	6.0

*σ'_p data points from CRS oedometer test.

Table A2. Basic information of the S-CLAY/7/168 database. σ'_p data points from CRS oedometer test.

Location	Depth (m)	s_u^{FV} (kPa)	σ'_v (kPa)	σ'_p (kPa)	LL (%)	PL (%)	w (%)	S_t
Drammen (Norway)	4.0	8.3	41.2	57.4	39.3	9.7	30.7	3.0
	5.2	11.8	50.4	78.7	58.7	10.3	65.5	3.0
	6.2	11.7	57.8	89.6	65.6	18.8	65.6	3.0
	7.1	12.3	64.7	98.5	75.2	20.6	56.2	3.0
	7.5	13.0	67.1	100.0	88.5	18.7	65.3	3.0
	7.5	22.8	68.0	95.2	88.0	18.0	65.0	6.0
	7.8	25.2	70.0	105.0	60.0	29.0	52.0	8.0
	8.5	20.6	74.5	114.4	75.8	15.4	61.7	3.0
	8.5	12.3	74.5	114.4	75.8	15.4	61.7	3.0
	9.0	13.7	78.7	124.3	78.2	19.1	58.2	3.0
	9.3	11.2	80.0	104.0	33.0	23.0	32.0	8.0
	9.4	20.9	81.5	113.4	92.2	20.4	64.1	3.0
	11.9	10.0	102.6	108.0	40.2	8.8	27.6	7.0
	13.0	20.8	112.5	135.0	25.0	3.0	26.0	6.0
	13.0	14.0	112.5	129.3	25.0	3.0	25.7	7.0
	17.4	19.0	152.6	182.3	23.3	2.7	17.3	7.0
Ellingsrud (Norway)	10.5	7.8	60.0	60.0	24.0	20.0	36.0	42.5
Fredrikstad (Norway)	6.5	10.8	43.0	47.3	34.0	21.0	40.5	20.0
Haga (Norway)	2.8	41.6	52.0	315.6	41.1	26.3	37.9	—
	2.8	40.4	53.0	282.5	40.6	27.5	38.8	—
	3.9	40.3	72.0	274.3	40.8	26.1	36.9	—
	4.9	45.0	92.0	296.2	62.5	28.2	54.2	—
	5.2	48.7	97.0	257.1	68.0	29.6	60.7	—
	6.2	39.3	115.0	310.5	40.4	25.4	36.5	—
	6.5	39.3	121.0	150.0	39.0	25.4	34.4	—
Onsøy (Norway)	1.9	10.8	12.2	61.1	50.2	32.1	65.1	3.0
	2.1	12.7	13.9	58.4	65.2	32.1	67.1	3.0
	3.5	11.8	22.4	48.2	59.9	29.4	57.6	3.0
	5.2	12.1	32.6	45.1	56.8	33.9	58.5	3.0
	5.5	12.0	34.3	46.1	56.4	34.0	58.9	3.0
	7.6	12.9	47.5	54.3	66.3	34.8	62.3	3.0
	7.9	13.5	48.9	56.3	66.2	34.9	65.8	3.0
	10.8	17.6	66.2	85.2	74.4	38.3	67.5	7.0
	11.0	19.5	67.5	86.9	72.9	36.8	69.4	7.0
	13.4	22.2	82.2	106.3	71.4	35.6	66.7	7.0
	13.6	22.0	83.5	107.0	71.5	35.6	68.9	7.0
	16.3	27.4	99.8	100.2	72.7	37.9	64.5	7.0
Studenterlunden (Norway)	15.0	16.5	87.0	108.8	37.0	20.0	33.0	5.0
	15.0	17.0	87.0	87.0	44.0	25.0	37.4	4.0
Sundland (Norway)	6.5	15.1	43.0	55.9	58.0	30.0	59.0	11.0
Unknown location 1 (Norway)	3.1	14.8	21.4	49.1	56.1	29.2	59.2	—
	5.0	14.6	31.3	56.2	58.8	30.2	61.2	—
	7.0	13.1	43.4	64.8	63.6	31.6	68.3	—
	9.2	17.6	54.8	96.8	71.3	27.9	68.7	—
	10.0	17.9	61.2	83.3	68.6	27.9	68.9	—
Unknown location 2 (Norway)	4.5	16.6	34.6	142.5	22.8	18.9	40.3	—
	6.0	17.9	42.7	119.0	29.0	17.2	44.3	—
	7.5	14.6	52.3	123.5	25.8	19.8	41.1	—
	8.0	11.4	54.6	130.1	24.8	20.7	41.3	—
Vaterland (Norway)	7.5	24.4	52.0	52.0	47.0	27.0	40.0	5.0
Bäckebol (Sweden)	9.1	18.2	55.4	81.8	87.1	32.1	74.7	15.0
	11.1	26.6	66.6	75.1	85.6	37.3	94.9	24.0
	13.1	32.1	78.7	84.1	86.1	39.9	89.2	—
	14.1	33.2	84.7	226.6	89.7	38.4	93.3	—
	15.1	34.3	91.6	177.0	89.2	38.4	92.8	—
	4.0	17.7	26.7	36.1	85.8	25.3	78.4	11.0
	6.0	16.3	36.4	44.5	84.7	31.1	103.1	32.0
	7.0	16.5	41.5	51.6	83.0	35.1	88.1	28.0
Göta Älv (Sweden)	2.6	12.7	20.5	45.6	76.5	33.2	85.3	—
	3.0	13.4	23.1	42.7	75.8	33.9	84.4	—
	3.5	13.1	26.1	41.8	75.2	34.2	83.4	—
	3.9	13.1	28.2	53.0	72.7	34.6	82.4	—
	4.5	12.8	32.0	47.1	70.3	35.2	83.0	—
	5.0	12.7	34.4	53.6	78.8	35.9	92.2	—
	5.5	12.5	37.3	60.1	82.1	35.9	98.1	—
	5.9	12.5	39.4	69.0	75.8	33.2	93.8	—
	6.9	12.6	46.2	63.4	69.6	32.6	83.4	—
	7.9	13.3	51.8	65.4	65.7	31.3	79.4	—
	8.9	14.7	56.9	63.4	78.1	35.5	83.0	—
Järva Krog (Sweden)	5.0	18.6	48.8	72.0	88.1	37.7	93.2	26.0
	7.0	21.1	61.7	69.5	51.4	24.4	57.5	20.0
	9.0	25.8	74.4	79.5	50.4	23.9	62.6	23.0
Kalix (Sweden)	2.0	13.5	15.0	40.1	201.8	73.9	180.1	17.0
	3.0	14.8	16.5	31.8	191.3	70.4	176.0	15.0
	5.0	15.8	23.2	37.8	157.8	61.0	136.1	10.0
Lilla Mellösa (Sweden)	2.1	8.7	14.9	20.9	129.7	47.5	130.8	—
	2.8	8.4	18.4	21.1	129.7	47.0	122.6	—
	3.6	8.6	21.8	25.3	124.2	43.7	114.9	—
	4.2	9.4	24.7	28.5	119.3	41.0	111.1	—
	5.0	10.3	28.3	32.6	110.0	38.2	108.3	—
	5.7	10.8	31.9	35.9	105.1	36.0	100.7	—
	6.4	11.2	35.2	40.2	100.7	31.7	97.4	—
	7.1	12.1	39.2	45.1	93.0	30.0	95.2	—
	7.9	13.2	43.4	49.9	84.8	27.3	83.1	—
	8.5	14.2	47.0	54.3	82.1	26.2	82.6	—
	9.0	17.0	50.0	65.0	76.0	25.0	69.9	17.5
	9.1	15.3	50.5	58.4	78.8	25.1	78.2	—
	9.9	17.4	55.3	64.4	73.8	22.3	72.2	—
	10.7	18.4	61.2	71.5	71.1	23.4	71.1	—
	11.5	18.6	67.5	79.1	73.3	22.3	74.4	—
	12.4	18.6	74.8	86.7	73.3	22.9	83.1	—
Munkedal (Sweden)	3.2	25.0	37.7	126.6	65.1	31.3	98.9	—
	4.1	22.7	45.4	105.0	64.0	31.0	97.0	—
	6.1	31.6	63.5	102.9	61.6	30.4	92.7	—
	7.2	22.1	73.3	122.8	60.3	30.1	90.4	—
	8.1	22.7	82.2	135.5	59.2	29.8	88.5	—
	9.2	29.2	91.9	132.9	57.9	29.5	86.3	—
	10.1	30.9	100.3	143.5	56.7	29.2	84.2	—
	12.2	28.7	120.7	149.8	54.1	28.5	79.7	—
	16.2	33.5	160.4	184.5	49.3	27.3	71.2	—
	17.1	34.4	169.7	215.4	48.1	27.0	69.2	—
	21.2	31.5	212.9	240.8	43.1	25.8	60.4	—
Nörrkaping (Sweden)	2.1	10.9	27.5	42.8	82.0	35.5	85.0	—
	2.9	10.0	31.2	42.8	83.0	35.8	120.0	—
	3.4	10.3	33.9	43.8	79.0	34.8	115.0	—
	4.1	10.6	37.5	45.8	75.0	33.8	110.0	—
	4.7	11.2	40.2	48.5	60.0	30.0	85.0	—
	5.3	12.0	43.1	50.8	65.0	31.3	77.0	—
	5.9	13.1	45.8	54.4	70.0	32.5	70.0	—
	6.6	14.3	49.5	59.1	71.0	32.8	82.0	—
	7.3	15.6	52.4	64.7	72.0	33.0	95.0	—
	7.8	16.1	55.1	69.4	71.0	32.8	90.0	—
	8.6	16.5	59.1	78.3	70.0	32.5	85.0	—
	9.4	16.7	64.1	89.6	60.0	30.0	65.0	—
	10.3	16.9	69.0	101.6	70.0	32.5	72.0	—
	11.1	16.9	74.7	113.5	35.0	23.8	40.0	—
	12.0	17.0	80.3	125.8	40.0	25.0	40.0	—
	12.9	17.5	86.0	136.1	40.0	25.0	40.0	—

Table A2 (*concluded*).

Location	Depth (m)	s_u^{FV} (kPa)	σ'_v (kPa)	σ'_p (kPa)	LL (%)	PL (%)	w (%)	S_t
Skå-Edeby (Sweden)	10.0	15.6	60.0	84.0	51.0	23.0	63.0	20.0
	2.0	11.1	12.5	24.1	126.1	58.5	122.5	8.0
	4.0	6.9	21.0	24.9	66.4	30.2	95.9	18.0
	6.0	10.5	31.5	38.1	51.3	24.1	71.8	14.0
	8.0	13.8	44.7	40.1	55.5	26.6	73.0	23.0
	9.9	15.0	59.1	59.5	50.7	24.1	64.6	21.0
Stora an (Sweden)	1.5	10.2	10.4	43.8	113.8	40.0	107.8	—
	2.0	8.9	11.3	26.0	115.3	40.7	109.3	—
	2.3	8.2	11.9	24.0	125.0	54.2	122.8	—
	3.1	7.2	14.0	18.7	118.3	42.2	117.5	—
	3.8	7.1	16.4	20.2	123.5	37.7	113.8	—
	4.6	9.0	19.6	28.9	104.1	46.0	107.1	—
	5.3	11.3	22.8	31.7	104.9	41.5	103.4	—
Svartiolandet (Sweden)	2.0	8.8	14.0	36.0	92.5	32.4	91.3	—
	2.5	8.5	16.2	33.1	81.2	27.6	87.7	—
	3.0	8.4	18.4	31.6	76.4	24.6	80.6	—
	3.7	8.3	22.1	31.6	70.5	26.4	78.8	—
	4.3	8.2	25.0	32.4	68.7	26.4	78.8	—
	4.9	8.5	28.3	34.9	67.5	27.0	78.8	—
	5.5	9.3	32.0	37.9	58.0	24.0	74.6	—
	6.0	9.7	36.0	41.2	53.2	20.5	65.7	—
	6.4	10.3	37.9	43.4	51.4	20.5	65.1	—
	6.8	11.0	40.1	46.3	49.6	19.3	63.9	—
	7.3	11.9	43.4	51.1	49.6	19.3	63.9	—
	7.9	13.0	46.3	55.5	49.6	21.0	62.1	—
	8.5	13.7	50.4	60.7	49.6	21.0	60.9	—
	9.0	14.6	54.4	65.4	49.0	19.3	59.7	—
	9.6	15.5	58.1	71.3	49.0	19.9	58.0	—
	10.3	16.8	62.5	76.8	51.4	19.3	57.4	—
Tuve (Sweden)	2.1	5.9	6.9	16.7	110.0	40.0	121.0	—
	3.1	6.7	9.2	15.2	105.0	40.0	115.5	—
	4.0	7.7	12.0	22.1	100.0	40.0	110.0	—
	5.0	8.7	14.7	25.5	100.0	40.0	110.0	—
	6.0	9.5	17.4	27.5	95.0	40.0	104.5	—
	7.0	10.4	20.5	47.1	75.0	30.0	82.5	—
	7.9	13.2	23.5	45.1	83.0	30.0	91.3	—
	8.9	15.8	26.9	55.9	95.0	30.0	104.5	—
	10.0	19.2	30.4	54.9	87.0	30.0	95.7	—
	11.0	19.9	33.8	61.3	86.0	30.0	94.6	—
	11.5	20.4	35.5	63.2	85.0	30.0	93.5	—
	12.1	21.0	38.2	66.2	85.0	30.0	93.5	—
	12.6	21.4	39.5	68.1	84.0	30.0	92.4	—
	13.2	22.2	41.6	70.6	83.0	30.0	91.3	—
Ursvik (Sweden)	2.0	5.6	11.3	29.6	47.9	18.5	57.5	14.0
	4.0	6.9	20.2	49.4	49.2	21.7	97.8	18.0
	5.0	7.2	25.7	50.2	40.3	14.7	60.1	22.0
	6.0	9.0	31.9	62.3	49.9	21.7	59.5	27.0
	6.9	11.7	38.1	55.6	47.3	21.1	55.0	26.0
	8.0	11.2	44.7	91.8	47.3	21.7	51.8	26.0
	10.0	16.1	58.4	100.8	44.7	19.2	53.1	17.0