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ORIGINAL PAPER

On Empirical Correlations for Normalised Shear Strengths from Fall Cone and Direct Simple Shear Tests in Soft Swedish Clays

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Abstract Empirical correlations provide valuable information in early design stages, and they help to validate or discard single values from site investigations. This paper presents a multivariate database from commercial projects consisting of evaluated shear strengths obtained from direct simple shear tests and fall cone tests (which are calibrated to the field vane test), including index tests. The multivariate database is used to investigate the performance of common transformation models and to test the recommended correction for fall cone tests. It is found that the measured normalised shear strength evaluated from direct simple shear tests and fall cone tests is correlated to the liquid limit and that the results conform to Swedish and Norwegian recommendations. However, the scatter is large, more for fall cone tests than for direct simple shear tests, which is thought to depend mainly on sample disturbance. It can however be concluded that the trend of normalised shear strengths increases with increasing plasticity.

Keywords Undrained shear strength · Fall cone tests · Direct simple shear tests · Empirical correlations

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1 Introduction

Soft clays are challenging because of their low undrained shear strength (s_u) and high compressibility. In geotechnical designs, it is therefore important to carefully evaluate s_u to obtain a reliable safety level. However, in engineering practice, the quantity and quality of site investigations may not always be as desired, and thus, empirical correlations are commonly used in cases where s_u is not measured directly (i.e. when evaluated using representative measurements through a transformation model), or when measurements are considered unreliable. Transformation models are commonly based on the correlation between s_u and the preconsolidation pressure (σ'_p) (Hansbo 1957; Mesri 1975; Larsson 1980; Jamiolkowski et al. 1985). These correlations may give valuable input in early design stages when specific

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field and laboratory investigations have not yet been performed, and may be used to validate or discard measurements in subsequent design stages.

Recently, D'Ignazio et al. (2016) and the following discussion between Mesri and Wang (2017) and D'Ignazio et al. (2017), have provided additional knowledge on this subject. One of the important findings by D'Ignazio et al. (2016) is that the correlation between s_u, which was obtained by field vane (FV) tests ($s_u^{FV}(\text{mob})$), and σ'_p, which was obtained from incremental or constant rate of strain (CRS) oedometer tests, are independent of the soils plasticity, i.e. the plasticity index (PI) or liquid limit (LL). Their findings are similar to that obtained by Karlsson and Viberg (1967), who also studied FV tests, as well as Mesri (1975, 1989), Ching and Phoon (2014), among others, who studied a variety of different in situ and laboratory tests. However, throughout history, several studies have shown the opposite, i.e. that the normalised s_u (s_u/σ'_p) increases with increasing plasticity, e.g. Larsson (1980), which questioned the $s_u/\sigma'_p \approx 0.22$(Mesri 1975) correlation based on the results obtained from direct simple shear (DSS) tests, from which s_u was validated by the shear stress at failure in a number of reported failures. Larsson's conclusion was that the quotient s_u/σ'_p was constant for the active shear condition, but it instead increased with increasing plasticity for direct and passive shear strengths, in line with other reported studies, such as Skempton (1954), Hansbo (1957), Leroueil et al. (1983), Jamiolkowski et al. (1985), Jardine and Hight (1987) and Mayne and Mitchell (1988).

Transformation models which are commonly used to determine s_u for clays in the Nordic countries were tested by D'Ignazio et al. (2016) using a multivariate database which included FV data points. This paper presents additional data on the s_u value obtained from a large number of fall cone (FC) tests (s_u^{FC} and corrected $s_u^{FC}(\text{mob})$), and DSS tests (s_u^{DSS}) in soft Swedish clays. The multivariate database also includes the index parameter LL, and σ'_p evaluated from CRS oedometer tests. All the data is collected from commercial projects and will hence also give valuable input on the status of commercial soil investigation quality, especially in Sweden. The FC test is used as a standard routine test in Sweden, and it is therefore valuable to understand how its evaluated s_u corresponds to the σ'_p obtained from CRS oedometer tests and index parameters (PI and LL). The FC test is generally considered to give uncertain values (the typical scatter is large), and DSS, and/or triaxial tests, are therefore preferred. However, these more advanced tests are done in a limited number of commercial projects, and it is hence important to determine the degree of confidence which can be assigned to the value of s_u which is evaluated from the FC test, and on the applied transformation model. To date, there have been few studies on normalised s_u from FC tests.

The objectives of this paper are: (i) to test common transformation models for the relationships LL – $\left(s_u^{DSS}/\sigma'_p\right)$ and LL – $\left(s_u(\text{mob})/\sigma'_p\right)$, based on 91 values of s_u^{DSS}/σ'_p vs. LL and 313 values of s_u^{FC}/σ'_p vs. LL, and (ii) to test the recommended correction of FC-tests with respect to LL, given the plotted values of s_u^{DSS}/s_u^{FC} vs. LL.

2 Background of Applied Transformation Models

Since the early 1920s, the FC test has been applied in Nordic countries for the estimation of s_u (Olsson 1921). Initially, the test was calibrated to s_u from different types of laboratory shear tests as well as back calculations of large-scale pile tests and embankment failures (Lundin 2000; Larsson et al. 2007). Cadling and Odenstad (1950) performed extensive research on the FV test, after which FV tests became an important and frequently used test for measuring the in-situ s_u, primarily because of its simple and logic mathematical evaluation based on a cylindrical failure mode around the vane, in addition to its avoidance of any potential sampling disturbance. In an attempt to improve the evaluation of the FC test, Hansbo (1957) performed a detailed theoretical and empirical study, and re-calibrated the FC test so that s_u would correspond to that of the FV test. At this time, it was recognised that the shear strengths obtained from the FV test (s_u^{FV}), and hence the FC test (s_u^{FC}), had to be corrected with respect to plasticity using a correction factor (μ) (Eq. (1)) in order to obtain the mobilised undrained shear strength, $s_u(\text{mob})$ (Swedish Geotechnical Institute 1969; Bjerrum 1972). The current recommended μ for normally or slightly over-consolidated clays in

Sweden is presented in Eq. (2) (Larsson et al. 1987, 2007).

$$s_u^{FV,FC}(\mathrm{mob}) \approx \mu s_u^{FV,FC} \tag{1}$$

$$\mu = \left(\frac{0.43}{\mathrm{LL}}\right)^{0.45} \tag{2}$$

The derivation of μ (the Swedish recommendation) is mainly based on a comparison of mean values of s_u^{FV} and s_u^{FC} with the mobilised shear stress in a number of reported failures, and it is validated by mean values of s_u evaluated from DSS tests (Larsson et al. 1987, 2007). Hence, $s_u^{FV,FC}(\mathrm{mob})$ is a function of the failure mode, stress state and strain-rate effects, and includes the uncertainty from slope-stability calculation models. In addition, for the FC test, the evaluation is also dependent on the degree of sample disturbance.

The Swedish recommendation for μ (Eq. (2)) is approximately 7–10% lower than the corresponding Finnish correction used in D'Ignazio et al. (2016). The $s_u^{FV,FC}(\mathrm{mob})$ value is reduced for clays with LL>43% in Sweden, and $> 50\%$ in Finland. Both are comparable with the correction factor used by Bjerrum (1972, 1973); however, Bjerrum used PI instead of LL.

Hansbo (1957) compiled measurements ofs_u^{FV}, which he normalised with respect to in-situ vertical effective stresses (σ_v'), and proposed that it is directly proportional to LL (Eq. (3)). Subsequently, it was assumed that the correlation was also valid for the case when s_u^{FV} and s_u^{FC} are normalised with σ_p', which is the typical way in which Hansbo's correlation is presented today. Hansbo's relation is based on FV measurements on typical Swedish clays and on Norwegian clays reported by Bjerrum (1954).

$$\frac{s_u^{FV,FC}}{\sigma_v'} \approx 0.45\mathrm{LL} \tag{3}$$

Larsson (1980) reported that the typical scatter for s_u^{FV} evaluated from Eq. (3) for Swedish clays is $\pm 20\%$, but can be as much as $\pm 50\%$. Nevertheless, Hansbo's correlation is commonly considered valuable because the results from FV and FC tests (s_u^{FV} and s_u^{FC}) should mainly agree with Eq. (3) to yield appropriate values of $s_u^{FV,FC}(\mathrm{mob})$ for clays in the Nordic countries.

Notably, Mesri (1975) opposed a correlation between s_u and the plasticity, and proposed that $s_u(\mathrm{mob})$ is directly proportional to σ_p' (Eq. (4)), while Larsson (1980) and Larsson et al. (1987, 2007) asserted that Eq. (4) overestimates s_u in low-plastic clays and underestimates s_u in high-plastic clays.

$$\frac{s_u(\mathrm{mob})}{\sigma_p'} \approx 0.22 \tag{4}$$

It should be noted that $s_u^{FV,FC}(\mathrm{mob})$ in Eq. (1) and $s_u(\mathrm{mob})$ in Eq. (4) should correspond approximately to s_u^{DSS}.

The current recommendation in Sweden is based on the research by Larsson (1980) and Larsson et al. (1987, 2007), and is given in the form of the stress history and normalised soil engineering properties (SHANSEP) framework (Eq. (5)).

$$\frac{s_u}{\sigma_v'} = \alpha \mathrm{OCR}^m, \tag{5}$$

where m and α are constants which are dependent on the material and type of soil test. The constant $m \approx 0.8$ and α are estimated differently for the three cases: active shear, direct shear and passive shear. For active triaxial tests, the active undrained shear strength (s_u^A) is assumed independent of the plasticity, and $\alpha \approx 0.33$. For the direct shear, Eq. (5) can be expressed by Eq. (6) (Larsson et al. 2007).

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

For normally consolidated soils which have an OCR value less than approximately 1.2–1.3, Eqs. (5) and (6) can be simplified to $s_u/\sigma_p' = \alpha$. According to Larsson et al. (2007), the shear strengths obtained from FC, FV and DSS tests are similar for Swedish clays, and the above recommendation (Eq. (6)) is therefore assumed valid for all these tests. The Larsson et al. (2007) correlation is almost identical with Hansbo (1957) for corrected values.

The current recommendations in Norway, e.g. Thakur et al. (2016, 2017), are based on a large body of data obtained for high-quality block samples presented in e.g. Karlsrud and Hernandez-Martinez (2013). In agreement with Larsson et al. (1987, 2007), they conclude that s_u^{DSS}/σ_p' is a function of the soil's plasticity, and indicates that there is a relationship between the anisotropy ratio s_u^{DSS}/s_u^A and PI (Eq. (7)), which is valid for clays with a PI value above 10% (Thakur et al. 2017). Notably, the Norwegian recommendation for s_u^A/σ'_p (given in the SHANSEP framework, Eq. (5)) is independent of the plasticity. Thus, reformulating Eq. (5) into an expression of s_u^A, and inserting it into Eq. (7), gives a model for the relationship PI $-\left(s_u^{DSS}/\sigma'_p\right)$ (Eq. (8)). Using the relationship LL $\approx 15 + 1.4$PI given in Christensen (2014), Eq. (8) may be re-calculated as a function of LL (Eq. (9)).

$$\frac{s_u^{DSS}}{s_u^A} \approx 0.63 + 0.00425(\mathrm{PI} - 10) \tag{7}$$

$$\frac{s_u^{DSS}}{\sigma'_p} \approx [0.63 + 0.00425(\mathrm{PI} - 10)]\alpha \mathrm{OCR}^{-(1-m)} \tag{8}$$

$$\frac{s_u^{DSS}}{\sigma'_p} \approx (0.541 + 0.003036\mathrm{LL})\alpha \mathrm{OCR}^{-(1-m)} \tag{9}$$

Based on the block sample database (Karlsrud and Hernandez-Martinez 2013), the values for an active shear of m varies between 0.65 and 0.75, showing a higher dependency on OCR compared to the Swedish research, and α is between 0.25 and 0.35 (Thakur et al. 2016). From this, it can be seen that the Norwegian and Swedish recommendations follow the same trend, as shown in Fig. 1. The data compiled by Christensen (2014) also shows that s_u^{FV} and s_u^{DSS} are similar for Norwegian clays with PI values exceeding 25–30%, i.e. an LL value above $\sim$ 50%.

3 Multivariate Database

The multivariate clay database consists of 313 data points from sites which are mainly located in south-eastern Sweden. Each data point contains the multivariate information: s_u^{FC}, LL, σ'_p, and σ'_v, which enables the evaluation of OCR. σ'_v is estimated based on the assumption of hydrostatic conditions, which is typical in the deposits and sites used to compile the database. Still, this can be a source of error affecting σ'_p, and σ'_v. Of all data points, 91 contain additional information on s_u^{DSS}. The basic statistics are summarised in Table 1. All samples were taken with the Swedish standard 50-mm piston sampler (Kallstenius 1963). Natural water contents (w) are normally relatively close to LL. The sensitivity varies between 10 and 20, but with single values up to 50. All tests were performed and evaluated according to the Swedish standards. The evaluation of the FC tests was done according to Hansbo (1957). The DSS test was performed using a strain rate of approximately 0.6%/h, and s_u^{DSS} was taken as the peak shear stress or the shear stress at approximately 15% if no peak was obtained. CRS tests were performed with a strain rate of 0.75%/h, and the evaluation of σ'_p was done according to Sällfors (1975).

4 Methodology

The analysed relationships in (i) and (ii) (Table 2) are evaluated based on regression analysis in accordance with the methodology proposed by Ching and Phoon (2014) (Eq. (10)).

$$\varepsilon = \frac{(\text{Actual target value})}{(\text{Unbiased prediction})} = \frac{(\text{Actual target value})}{(b \times \text{Predicted target value})} \tag{10}$$

The term ε is the variability of the scatter of the transformation model and has a mean = 1 and COV = δ. As noted by D'Ignazio et al. (2016), δ=0 implies that there is no scatter about the transformation model, indicating that the prediction is deterministic rather than uncertain. Furthermore, the term b is a bias factor, and represents the difference between the unbiased prediction and the predicted target value. Accordingly, for example, comparing values of $s_u^{FC}(\mathrm{mob})/\sigma'_p$ vs. LL, with the transformation model proposed by Mesri (1975) (Eq. (4)), they represent the unbiased prediction and the predicted target value, respectively.

Notably, when $s_u^{FC}(\mathrm{mob})$ is calculated using Eqs. (1) and (2), the relationship LL $-\left(s_u^{FC}(\mathrm{mob})/\sigma'_p\right)$ includes an LL-dependency in $s_u^{FC}(\mathrm{mob})$ through μ which is nonlinear. A comparison of a linear regression line which is estimated based on values of $s_u^{FC}(\mathrm{mob})/\sigma'_p$ with common transformation models for $s_u(\mathrm{mob})$ and s_u^{DSS} would therefore result in statistical artefacts inherited from μ. Because of this, s_u^{FC} (the uncorrected values) is compared with the transformation models proposed by Mesri (1975), Larsson et al. (2007) and Thakur et al. (2016) by normalising them with respect to μ in Fig. 2.

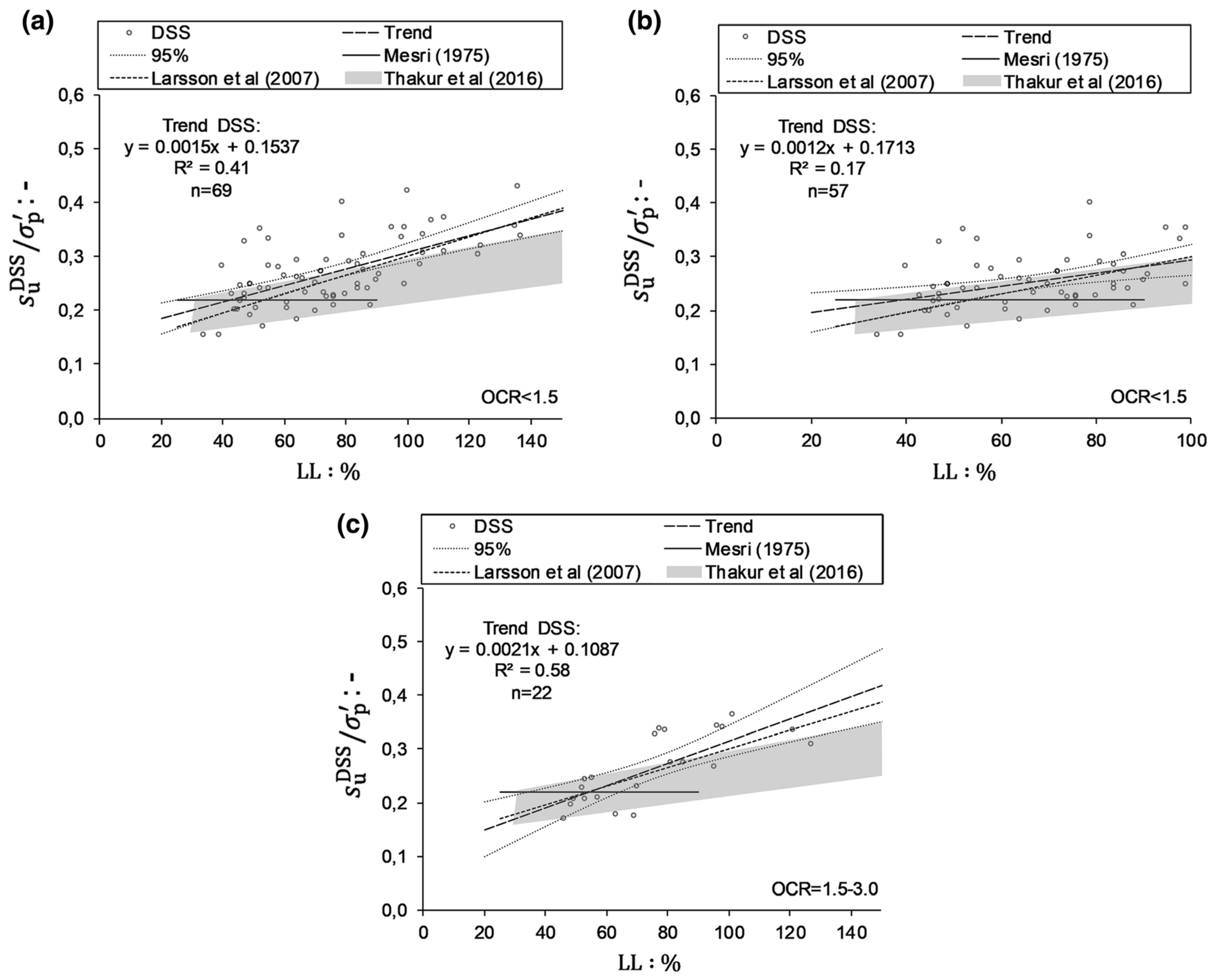

Fig. 1 Normalised shear strength from DSS: **a** for samples with LL between 30 and 150% (OCR = 1.0–1,5); **b** for samples with LL between 30 and 100% (OCR = 1.0–1.5); **c** for samples with LL between 30 and 150% (OCR = 1.5–3.0)

Table 1 Basic statistics of the parameters in the multivariate database

Variable	n	Mean	Max	Min
s_u^{FC}(kPa)	313	19.58	70	5
s_u^{DSS}(kPa)	91	15.65	29.5	6
σ_p(kPa)	313	79.81	401	13
OCR(-)	313	1.33	2.75	1.0
LL(%)	313	62.48	145	22

Two separate analyses have been performed with OCR = 1.0–1.5, i.e. normally to slightly over-consolidated clays, and OCR = 1.5–3.0, i.e. over-consolidated clays to account for differences in over-consolidation effects. No data points with OCR > 3.0 have been analysed.

The comparison of data with common transformation models and evaluation of significant trends in the presented data is performed with respect to a 95% confidence interval of the mean value. The variance has been determined from the sample values based on Ang and Tang (2007) (page. 373) and the parabolic expression of the confidence interval is given from the uncertainty in the inclination of the trend line, as per the example of Tang (1980).

Table 2 Results from calibration analysis of transformation models, for OCR between 1.0 and 1.5

Relationship	Literature	n	Transformation model	Comparison to database		Figure
				Bias factor, b	COV of ε, δ	
$LL - s_u^{DSS}/\sigma'_p$	Mesri (1975)	69	0.22	1.22	0.23	1a
($30\% < LL < 150\%$)	Larsson et al. (2007)	69	$0.125 + 0.205LL/1.17$	1.05	0.19	1a
	Thakur et al. (2016)	69	$(0.541 + 0.003036LL)0.3$ [a]	1.16	0.18	1a
$LL - s_u^{DSS}/\sigma'_p$	Mesri (1975)	57	0.22	1.15	0.20	1b
($30\% < LL < 100\%$)	Larsson et al. (2007)	57	$0.125 + 0.205LL/1.17$	1.05	0.19	1b
	Thakur et al. (2016)	57	$(0.541 + 0.003036LL)0.3$ [a]	1.13	0.19	1b
$LL - s_u^{FC}/\sigma'_p$	Mesri (1975)	213	$0.22/\mu$ [b]	1.09	0.31	2a
($30\% < LL < 150\%$)	Larsson et al. (2007)	213	$(0.125 + 0.205LL/1.17)/\mu$ [b]	1.04	0.30	2a
	Thakur et al. (2016)	213	$(0.541 + 0.003036LL)0.3/\mu$ [b]	1.09	0.29	2a
$LL - s_u^{FC}/\sigma'_p$	Mesri (1975)	195	$0.22/\mu$ [b]	1.04	0.29	2b
($30\% < LL < 100\%$)	Larsson et al. (2007)	195	$(0.125 + 0.205LL/1.17)/\mu$ [b]	1.04	0.31	2b
	Thakur et al. (2016)	195	$(0.541 + 0.003036LL)0.3/\mu$ [b]	1.08	0.30	2b

[a] The Norwegian recommendations are presented for the interval given by $\alpha = 0.25 - 0.35$. The relationships were evaluated for the transformation model given by the mean $\alpha = 0.30$

[b] Normalised with respect to μ

5 Results

5.1 Normalised Shear Strengths Obtained from DSS- and FC-Tests

The derivation of $s_u^{FV,FC}(\mathrm{mob})$ through Eq. (1) is mainly based on a comparison of mean values of s_u^{FV} and s_u^{FC} with the mobilised shear stress in a number of reported failures, and is validated by mean values of s_u which are evaluated from triaxial tests and DSS tests (Larsson et al. 2007). In Fig. 1a, b, common transformation models are compared with plotted values on the measured normalised s_u^{DSS} (i.e. s_u^{DSS}/σ'_p) vs. LL for OCR = 1.0–1.5, and Fig. 1c shows s_u^{DSS}/σ'_p vs. LL for OCR = 1.5–3.0. Figure 1a shows s_u^{DSS}/σ'_p for samples with LL values between 30 and 150%, and Fig. 1b shows the corresponding plot for samples with LL values between 30 and 100%. This distinction is motivated by the fact that in Sweden, clays with $LL > 90–100\%$ are commonly interpreted as organic clays, and should be considered separately. In Fig. 1a–c, s_u^{DSS}/σ'_p exhibits an increase with increasing LL, and the transformation model proposed by Larsson et al. (2007) is located within the 95% confidence interval evaluated for the trend for both OCR = 1.0–1.5 and OCR = 1.5–3.0. According to the comparison method proposed by Ching and Phoon (2014) (Table 2), Larsson et al. (2007) has a bias factor (b) of 1.05/1.05 (Fig. 1a, b), while the transformation model proposed by Mesri (1975) and Thakur et al. (2016) have bias factors of 1.22/1.15 and 1.16/1.13, respectively.

The interval proposed by Thakur et al. (2016) is too low for $LL > 100\%$ for these types of clays. Furthermore, it should be noted that according to Mesri (1975), the correlation is only valid for LL values between $\sim 30\%$ and $\sim 90\%$, i.e. mainly inorganic clays.

Figure 2a–c presents a comparison between the measured normalised s_u^{FC} (i.e. s_u^{FC}/σ'_p) and common transformation models for the relationship $LL - \left(s_u(\mathrm{mob})/\sigma'_p\right)$, which are normalised with respect to μ. As previously noted, this normalisation is made in order to eliminate statistical artefacts in the comparison of regression lines. In both Fig. 2a, b, i.e. OCR = 1.0–1.5, s_u^{FC}/σ'_p displays a significant increase with increasing LL. Figure 3, for comparison, presents the data in Fig. 2a without the normalisation with respect to μ. In Fig. 2b, the transformation model

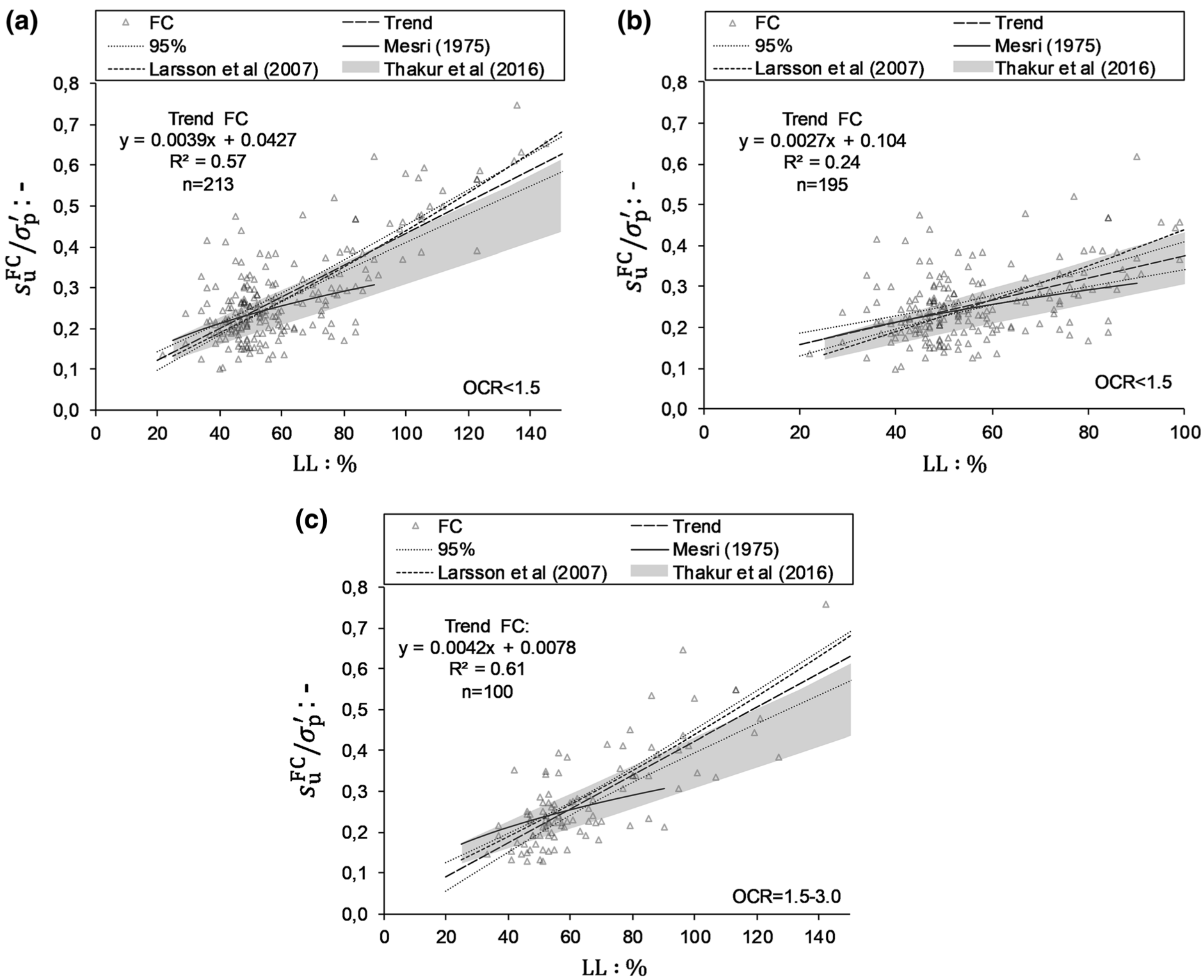

Fig. 2 Normalised shear strength from FC (uncorrected): **a** for samples with LL between 30 and 150% (OCR = 1.0–1,5); **b** for samples with LL between 30 and 100% (OCR = 1.0–1.5); **c** for samples with LL between 30 and 150% (OCR = 1.5–3.0)

proposed by Mesri (1975) is located mainly within the 95% confidence interval evaluated for the trend up to LL ≈ 70%, and the interval proposed by Thakur et al. (2016) agrees well over the evaluated confidence interval. The same tendencies can be seen in Fig. 2c for OCR = 1.5–3.0; however, the Mesri (1975) correlation is too high for LL < 40%. According to the comparison method proposed by Ching and Phoon (2014) (Table 2), the transformation model proposed by Mesri (1975) has a bias factor (*b*) of 1.09/1.04 (Fig. 2a, b), while the transformation models proposed by Larsson et al. (2007) and Thakur et al. (2016) have bias factors of 1.04/1.04 and 1.09/1.08, respectively.

5.2 Correction factor

Figure 4a–c presents a comparison between the quotient s_u^{DSS}/s_u^{FC}, with uncorrected FC values, and the correction factor μ proposed by Larsson et al. (2007). Figure 4a shows s_u^{DSS}/s_u^{FC} for samples with LL values between 30 and 150%, and Fig. 4b shows the corresponding plots for samples with LL values between 30 and 100%. Considering that there is a very weak correlation between s_u^{DSS} and LL, which may be fitted to the transformation model proposed by Larsson et al. (2007) with a 95% confidence interval (Fig. 1), a comparison of the evaluated trend lines for the quotient s_u^{DSS}/s_u^{FC} show that μ is questionably low for LL values between 50 and 100%. Notably, clays

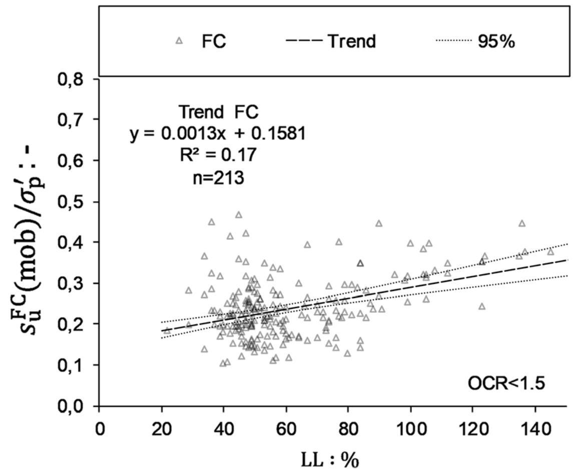

Fig. 3 Normalised shear strength from FC (corrected) for samples with LL between 30 and 150% (OCR = 1.0–1.5)

with LL > 100% are commonly interpreted as organic clays. For these values of LL, the correction by μ is in relatively good agreement with the scatter of evaluated values on s_u^{DSS}/s_u^{FC}.

Figure 4c presents s_u^{DSS}/s_u^{FC} for samples with LL ranging between 50 and 90%. Clays with LL < 50% and LL > 100% are relatively common; however, the presented interval is representative of a significant proportion of clays in Sweden. A constant value of $s_u^{DSS}/s_u^{FC} = 1$ for LL = 50–90% may be fitted within the 95% confidence interval for the trend.

6 Discussion

Both s_u^{DSS}/σ'_p and s_u^{FC}/σ'_p display a very weak correlation to LL (Figs. 1, 2), however, the trend is significant with respect to the 95% confidence interval for the mean value, showing that both s_u^{DSS}/σ'_p and s_u^{FC}/σ'_p increases with increasing LL. There is a significant scatter about the regression lines, especially for the s_u^{FC}/σ'_p values, which indicates that the data are affected by sampling disturbance and measurement errors. Sampling disturbance will in various degrees alter the clay's structure, both the 'sedimentation' and 'post-sedimentation' structure as described by Cotecchia and Chandler (2000), which in turn affects the strength and deformation properties. Nevertheless, collecting a large number of data values, trends can be found even if the data displays a large scatter. Based on the authors' experience, and as reported by e.g. DeGroot et al. (2010), index tests such as the FC test are more prone to sampling disturbances, and will hence affect the FC tests more than the DSS tests. Sample disturbances increase the scatter, but will also generally be shown as a decrease in shear strength. The main reason for this is the reconsolidation to in situ stresses in the DSS test, which normally remediates some of the disturbance effects, e.g. Lacasse et al. (1985). This study shows that s_u^{DSS} values are generally higher than those of $s_u^{FC}(\mathrm{mob})$ (Fig. 4), especially for low-plastic clays, which are known to be more susceptible to sampling disturbances compared with higher-plastic homogenous clays. This is also the case for undrained shear strengths above 10–15 kPa and/or depths exceeding 10–12 m. This indicates that $s_u^{FC}(\mathrm{mob})$ are underestimated in most cases, especially for low values of LL. This is also true for samples containing silt and sand layers. Nevertheless, according to Sällfors and Larsson (2016), high-quality sampling and a short time from sampling to testing can give representative values of $s_u^{FC}(\mathrm{mob})$, even at great depths. However, the data presented here were collected from commercial projects, and there is no way of verifying that all samples were carefully stored, while the time from sampling to testing also varies.

An analysis of sample quality for the CRS tests, e.g. according to Lunne et al. (1997), has not been performed as the data was not available. The suggested criteria in Lunne et al. (1997) is also based on clays having a relatively low clay content, very low organic content and very high sensitivity, and hence not necessarily applicable to East Swedish clays. For these types of clays, the strain to in situ effective stresses do not deviate much from appr. 1.5–3.5% axial strain in almost all tests which are taken with the same type of sampler. The Authors' experience is that the quality criteria given in e.g. Karlsrud and Hernandez-Martinez (2013) is more suitable for CRS-tests on these types of clays. The database does however not contain sufficient data for such an analysis to be done.

The results in D'Ignazio et al. (2016) indicate that there is not a significant correlation between $s_u^{FV}(\mathrm{mob})/\sigma'_p$ and LL, but there is also a significant scatter in the plotted $s_u^{FV}(\mathrm{mob})/\sigma'_p$ values. Notably, the FC test is calibrated to the FV test, and the observations in D'Ignazio et al. (2016) are therefore consistent

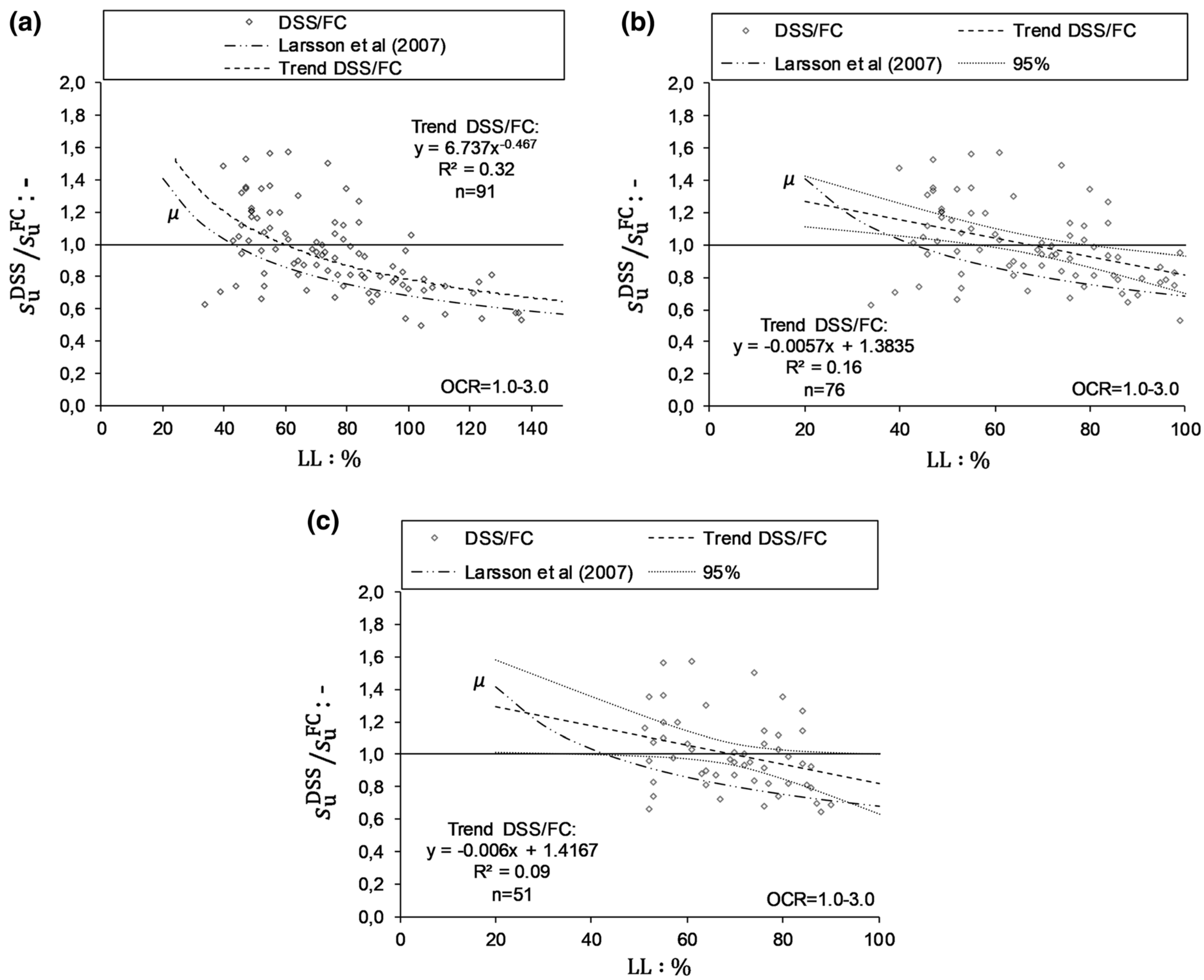

Fig. 4 Ratio of shear strength from DSS tests to uncorrected shear strengths from FC tests: **a** for samples with LL between 30 and 150%; **b** for samples with LL between 30 and 100%; **c** for samples with LL between 50 and 90%

with the results presented here in terms of the correlation between s_u^{FC}/σ'_p and LL for LL = 30–100% and OCR = 1.0–1.5 (Fig. 2). A large part of the scatter may be caused by measurement errors and natural variations in the soil properties. Hence, the FV and FC tests are simple methods that are typically associated with large measurement errors which may result from equipment, procedures, operators and random testing effects. The most significant errors are related to measurements of the torque of the actual vane at great depths and at relatively high strain rates. Errors may also be related to the disturbance of soil during penetration and before rotation of the vane, and the interpretation assumes that failures exist primarily on vertical planes. These are reasons, primarily the strain rate effects in soils, for which the FV test, including the FC test, needs to be corrected with the clay plasticity to obtain s_u(mob). Naturally, the correction factor, μ, which is based on the PI or LL, also includes various uncertainties, and thus, s_u^{FV}(mob) and s_u^{FC}(mob) typically display a larger scatter than *direct* methods, e.g. s_u^{DSS}.

Furthermore, for FC, FV and DSS tests, a part of the scatter can be explained by the natural variation in the water content, *w* and LL. Studies by Hov and Holmén (2018) on clays from south-eastern Sweden have shown that the LL may differ by 10 percentage points over a vertical distance of 100 mm, and the *w* may differ by as much as 5 percentage points over a vertical distance of 20 mm, this excluding any silt or sand layers which can show significantly larger variations. This will naturally create a scatter as the compared shear and oedometer tests are performed on different parts of the clay with slightly different values of *w* and LL.

The correlation given by Larsson et al. (2007) has the least bias factor (*b*) for the relationship LL – $\left(s_u^{DSS}/\sigma'_p\right)$ (Fig. 1 and Table 2), and for the relationship LL – $\left(s_u^{FC}(mob)/\sigma'_p\right)$ (Fig. 2 and Table 2) over the whole LL range, although Mesri (1975) has the same bias factor for the latter, i.e. 1.04, for LL values between 30 and 100% and OCR = 1.0–1.5. The results for LL – $\left(s_u^{DSS}/\sigma'_p\right)$ are consistent with the Swedish recommendations over the whole LL range, and also with Norwegian recommendations for inorganic clays, i.e. LL $<$ 100%, which both indicate a positive LL dependency. However, the results for LL – $\left(s_u^{FC}(mob)/\sigma'_p\right)$ for the LL interval of 30–100% and OCR = 1.0–1.5 do not show an LL dependency, Fig. 2b, i.e. they are consistent with Mesri (1975). As previously mentioned, a reason for this difference may be related to sample disturbance and measurement errors. The DSS test is typically considered a more reliable measurement of the representative shear strength value for most design situations. Apart from the fact that DSS tests do not have to be corrected with respect to the clay plasticity (avoiding many uncertainties and errors), the failure mode in a DSS test is relatively similar to the formation of slip surfaces in the direct shear zone. For example, the DSS test has proven to be a representative value of s_u in the design of full-scale embankments (Ladd and Foott 1974; Graham 1979; Trak et al. 1980; Jardine and Hight 1987; Larsson et al. 2007).

Furthermore, the reported values of s_u^{FC}/σ'_p have a larger scatter than s_u^{DSS}/σ'_p, and consequently, the evaluated uncertainty (δ) is greater for the correlations with $s_u^{FC}(mob)/\sigma'_p$ than with s_u^{DSS}/σ'_p (Table 2). Several data points for LL $<$ 100% lie above $s_u/\sigma'_p \approx 0.33$, which can be seen as a general upper bound for inorganic clays as these s_u/σ'_p values correspond to the normalised active shear strengths obtained from triaxial tests (Larsson 1980; Jamiolkowski et al. 1985; Mayne 1988). These values are thus not considered as representative of real soil behaviour, but may occur because softer or stiffer layers in the clay affect either the FC, DSS or CRS oedometer tests. A lower bound of around $s_u/\sigma'_p \approx 0.12$, which conforms to Larsson et al. (2007), can be observed.

Assuming that DSS tests give representative values for engineering purposes, the comparison between s_u^{FC} and s_u^{DSS} in Fig. 4 indicates that the correction (μ) may be somewhat high for the FC test performed on inorganic clays. For example, for samples with LL values between 50 and 90% (Fig. 4c), the quotient $s_u^{DSS}/s_u^{FC} = 1$ may be fitted within the confidence interval for the trend. However, as proposed by Sällfors and Larsson (2016), this may be an effect of the sample disturbance and measurement error. Based on these results, the use of the FC test to investigate the in situ shear strength for design purposes should be done with caution.

7 Conclusion

This study shows that there is a considerably larger scatter for normalised shear strength from FC tests than from DSS tests on soft Swedish clays. Notably, the DSS test is generally considered as a more reliable and representative method, and the results of LL – $\left(s_u^{DSS}/\sigma'_p\right)$ presented herein conform to Swedish and Norwegian recommendations. It can be concluded that the measured values of both s_u^{DSS}/σ'_p and s_u^{FC}/σ'_p increases with increasing LL, however the correlation is very weak.

The results from this study confirms that strength values from FC tests must always be used with care, and should consider the sample disturbance (including aging), measurement errors, and natural variations of the properties. It is vital that high quality samples are obtained. Furthermore, the approach of collecting and comparing data from different locations and with different geological history – thus comparing clays with varying engineering properties, stress history and anisotropy – is not always a rational procedure. Hence, it is unlikely that a global empirical correlation between σ'_p and s_u which is valid for all clays exist, and it is therefore the authors opinion that local empiricism should always be taken into account and that empirical correlations should at least be evaluated for certain intervals of the input parameter. However, the SHANSEP framework is thought to be a useful tool for empirical correlations in general. Specific advanced laboratory shear and oedometer tests should be performed on high-quality samples in detailed design work. However, empirical correlations has shown to be useful in the early design stages, and to validate or discard single values from site investigations.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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