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Uncertainties in modelling undrained shear strength of clays using Critical State Soil Mechanics and SHANSEP

M D'Ignazio[1,2], K K Phoon[3] and T T Länsivaara[1]

[1] Department of Civil Engineering, Tampere University, Korkeakoulunkatu 5, 33720, Tampere, Finland
[2] Ramboll Finland Oy, Pakkahuoneenaukio 2, 33100, Tampere, Finland
[3] Department of Civil and Environmental Engineering, National University of Singapore, 1 Engineering Drive 2 Block E1A #07-03, Singapore 117576

marco.dignazio@tuni.fi

Abstract. The determination of the undrained shear strength of clays relies upon the goodness of the available in-situ and laboratory tests. Often, limited soil investigation data is available, or the collected data may suffer of low quality associated with poor test execution or sampling operations. The use of reliable correlations can then play an important role in geotechnical design. In that perspective, it is vital to choose the most appropriate correlation models that are suitable with the local soil conditions and that are possibly characterized by low uncertainty. The SHANSEP empirical model describes the undrained shear strength of clays in terms of normalized properties, where the soil strength is defined by means of the overconsolidation ratio (OCR) and two material coefficients that require empirical calibration. The SHANSEP model can be further combined with analytical solutions based on Critical State Soil Mechanics (CSSM) in order to define the undrained shear strength as a function of two fundamental properties, such as the preconsolidation stress (or the OCR) and the friction angle at critical state. The paper deals with the uncertainties associated with modelling the undrained shear strength of clays using a hybrid CSSM-SHANSEP model. The performance of the model is assessed by comparing the predicted undrained shear strength to an existing multivariate database of field vane data points from Finland. For each data point, the friction angle is estimated indirectly from the plasticity index using a correlation in the literature, while the OCR is taken directly from the database. Bias and uncertainties of the CSSM-SHANSEP model associated with the multivariate database are evaluated. Finally, a sensitivity study on the model parameters is presented.

1. Introduction

The undrained or short-term shear strength (s_u) of clays acts as governing parameter in different geotechnical applications, including foundation bearing capacity and stability of slopes, embankments and excavations, among others. It can be evaluated from both in-situ, e.g. field vane (FV), piezocone (CPTU), and laboratory tests, e.g. triaxial, direct simple shear, fall cone. Furthermore, s_u is stress-path, rate as well as temperature dependent (e.g., [1],[2]). These are features that need to be accounted for in design when selecting the s_u that describes the anticipated deformation or failure mechanism under given geometries and loading conditions (e.g. [3],[4]).

Laboratory test results are usually affected by the quality of the retrieved samples ([5],[6]) and specimen handling prior to testing. Therefore, in presence of low sample quality, s_u may be severely

underestimated, which may result in costly design strategies (e.g. [7]) or unrealistic modeling outputs (e.g. [8]). In-situ tests such as CPTU require reference laboratory tests for a proper site-specific calibration, whose success is linked to sample quality. Exception is made for FV test, where s_u is directly interpreted from the in-situ measurements. However, FV test may suffer from inaccuracies related to testing apparatus and procedure ([9]).

In presence of unreliable or insufficient test data, the choice of the design s_u is guided by estimates from correlations or transformation models reported in the literature that are representative of the site conditions and characterized by the lowest possible uncertainty. These models can be based on site-specific, regional (e.g. [10],[11],[12]) or global ([13]) databases and often require basic clay properties as input to estimate s_u. However, for some correlations, the uncertainties associated with site-specific data can be substantial ([10],[11],[13]) and, therefore, their use requires judgment and, often, a large conservative discount. Furthermore, information on the quality of the laboratory tests which constitute the basis of such models is generally unavailable.

One well-established and reliable ([10],[12],[14]) model for s_u is the SHANSEP empirical model ([15]). It describes the relationship between the normalized s_u of clays and the overconsolidation ratio (OCR) by means of empirical material coefficients that are calibrated from laboratory test results. This paper attempts to combine the SHANSEP model with analytical Critical State Soil Mechanics (CSSM) based solutions. The intent is to establish a framework to model s_u from two fundamental properties, such as the preconsolidation stress σ'_p (or the OCR) and the friction angle ϕ' at critical state. Moreover, the paper aims to evaluate bias and uncertainties of the hybrid CSSM-SHANSEP model associated with large existing multivariate databases of clays from Finland, Sweden and Norway. As friction angle measurements are missing from the multivariate datasets, ϕ' is estimated indirectly from the plasticity index using a correlation in the literature; while the OCR is used directly as reported in the databases. Finally, a sensitivity study is performed on the CSSM-SHANSEP model parameters.

2. Transformation models for undrained shear strength

2.1. SHANSEP empirical model for clays
Several transformation models for s_u have been proposed in the literature. They link basic clay properties such as Atterberg limits, water content, and consolidation stresses with s_u ([10],[12],[16],[17],[18],[19],[20],[21]). In general, s_u shows the strongest correlation with the preconsolidation stress σ'_p, increasing with increasing σ'_p; while a generally weaker correlation exists with index properties ([10],[13],[21]). Ladd and Foott ([15]) first introduced the SHANSEP concept, which describes the normalized s_u with respect to the effective vertical consolidation stress (s_u/σ'_{vc}) as a function of the OCR ($=\sigma'_p/\sigma'_{vc}$), following equation (1):

$$\frac{s_u}{\sigma'_{vc}} = \left(\frac{s_u}{\sigma'_{vc}}\right)_{NC} OCR^m = S\ OCR^m \qquad (1)$$

where S is the (s_u/σ'_{vc}) for the normally consolidated state and m an empirical material coefficient.

The normalized strength ratio S is load-path dependent, i.e. varies under different laboratory test conditions. For instance, undrained triaxial compression, extension and DSS tests yield to different values of S (e.g. [19],[21]). Typical values of S are 0.28-0.35 for triaxial compression (e.g. [21],[22]) and 0.20-0.27 for direct simple shear (DSS) ([10],[18],[19],[21],[22]). Furthermore, some studies reported the parameter m to be load-path dependent and varying between 0.7-1 for OCR less than 4, with the highest values observed for triaxial extension ([21],[23]). Other studies suggested m to be fairly constant and equal to ≈ 0.8 (e.g. [10],[20],[24]). For instance, data from Drammen clay in [24] suggest m$\approx$0.8 for OCR between 1 and 40.

Table 1 summarizes the typical values of S and m for clays from Finland, Sweden and Norway according to literature. As it can be observed, the SHANSEP parameters seem to be consistent, despite the differences in plasticity index (PI) and water content (w). Both PI and w are lowest for the Norwegian clays, while they are more consistent for clays from Sweden and Finland. For Swedish

clays, [20] reported a dependency of DSS and TXE strength on the liquid limit (LL), while [25] and [12] observed a dependency of s_u on the natural water content w. No dependency of S and m on index parameters was observed from FV tests on Finnish clays ([10]).

Figure 1 illustrates the undrained strength ratio versus OCR for samples of Norwegian clays that were reconsolidated to the in-situ vertical stress ($\sigma'_{vc} = \sigma'_{vo}$) prior to testing and FV data from Finland. The range of DSS tests on Norwegian clays ([25]) is consistent with the range of FV tests from Finland. Note that s_{uFV} test results in Figure 1 are corrected to account for rate effects and converted into s_u *(mob)* ([10]). Therefore, Figure 1 suggests $s_{uDSS} \approx s_u$ *(mob)*. As anticipated, the triaxial compression test results on Norwegian clays show a generally higher trend than the DSS and FV tests.

Table 1. Typical index and SHANSEP parameters of clays from Finland, Sweden and Norway.

Country	w (%)[a]	PI (%)[a]	Test type	S	m	Dependencies	Reference
Finland	78	38	FV	0.24	0.76	-	[10]
Sweden	87	46	TXC	0.33	0.8	-	[10]
			DSS	0.21 - 0.39	0.8	S=f(LL)	[10],[20]
			TXE	0.17 - 0.29	0.8	S=f(LL)	
Norway	42	20	TXC	0.30 - 0.34	0.53-1.0	S,m=f(w)	
			DSS	0.19 – 0.27	0.57-0.90	S,m=f(w)	[12][25]
			TXE	0.94 – 1.1	0.94-1.1	S,m=f(w)	

[a] Mean values based on sources.
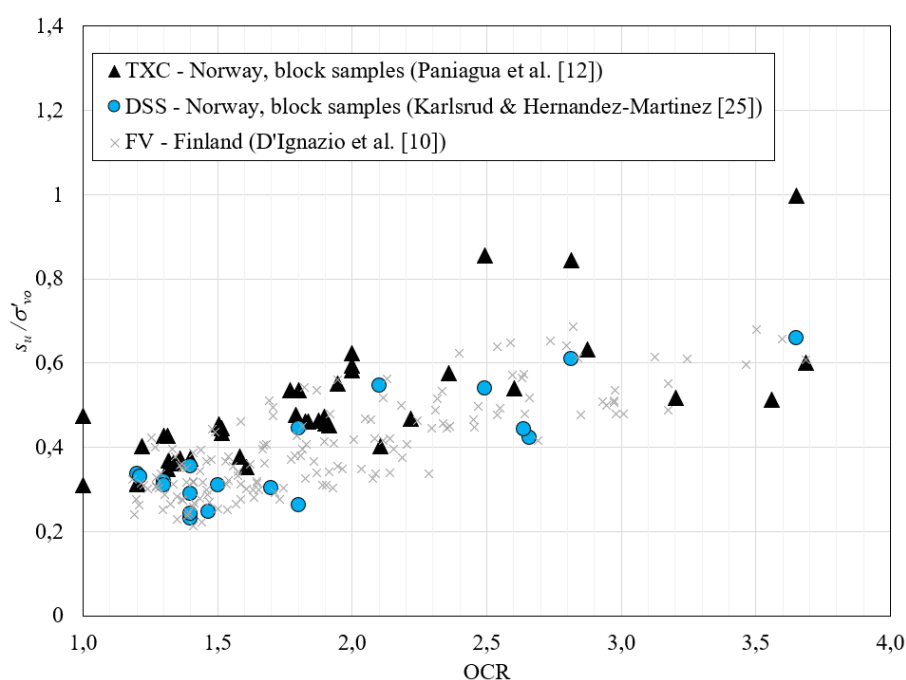
Figure 1. s_u / σ'_{vo} vs OCR from FV, CK$_o$UC and DSS tests.

2.2. Analytical solutions for undrained shear strength of normally consolidated clays

Analytical expressions for the normally consolidated strength ratio $S = (s_u/\sigma'_{vc})_{NC}$ in equation (1) have been proposed based on Critical State Soil Mechanics (CSSM) and Modified Cam-Clay (MCC) model ([26],[27]). The parameter S is mainly defined as a function of the friction angle ϕ' and stress-path. For

both isotropically (CIUC) and anisotropically (CK$_o$UC) consolidated triaxial compression and DSS tests, S can be defined analytically as:

$$S_{CIUC} = \frac{M}{2}\left(\frac{1}{2}\right)^{\Lambda} \tag{2}$$

$$S_{CKoUC} = \frac{sin\phi'}{2a}\left(\frac{a^2+1}{2}\right)^{\Lambda} \tag{3}$$

$$S_{DSS} = \frac{1}{2}sin\phi' \tag{4}$$

where M = slope of the critical state line, defined as $M = 6sin\phi'/(3-sin\phi')$, $a = (3-sin\phi')/(6-4sin\phi')$, and $\Lambda = 1 - C_s / C_c$, where C_s and C_c are the swelling and compression index, respectively. Often, Λ is taken equal to m and is generally less than 1 for CIUC, CK$_o$UC and DSS tests ([28],[29]). D'Ignazio et al. ([14]) reported m less than 1 on average for FV tests on Finland, Sweden and Norway clays. Further, [28] proposed an empirical correction for m to account for different test procedures.

Casey et al. ([30]) measured S_{CKoUC} for different initial stress ratios K_{oNC} over a wide effective stress range of 0.1 to 100 MPa. Assuming Jaky's ([31]) formulation $K_{oNC} = 1 - sin\phi'$, the S_{CKoUC} data points are plotted as shown in Figure 2 as a function of ϕ'. Equations (2) and (3) are illustrated in Figure 2 along with the experimental data by [30]. For $\phi' > 20°$, equation (3) seems to capture the trend of the experimental data better than equation (2). Furthermore, equation (3), which accounts for the initial anisotropic consolidation, appears to be representative of the lower bound of the data points for $\Lambda = 0.7$-0.9.
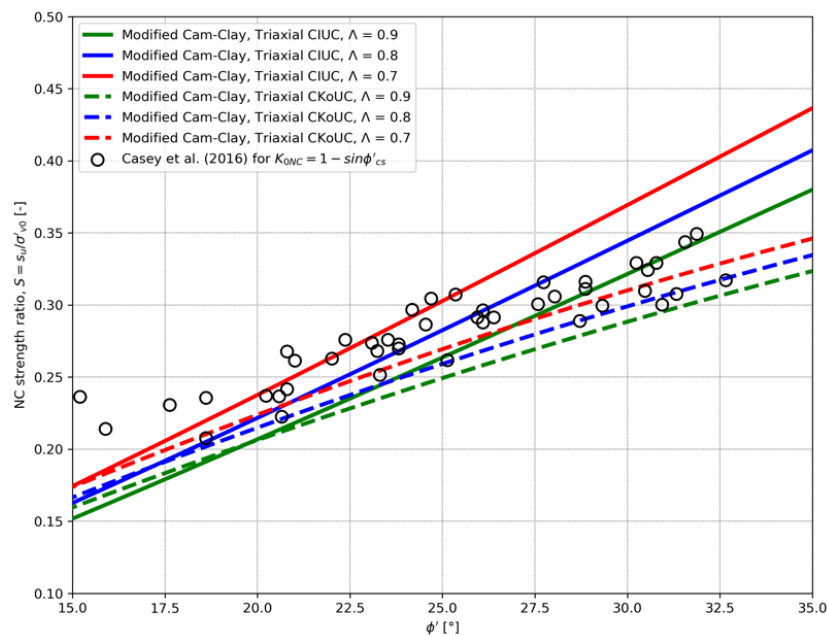
Figure 2. NC strength ratio S vs ϕ' – MCC prediction vs experimental data.

3. Hybrid CSSM-SHANSEP model for clays

3.1. Rationale

The hybrid CSSM-SHANSEP model results from the combination of equation (1) and equations (2), (3), (4), where the NC strength is defined based on analytical MCC-based solutions and the change in

shear strength with OCR follows the experimental trend. Therefore, the calculated s_u / σ'_{vc} will be a function of two fundamental clay parameters, i.e. ϕ' and OCR, and the stress-path. The concept is illustrated by equation (5).

$$\frac{s_u}{\sigma'_{vc}} = S(\phi', stress\ path)\ OCR^m \tag{5}$$

3.2. Validation

3.2.1. Reference databases. The performance of the hybrid CSSM-SHANSEP model is verified with respect to regional clay databases from Finland, Sweden and Norway. The clay properties contained in the databases cover a wide range of sensitivity (S_t) values varying from 2 (insensitive clays) to 240 (highly sensitive or quick clays), and a wide range of PI (2–128%) and w (25–150%). The OCR range of the data points is ~1-6. The databases considered are summarized in Table 2.

Table 2. Summary of databases used for validation of CSSM-SHANSEP model.

Database	Country	Number of points	Test type	PI (%)	OCR	Reference
F-CLAY/10/173	Finland	173	FV	2 - 95	1.2 - 3.7	[10]
S-CLAY/10/168	Sweden/Norway	168	FV	4 - 128	1 - 6.1	[10]
NGI Block – TXC	Norway	61	CK$_o$UC	4 - 49	1 - 6.3	[12]
NGI Block - DSS	Norway	22	DSS	5 - 42	1.2 - 5.3	[25]

3.2.2. Evaluation of input parameters. Equation (5) requires the definition of ϕ', Λ, OCR and m. While OCR is given in the databases, ϕ' is evaluated from PI according to equation (6) proposed by [32] for NC clays:

$$sin\phi' = 0.8 - 0.094 lnPI \tag{6}$$

For the PI range of data contained in the reference databases, the estimated ϕ' values range from 20° to 42°. Such values appear to be reasonable for Scandinavian clays based on the Authors' experience. Please refer to [33] for the transformation uncertainty of equation (6).

The coefficient m is selected according to the mean trend of the s_u / σ'_{vc} vs OCR relationship exhibited by the different datasets. The coefficient Λ is then taken equal to m.

3.2.3. Bias and uncertainties associated with the experimental data. Uncertainties of the simulated data points, including bias factor (b') and coefficient of variation (COV), are evaluated using the method suggested by [13]. The parameters b' and COV represent the sample mean and ratio of standard deviation and mean, respectively, of the ratio (actual target value/predicted target value). The "actual" normalized s_u target values are the measured values contained in the validation databases. The "predicted" target values are the s_u / σ'_{vc} values obtained from equation (5) using the input parameters discussed in section 3.2.2. and S calculated from equations (2), (3) and (4).

3.2.4. Results. Uncertainties (b' and COV) of the hybrid CSSM-SHANSEP model associated with the validation databases are summarized in Table 3. The CSSM-SHANSEP model appears to underestimate by ~6% the mean trend of the data in F-CLAY/10/173 ($b' = 1.06$), as shown in Figure 3, along with COV = 0.19. The prediction is unbiased (b'~1) with respect to the S-CLAY/10/168 database, even though the scatter around the mean trend is larger than for F-CLAY/10/173 (COV = 0.31 vs 0.19). Furthermore, the CSSM-SHANSEP model slightly overpredicts the mean trend of the DSS data on Norwegian clays ($b' = 0.95$) with a COV = 0.27 (Figure 4). It must be noted that the

calculated COV is potentially inaccurate because of significant statistical uncertainty associated with small sample size ($n = 22 < 30$).

Figure 5 compares the calculated s_u^{CKoUC}/σ'_{vc} and s_u^{CIUC}/σ'_{vc} with s_u^{CKoUC}/σ'_{vo} from block samples of Norwegian clays. The anisotropic CSSM-SHANSEP model, resulting from the combination of equation (3) and (5), provides an unbiased prediction ($b'\sim1$) with COV = 0.20. On the other hand, when using equation (2) for CIUC triaxial, the model overestimates the experimental data by ~20%. Such a result could be anticipated based on Figure 2, as equation (2) gives higher NC strength than equation (3).

According to Table 3, an equation for s_u^{DSS} of Finnish clays, which represents the unbiased prediction of the mean trend of F-CLAY/10/173, can be derived as:

$$\frac{s_u^{DSS}}{\sigma'_{vc}} = b'S_{DSS}OCR^m \approx 0.53 sin\phi' OCR^{0.76} \tag{7}$$

Table 3. Bias and COV of the CSSM-SHANSEP model.

Database	Number of points	Test type	Reference s_u	S	ϕ' (°)	m	b'	COV
F-CLAY/10/173	173	FV	$s_u(mob)$	equation (4)	22-36	0.76	1.06	0.19
S-CLAY/10/168	168	FV	$s_u(mob)$	equation (4)	20-42	0.76	1.00	0.31
NGI Block - DSS	22	DSS	s_u^{DSS}	equation (4)	26-40	0.62	0.95	0.27
NGI Block – TXC	61	CK$_o$UC	s_u^{CKoUC}	equation (2)	26-42	0.58	0.80	0.23
NGI Block – TXC	61	CK$_o$UC	s_u^{CKoUC}	equation (3)	26-42	0.58	1.00	0.20
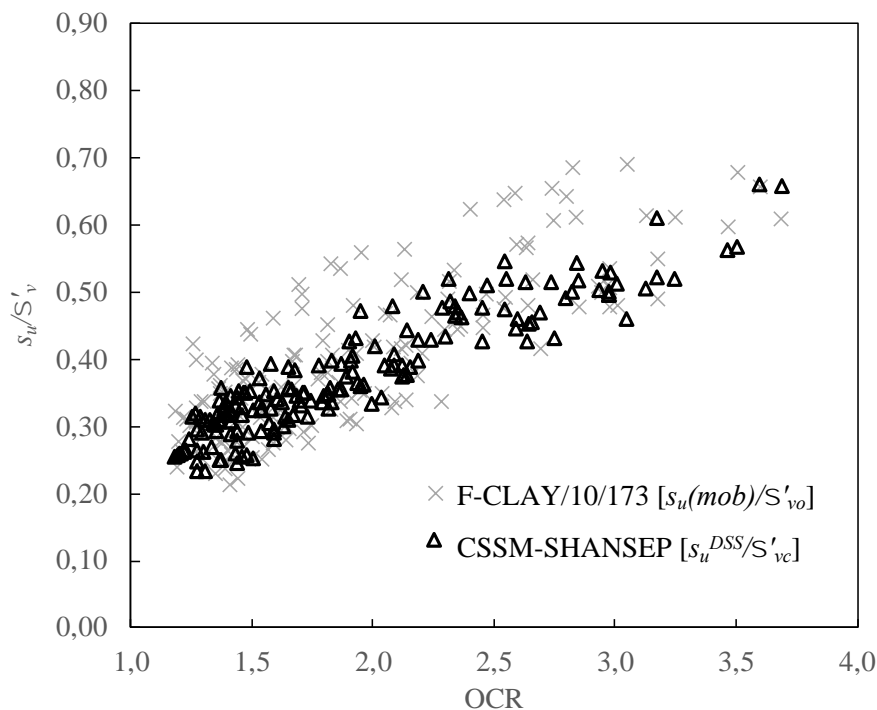
Figure 3. Comparison between s_u^{DSS}/σ'_{vc} from CSSM-SHANSEP and $s_u(mob)/\sigma'_{vo}$ in F-CLAY/10/173 database vs OCR.
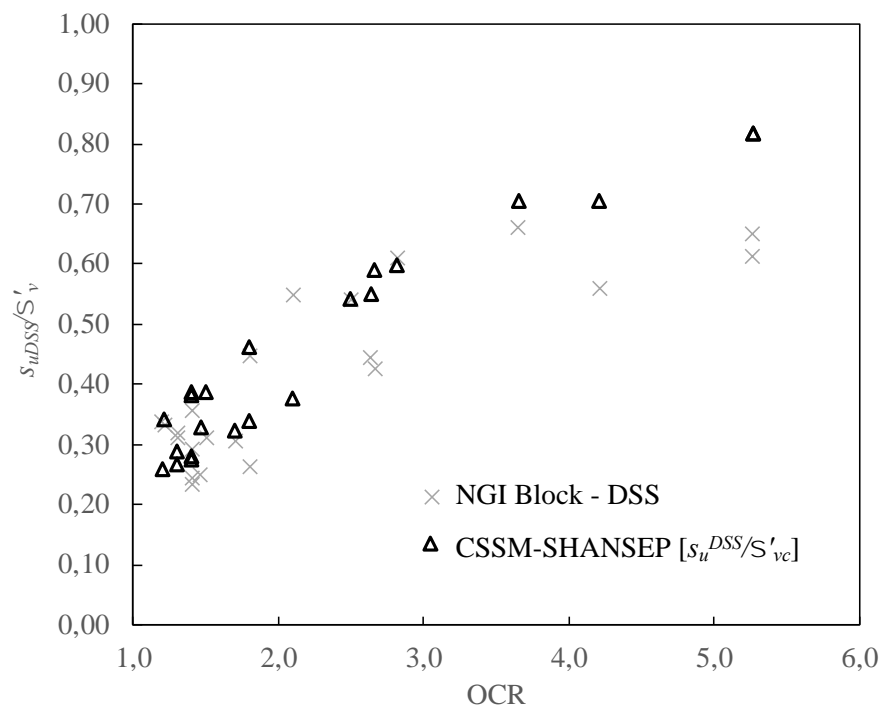
Figure 4. Comparison between s_u^{DSS}/σ'_{vc} from CSSM-SHANSEP and s_u^{DSS}/σ'_{vo} in NGI Block - DSS database vs OCR.
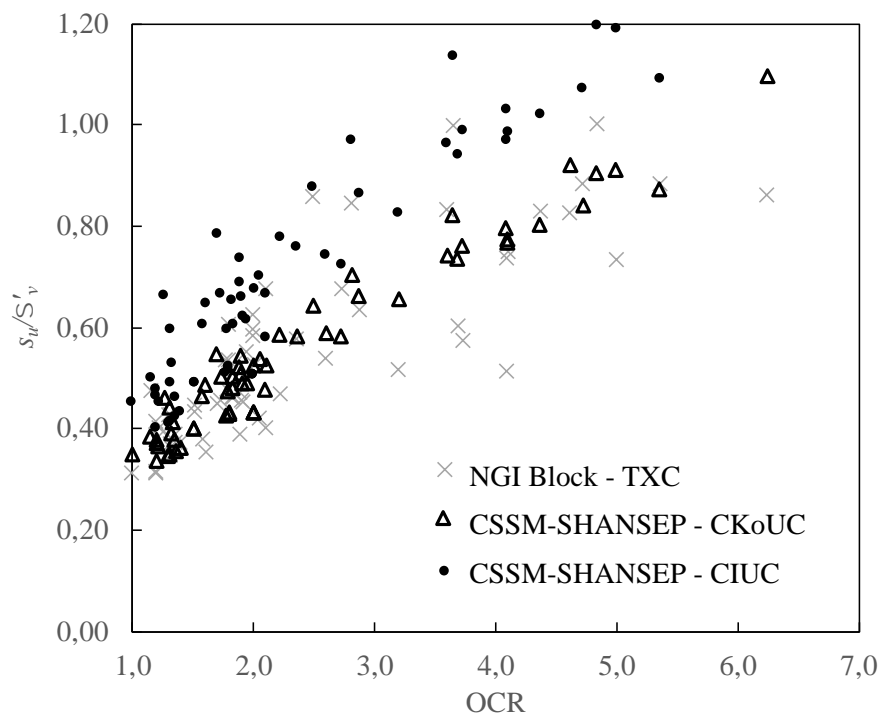
Figure 5. Comparison between s_u^{CKoUC}/σ'_{vc} and s_u^{CIUC}/σ'_{vc} from CSSM-SHANSEP and s_u^{CKoUC}/σ'_{vo} in NGI Block - TXC database vs OCR.

3.3. Sensitivity of CSSM-SHANSEP input parameters

For a given OCR, a 10% variation of ϕ', fixed $\Lambda = m = 0.8$, results in a ~9-9.5% variation of s_u^{DSS}/σ'_{vc} and s_u^{CKoUC}/σ'_{vc}. A variation of 10% on ϕ' is consistent with the COV $= 5 - 10\%$ reported by [34] for good quality direct laboratory measurements of effective friction angle. By varying $\Lambda = m$ by 10%, given ϕ', the variation of s_u^{DSS}/σ'_{vc} and s_u^{CKoUC}/σ'_{vc} increases with increasing OCR, up to 2.3-5.5% at OCR $= 2$ and 14-20% at OCR $= 10$, as shown in Table 4. Further, when a 10% variation is contemporarily applied to ϕ' and m, the impact on the undrained strength ratio is 5-10% at OCR=1, increasing up to 21-32% at OCR=10 as illustrated in Table 4. In addition, a 10% variation of OCR, given ϕ' and $m = 0.8$, will produce a ~8% variation of both s_u^{DSS}/σ'_{vc} and s_u^{CKoUC}/σ'_{vc}.

Table 4. Sensitivity of CSSM-SHANSEP parameters given ϕ'_0, $\Lambda_0 = m_0 = 0.8$

OCR	$\Delta(s_u^{DSS}/\sigma'_{vc})$ $\phi' = \phi'_0$ $\Lambda_0 = m_0 \pm 10\%$	$\Delta(s_u^{DSS}/\sigma'_{vc})$ $\phi' = \phi'_0 \pm 10\%$ $\Lambda_0 = m_0 \pm 10\%$	$\Delta(s_u^{CKoUC}/\sigma'_{vc})$ $\phi' = \phi'_0$ $\Lambda_0 = m_0 \pm 10\%$	$\Delta(s_u^{CKoUC}/\sigma'_{vc})$ $\phi' = \phi'_0 \pm 10\%$ $\Lambda_0 = m_0 \pm 10\%$
1	-	9.5%	3%	5-6%
2	5.5%	15-16%	2.3%	11%
4	11%	19-22%	8%	16-17%
10	17-20%	25-32%	14-16%	21-26%

4. Summary and conclusions

This paper discusses the uncertainties in modelling undrained shear strength of clays when using Critical State Soil Mechanics (CSSM) concepts and SHANSEP. In the proposed hybrid CSSM-SHANSEP framework, the normally consolidated behaviour is described by analytical CSSM solutions based on Modified Cam-Clay model, where the undrained strength ratio is defined as a function of the effective friction angle and the stress-path (triaxial compression, direct simple shear); while the change in undrained shear strength with overconsolidation ratio (OCR) is based on experimental data by means of an empirical material coefficient.

Model uncertainties associated with databases from Finland, Sweden and Norway are evaluated by means of bias factor and coefficient of variation (COV). Input parameters to the hybrid model are based on basic clay properties and consolidation stresses extracted from the databases. The calculated triaxial compression and DSS strengths suggest that the hybrid CSSM-SHANSEP model provide unbiased predictions of CK$_o$UC tests on Norwegian clays and DSS strength of Finnish clays with low prediction uncertainty (COV~0.2) for OCR~1-6. Unbiased prediction of DSS strength of Swedish clays is associated with a slightly larger COV ≈ 0.3. Given that the estimate of friction angle for each data point is based on the plasticity index, the outcome appears to be satisfactory. However, the CSSM-SHANSEP model needs to be further validated against datasets where the friction angle is measured from laboratory tests.

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