Title: Yield stress evaluation of Finnish clays based on analytical CPTu models

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ABSTRACT

A well-established analytical model based on spherical cavity expansion and critical state soil mechanics theories is applied to piezocone soundings for profiling the yield stress and overconsolidation ratio of five soft sensitive test sites located in Finland. Yield stress is related to three piezocone parameters: net cone resistance, excess porewater pressure, and effective cone resistances. Input geoparameters include the effective stress friction angle, defined at both peak strength and at maximum obliquity, and the model directly provides the operational value of the undrained rigidity index. The piezocone-evaluated profiles compare favorably with results from laboratory constant-rate-of-strain consolidation tests for all the investigated sites.

Based on the obtained experimental results, simplified correlations valid for Finnish soil conditions are derived. Their validity is assessed based on the bias factor, coefficient of variation and coefficient of determination, showing a fairly good agreement between the predicted and the target values.

Key words: sensitive clays, piezocone, yield stress, correlations

INTRODUCTION

The piezocone penetration test (CPTu) is an excellent and reliable field test that collects geotechnical data in a quick, efficient, and economical way. Three continuous readings with depth are obtained during cone penetration: cone tip resistance (q_t), sleeve friction (f_s), and penetration porewater pressure at the shoulder (u_2). Additional measurements can be performed by adding sensors to the traditional probe, including resistivity, pH, and shear wave velocity (e.g., Lunne et al. 1997). Over the past decades, various correlations have been proposed to link the CPTu measured data with key geotechnical parameters in different soil conditions. As an example, a unified approach in the interpretation of CPTu is presented by Robertson (2009) where a variety of engineering parameters is addressed. The validity of existing correlations for evaluating strength and deformation properties of Finnish clays has been assessed by Di Buò et al. (2018) and Selänpää et al. (2018). These studies highlighted that empirical correlations in the literature are often derived in a particular soil context, therefore require a proper validation or re-calibration when applied to Finnish soil conditions. Moreover, Di Buò et al. (2019) investigated the performance of different sampling techniques in Finnish soft clays and collected high-quality field and laboratory data. Results from these studies are further exploited herein to assess the yield stress of Finnish clays from CPTu.

In conventional geotechnical practice, the effective yield stress (σ'_p) is evaluated by means of laboratory consolidation tests. However, disturbance induced by sampling process, including stress relief, transportation, storage time, and specimen handling may negatively affect the test result interpretation, especially in soft sensitive clays (e.g., Hvorslev 1949; Lunne et al. 2006; Karlsrud and Hernandez–Martinez 2013; Karlsson et al. 2016; Mataic 2016; Di Buò et al. 2019). Therefore, the possibility to estimate σ'_p from field test data would overcome these issues as well as provide continuous information with depth. A well-established analytical model for CPTu interpretation in non-structured and low sensitive clays was derived using a hybrid spherical cavity expansion (SCE) and critical state soil mechanics (CSSM) formulation (Chen and Mayne 1994). However, this model provides inaccurate evaluations of σ'_p when applied to structured and highly sensitive clays. For this reason, a modified SCE-CSSM solution was developed to address the evaluation of yield stress in sensitive soils (Agaiby and Mayne 2018). The input parameters include two operational values of the effective friction angle, defined at peak and at maximum obliquity, which are associated to the measured cone tip resistance (q_t) and porewater pressure (u_2), respectively. The rigidity index (I_R = G/s_u), where G = shear modulus and s_u = undrained shear strength, is provided directly by this SCE-CSSM solution. In this study, both the original and the modified analytical SCE-CSSM solutions have been tested to evaluate the overconsolidation ratio (OCR) and σ'_p at five soft clay test sites located in Finland. The σ'_p and OCR profiles interpreted using the CPTu-based analytical approach are compared with the results of high-quality constant-rate-of-strain (CRS) consolidation tests for all the investigated sites. Simplified correlations valid for Finnish soils are finally derived from the generalized formulations and their validity is assessed by evaluating their bias and uncertainties associated with the available laboratory data set.

TEST SITES

In Finland, fine-grained soil sediments originated in the late Pleistocene as a result of the continental ice sheet retreat in the Weichselian ice age. The Scandinavian region was covered by a large ice sheet named Fenno-Scandian that spread out in the whole North Europe and Russia. During the Holocene, the ice sheet retreated and the meltwater accumulation gave rise to the formation of the Baltic Sea. In particular, this area has gone through four different environmental stages known as Baltic Ice Lake, Yoldia Sea, Ancylus Lake and Littorina Sea.

The investigation program has been conducted at five soft sensitive clay test sites characterized by low overconsolidation ratio (OCR < 2), which is likely to be the result of aging phenomena.

Differently from Norwegian clays, the depositional environment of Finnish clays is mainly characterized by fresh to brackish water as the sea water intrusion from the Atlantic Ocean was limited. Nevertheless, studies conducted on Finnish clays (Mataic 2016; Di Buò et al. 2016, 2019b) revealed that these soils are generally characterized by significantly high sensitivity (S_t>50). Despite the fact that salt leaching is considered as the main factor explaining the high sensitivity of Scandinavian clays, different depositional and post-depositional factors might be involved in the formation of Finnish clay deposits. In addition, these clays are generally characterized by significantly high natural water content and high clay fraction, while more notable differences in soil plasticity can be observed among different sites (Di Buò et al. 2016). This section presents an overview of the geotechnical properties of the investigated sites, with details of the soil stratigraphy and index properties which are summarized in Table 1. The site location is illustrated in Fig. 1.

Perniö

The Perniö test site is located in the southwestern coast of Finland, 140 km west from the city of Helsinki. The soil stratigraphy includes a 1.5 m thick dry crust layer overlaying an 8–9 m thick soft clay layer followed by silty and stiff sandy layers located at greater depth. The clay can be classified as inorganic (<2%) while the plasticity index (PI) ranges between 30% and 40%. The sensitivity (S_t) has been evaluated using the fall cone (FC) test, which gives values from 40 to 60. As typical in Finnish soils, the natural water content (w) is higher than the liquid limit (LL) with values ranging from 80% to 100%. The Perniö site is comprehensively described in Di Buò et al. (2019b).

Lempäälä

The Lempäälä test site is located near the city of Tampere, in the South of Finland. The soil stratigraphy includes a 1.5 m thick layer of weathered clay crust followed by 2 m of organic soil underlain by soft sensitive clay. The groundwater table is located at 0.60 m depth. The w is relatively high above 4 m depth (120–140%) while it varies in the range of 70–80% below.

The S_t is generally lower than 30 even though lenses with higher values (S_t > 50) can be observed, suggesting the presence of interlayers in the deposit. The PI ranges between 25–30% while the clay content is relatively constant below 5 m depth and on average equal to 60%. The organic content is approximately 5% above a depth of 3 m and less than 1% in the soft clay layer.

Masku

The Masku test site is situated near the city of Turku, along the southwestern coast of Finland. The investigation revealed the presence of an 8 m thick soft clay layer overlaying a 1.5 m weathered clay crust layer. Samples were taken only at 3 m, 5 m and 8 m depth. The *w* is 80% at 3 m and 8 m depth while higher values in the intermediate layer. The PI ranges between 40% and 70%. The Masku clay is the least sensitive of the clays presented in this study with values ranging between 10 and 30.

Paimio

Paimio site is located in the southwestern region of Finland, close to the city of Turku. The soil stratigraphy includes a 2 m dry crust layer overlying an 8 m soft sensitive clay layer. Two different clay layers are found: a leaner upper clay layer located above 6.5 m underlying and a more plastic clay layer. The upper layer is characterized by *w* of 50%–80% and PI of 15%–20% while higher values ($w \approx$ 90–110%; PI ≈ 30%) are found in the second layer. Paimio clay is high sensitive with S_t values varying between 60 and 90 without following any particular trend with depth.

Sipoo

The Sipoo test site is located about 30 km north of the city of Helsinki. The deposit consists of a homogeneous soft clay layer between 2 and 9 m depth. Compared to the other investigated test sites, Paimio clay is characterized by the highest PI values. In particular, a PI of 60% is measured between 5 and 6 m depth. The water content is very high at shallow depth ($w \approx$ 120%), decreasing then to 90−100% at 9 m depth. The sensitivity is relatively low, varying between 20 and 30.

EXPERIMENTAL PROGRAM

The investigation program includes CPTu soundings, index tests, CRS consolidation tests, and undrained triaxial compression tests with porewater pressure measurements carried out on undisturbed samples. All the tests have been conducted in accordance to the ISO standards (ISO 22476-1:2012 for piezocone testing and ISO/TS 17892-12:2004 for laboratory testing and CEN ISO/TS 17892-5:2004 for consolidation testing). This section presents an overview of the testing equipment, procedures and results obtained from both field and laboratory tests.

Piezocone testing

The field investigation was conducted by means of an electronic piezocone equipped with seismic and resistivity cones manufactured by A.P. van den Berg. The penetrometer consists of a standard 60° apex conical tip with a 150 cm^2 sleeve area. In particular, two different cones of different capacities have been used: a high capacity cone (75 MPa) and a lower capacity cone (7.5 MPa), herein after referred to as “high-resolution” cone, which is considered more suitable in soft soil conditions. The CPTu instrumentation employed for the field investigation is shown in Fig. 2.

The instrumented steel probe is pushed at a constant rate of 20 mm/s by means of a hydraulic pushing system mounted on a CPT crawler. Cone penetrometer readings are taken at regular intervals of 2 cm by the data acquisition system. The equipment used in the field investigation, as well as the test procedures, meet the requirements of the European Standards (EN ISO 22476-1). Figure 3 presents a representative CPTu sounding conducted at the Perniö site. Information on the testing program, equipment and procedures are detailed by Di Buò et al. (2016) and Di Buò et al. (2019b).

Consolidation testing

The CRS oedometer tests are carried out on undisturbed specimens of 45 mm diameter and 15 mm initial thickness at a constant strain rate of 0.001 mm/min (0.4 %/h), which is the standard strain rate used in Finland when testing clay samples. The stress-strain behavior is characterized by a clear pre-yielding and post-yielding response: a clear drop can be noticed when passing the yield stress (σ_p'), which is typically observed in structured clays. Representative CRS consolidation test results for each site are shown in Fig. 4. It is well recognized that soft sensitive clays are susceptible to sample disturbance. For this reason, in order to retrieve high-quality samples from the investigated sites, four different samplers were employed: two traditional piston samplers (ST:1 50 mm and the Aalto 86 mm), a 132 mm Laval-type tube sampler (TUT 132) and the mini-block sampler (Emdal et al. 2016). Details on sampling equipment, procedures and achieved sample quality are discussed by Di Buò et al. (2019a). In particular, the criterion proposed by Lunne et al. (1997), based on the normalized change in void ratio ($\Delta e/e_0$) to achieve the in-situ effective vertical stress (σ'_{v0}), has been adopted to evaluate the quality of the different specimens.

A total of 106 CRS consolidation tests have been performed, even though only 99 tests characterized by good to excellent quality are considered in the study ($\Delta e/e_0 < 0.07$ according to Lunne et al. 1997) for a more meaningful comparison between the model estimation and the experimental data. The interpretation method is based on a curve-fitting procedure applied to the CRS Swedish interpretation method (Sällfors 1978). In addition, the porewater pressure response has been taken into account to determine the correct value of σ_p'. These two different approaches are shown in Fig. 5 with reference to a CRS consolidation test conducted on a high-quality miniblock sample from Perniö. As shown, the σ_p' evaluation from high-quality test appears to be straightforward as the transition between the overconsolidated (OC) and the normally-consolidated (NC) range is evident.

Triaxial tests

Triaxial compression tests were carried out on 101 mm high and 50 mm diameter undisturbed specimens cut from the TUT tube samples. The laboratory program included consolidated isotropic and anisotropic undrained compression (CIUC, CAUC) tests. The samples were consolidated beyond the yield stress, choosing a cell pressure (σ'_{cell}) in the CIUC tests between σ'_p and $2\sigma'_p$ while the applied strain rate during the compression test is 1 %/h. Moreover, available tests from previous research studies (Mansikkamäki 2015; Lehtonen 2015) and tests carried out at the Laboratory of Earth and Foundation Structures at Tampere University have been exploited to evaluate the effective friction angle ϕ', which is used in the SCE-CSSM analytical framework. The test results and the interpretation of the parameters are discussed later in the paper for each investigated site.

SCE-CSSM ANALYTICAL MODELS

Among the existing analytical methods for evaluating the yield stress in clays, the expressions derived by Chen and Mayne (1994) using spherical cavity expansion (SCE) and critical state soil mechanics (CSSM) are employed herein. This solution is applicable to "well-behaved" clay soils of low sensitivity, while special attention is needed for structured sensitive clays. As such, a modified SCE-CSSM hybrid model has recently been proposed by Agaiby and Mayne (2018) for evaluating the OCR from CPTu results in highly sensitive clays. Both approaches are presented and used for assessing profiles of σ'_p for the sites considered in this study.

Simplified SCE-CSSM Solution

A hybrid SCE-CSSM formulation expresses the measured cone tip resistance (q_t) and porewater pressure (u_2) in closed-form equations as follows (Chen and Mayne 1994):

$$q_t = \sigma_{v0} + \left[\frac{4}{3}(\ln I_R + 1) + \frac{\pi}{2} + 1\right]\frac{M}{2}\left(\frac{OCR}{2}\right)^{\Lambda}\sigma_{v0}' \quad (1)$$

$$u_2 = u_0 + \left[\frac{2}{3}(\ln I_R)(M)\left(\frac{OCR}{2}\right)^{\Lambda}\sigma_{v0}'\right] + \left[1 - \left(\frac{OCR}{2}\right)^{\Lambda}\right]\sigma_{v0}' \quad (2)$$

where M=6 sinϕ'/(3-sinϕ') is the slope of the frictional envelope for triaxial compression in q/p' space, I_R=G/s_u is the rigidity index, G is the shear stiffness, s_u is the undrained shear strength; Λ is the plastic volumetric strain potential [Λ=1-(C_s/C_c)], C_s is the swelling index, and C_c the virgin compression index in 1D-compression).

The equations can be rearranged to express the OCR in terms of three normalized piezocone parameters, including: net cone tip resistance ($q_{net} = q_t - \sigma_{v0}$), excess porewater pressure ($\Delta u = u_2 - u_0$), and effective cone resistance ($q_{eff} = q_t - u_2$) as:

$$\mathrm{OCR} = 2\left[\frac{\left(\frac{2}{M}\right)(q_t - \sigma_{v0})/\sigma_{v0}'}{\frac{4}{3}(\ln I_R + 1) + \frac{\pi}{2} + 1}\right]^{(1/\Lambda)} \quad (3)$$

$$\mathrm{OCR} = 2\left[\frac{\left(\frac{\Delta u}{\sigma_{v0}'}\right) - 1}{\frac{2}{3}M\ln(I_R) - 1}\right]^{(1/\Lambda)} \quad (4)$$

$$\mathrm{OCR} = 2\left[\frac{1}{1.95M + 1}\left(\frac{q_t - u_2}{\sigma_{v0}'}\right)\right]^{(1/\Lambda)} \quad (5)$$

Considering low overconsolidated soils (OCR = 1 – 2), the three equations can be further simplified by assuming $\Lambda = 1$. The yield stress can be then evaluated as:

$$\sigma_p' = \frac{(q_t - \sigma_{v0})}{M(1 + \frac{1}{3}\ln I_R)} \quad (6)$$

$$\sigma_p' \approx \frac{(u_2 - u_0)}{\frac{1}{3}M \ln I_R} \quad (7)$$

$$\sigma_p' = \frac{(q_t - u_2)}{0.975\,M + 0.5} \quad (8)$$

Modified SCE-CSSM Solution

The application of the original hybrid SCE-CSSM method provides rather poor agreement when applied to structured sensitive clays, as discussed by Agaiby and Mayne (2018). The observed disagreement between CPTu estimation and consolidation test results is due to the different stress-strain and porewater-strain response. This can be understood by looking at the results of a representative CIUC triaxial test carried out on Perniö clay (Fig. 6): the deviator stress q reaches the peak strength at a relatively small axial strain level (≈1%), while the porewater pressure still develops and reaches its maximum value at much higher strain (≈15%). Similar behavior (strain-softening under undrained conditions) was observed from CIUC and CAUC tests on the other four clays investigated in this study. This stress-strain incompatibility is well documented in the literature for various soft sensitive clays (e.g., Leroueil and Hight 2003; Agaiby 2018).

In order to obtain an analytical solution valid in sensitive clays, Agaiby and Mayne (2018) derived modified SCE-CSSM expressions assuming two operational effective frictional parameters: (a) M_{c1} corresponding to the maximum deviatoric stress and related to the cone tip resistance (q_t); (b) M_{c2} corresponding to the friction angle at maximum obliquity (ϕ'_{MO}) related to measured porewater pressure (u_2). In these modified derivations, the OCR can be obtained based on three different formulations expressed by the following:

$$\mathrm{OCR} = 2\left[\frac{Q/M_{c1}}{[0.667\ln(I_R) + 1.95]}\right]^{(1/\Lambda)} \quad (9)$$

$$\mathrm{OCR} = 2\left[\frac{U^* - 1}{0.667M_{c2}\ln(I_R) - 1}\right]^{(1/\Lambda)} \quad (10)$$

$$\mathrm{OCR} = 2\left[\frac{Q - \left(\frac{M_{c1}}{M_{c2}}\right)(U^* - 1)}{1.95M_{c1} + \frac{M_{c1}}{M_{c2}}}\right]^{(1/\Lambda)} \quad (11)$$

where $Q = (q_t - \sigma_{v0})/\sigma'_{v0}$ is the normalized tip resistance and U* is an alternative normalized porewater pressure [$U^* = (u_2 - u_0)/\sigma'_{v0}$], as detailed by Schneider et al. (2008). The parameters M_{c1} and M_{c2} are the CSSM frictional parameters in the q/p' space taken at peak strength and maximum obliquity, defined respectively as:

$$M_{c1} = \frac{6\sin\varphi'_{peak}}{3 - \sin\varphi'_{peak}} \quad (12)$$

$$M_{c2} = \frac{6\ \sin\varphi'_{MO}}{3 - \sin\varphi'_{MO}} \tag{13}$$

Therefore, the modified SCE-CSSM analytical method requires the input of three different parameters: two friction angles (ϕ'_{peak} and ϕ'_{MO}) and the rigidity index (I_R). The evaluation of such parameters for the five sites is detailed later in the paper.

Effective friction angle evaluation

Values of effective friction angles for Finnish clays are obtained based on three different approaches: (a) exploiting available triaxial test results from the investigated sites; (b) based on an existing analytical limit plasticity solution; (c) as "operational" values providing the best fitting between the model estimation and the experimental data.

The analytical solution (referred to as "NTH solution") proposed by the Norwegian Institute of Technology (NTH) in Trondheim has been extensively used in Norway for the evaluation of the effective friction angle (ϕ') based on the piezocone parameter Q and pore pressure ratio B_q. Details of the method are presented by Janbu and Senneset (1974), Senneset and Janbu (1985), Senneset et al. (1989), Sandven (1990) and Sandven and Watn (1995). An approximate solution is given by (Mayne 2007):

$$\varphi' = 29.5\ B_q^{0.121}[0.256 + 0.336\ B_q + \log Q] \tag{14}$$

which is valid for the following ranges: OCRs < 2.5; 20° ≤ φ′ ≤ 45°; and $0.1 \le B_q \le 1.0$. This solution has been applied to evaluate the effective friction angle of the soft Finnish clays.

Undrained rigidity index

The rigidity index ($I_R = G/s_u$) is used in many geotechnical applications and is incorporated in various theories and analytical solutions, including bearing capacity, porewater dissipation analyses, and magnitudes of undrained distortion. The correct determination of I_R is often challenging and requires careful consideration (Krage et al. 2014). Foremost, difficulties arise when evaluating the shear modulus *G* due to its dependency on the shear strain (γ). Clearly, at small strains the value corresponds to a high value of the initial tangent shear modulus (G_0), while G reduces with increasing strain. Konrad and Law (1987) and Schnaid et al. (1997) suggested to use the value of shear modulus corresponding to 50% of the mobilized strength (G_{50}) to model an average response. Moreover, it has been shown that the I_R depends on soil sensitivity, OCR, PI, and organic content (Wroth 1979). Several empirical correlations have been proposed in the literature to evaluate the rigidity index based on various soil properties (Keaveny 1985; Keaveny and Mitchell 1986; Mayne 2001). It is evident that all these variables and factors, as well as the uncertainties inherent with empirical correlations, may lead to an inappropriate estimation of I_R. Therefore, it is of great interest to develop CPTu based models for evaluating the rigidity index, thus overcoming these issues. To this end, the hybrid SCE-CSSM model offers a direct assessment of the rigidity index in terms of CPTu data and friction parameter *M*. For uncemented, inorganic, and unstructured clays, the I_R can be expressed by combining equations (3) and (4) and introducing the slope parameter a_q, thus obtaining:

$$I_R = \exp\left[\frac{1.5 + 2.925 \cdot M \cdot a_q}{M \cdot (1 - a_q)}\right] \tag{15}$$

where $a_q = (U^*-1)/Q = (u_2 - \sigma_{v0})/(q_t - \sigma_{v0})$. Therefore, a_q can be evaluated for any clay deposit as the slope parameter of the plot (U^* - 1) versus Q. Alternatively, a_q is found simply as the slope of ($u_2 - \sigma_{v0}$) versus ($q_t - \sigma_{v0}$).

Similarly, the value of I_R can be derived from the modified SCE-CSSM framework for sensitive clays by combining equations (9) and (10), thus obtaining:

$$I_R = \exp\left[\frac{1.5 + 2.925 \cdot M_{c1} \cdot a_q}{M_{c2} - M_{c1} \cdot a_q}\right] \tag{16}$$

The rigidity index has been evaluated for each site based on equations (15) and (16), depending on the model adopted for predicting the yield stress.

APPLICATION OF THE SCE-CSSM MODELS TO SENSITIVE CLAYS

Both the original and the modified SCE-CSSM models were implemented to derive the preconsolidation stress in a variety of clay deposits worldwide. In particular, based on an extensive database of clay data, Mayne (2005) proposed simplified equations by adopting characteristic values for the effective stress friction angle $\phi' = 30°$ (i.e. $M = 1.2$) and rigidity index $I_R = 100$ which are used in eqs. (6), (7), and (8) obtaining:

$$\sigma'_p = 0.33(q_t - \sigma_{v0}) \quad (17)$$

$$\sigma'_p = 0.54(u_2 - u_0) \quad (18)$$

$$\sigma'_p = 0.60(q_t - u_2) \quad (19)$$

Overall, it has been observed that these correlations on a first-order basis with experimental data from an extensive database including 206 clays worldwide (Chen and Mayne 1996). More recently, Agaiby (2018) implemented the SCE-CSSM analytical solutions on twelve test studies covering natural clays with different geologies from several countries, obtaining rather good agreement between the predicted σ'_p profiles and the laboratory measured values. For "normal" clays that are inorganic and insensitive: $\sigma'_p \approx 0.33\, q_{net} \approx 0.54\, \Delta u_2 \approx 0.60\, q_{eff}$
However, a signature of sensitive and structured clays is that a hierarchy is observed when the profiles of σ'_p from (17), (18), and (19) are compared, such that: $0.60\, q_{eff} < 0.33\, q_{net} < 0.54\, \Delta u_2$.
The limitations of the original SCE-CSSM model implemented to sensitive and structured clays have been extensively detailed by Mayne et al. (2018) and Mayne et al. (2019) with reference to Norwegian (Tiller-Flotte site) and Canadian (e.g., Gloucester site) clays.

IMPLEMENTATION OF THE SCE-CSSM MODELS TO FINNISH CLAYS

In this study, the SCE-CSSM analytical framework has been implemented to the CPTu soundings obtained from each investigated site to derive the σ'_p profiles. Site-specific parameters including effective friction angles (ϕ'_{peak} and ϕ'_{MO}), rigidity index (I_R), and plastic volumetric strain potential (Λ) are evaluated to obtain the best-fit between the experimental and predicted values. The effective friction angles ϕ'_{peak} and ϕ'_{MO} at the different sites are obtained from CIUC/CAUC tests. The results obtained from the implementation of these models are discussed for each investigated site.

Perniö

A laboratory research program for undisturbed samples taken at Perniö site was conducted and detailed by Mansikkamäki (2015) and Lehtonen (2015). Mansikkamäki (2015) recommended an effective peak friction angle ϕ'_{peak} = 25–26° (assuming cohesion c' = 0) based on the interpretation of CAUC tests. Lehtonen (2015) suggested a value of ϕ'_{MO} = 27.8° and c' = 3.4 kPa. Fig. 7 shows the effective stress paths from CIUC and CAUC tests on Perniö clay. For the purpose of this study, a line is fitted through stress points at maximum obliquity and at the maximum q/p' value giving approximately values of ϕ'_{peak} = 28° and ϕ'_{MO} = 36 for c' = 0. The NTH solution gives a friction angle of 33.7°.

In order to obtain the best-fit to the experimental data, the modified SCE-CSSM solution is implemented on Perniö data assuming: ϕ'_{peak} = 31° and ϕ'_{MO} = 33°. As expected, the best-fit value of ϕ'_{peak} = 31° is larger than the measured ϕ'_{peak} = 28°, as the structure of Perniö clay may have been altered during reconsolidation of the samples. On the other hand, ϕ'_{MO} = 33° is more in line with the measurements and the NTH solution. The operational value of I_R is evaluated based on equation (16): the parameter a_q is determined as the slope of the plot (U^*-1) versus Q, giving a value of a_q = 0.54 (Fig. 8d), resulting in I_R = 191. The plastic volumetric strain potential Λ can be assumed equal to 1 at low OCRs (Chandler 1988). This set of parameters is applied to the modified SCE-CSSM model.

Figure 8 shows the comparison between the CPTu-based predictions for σ'_p and OCR obtained from equations (9), (10) and (11) and the experimental results. The coefficient of determination (R^2) ranges between 0.64 and 0.85 (Table 2), indicating that the analytical model provides a fairly good estimation of σ'_p. However, equation (11) which is based on the effective cone tip resistance ($q_{eff} = q_t - u_2$) provides the least accurate prediction.

Lempäälä

The NTH solution gives a friction angle of 30°. Unfortunately, triaxial tests are not available for this test site. As observed for Perniö, the modified SCE-CSSM solution provides rather good estimation of σ'_p and OCR for this site. In particular, the modified SCE-CSSM model has been implemented assuming $\Lambda = 1$, $\phi'_{peak} = 28°$ and $\phi'_{MO} = 30°$, which provide a value of I_R = 88 [eq. (16), a_q = 0.49]. The predicted OCR and σ'_p profiles are shown in Fig. 9 while the coefficients of determination (R^2) for each equation are presented in Table 2. In particular, as observed for Perniö, the correlation based on the effective cone tip resistance is characterized by the lowest accuracy ($R^2 = 0.32$). Equations (9), (10) and (11) resulted in notably different σ'_p and OCR predictions above 4 m depth in the organic layer. Further investigation is needed to verify the applicability of the method in organic soils.

Masku

Differently from Perniö and Lempäälä clay, the simplified SCE-CSSM solution is suitable for evaluating σ'_p and OCR also for this test site. A set of CIUC tests have been performed on undisturbed samples. The effective stress paths are presented in Fig. 10. Based on the available data, the characteristic friction angles value are $\phi'_{peak} = 30°$ and $\phi'_{MO} = 36.9°$. The NTH solution [eq. (14)] is applied on Masku data resulting in $\phi' = 35.9°$. The slope parameter is evaluated using the same procedure adopted for the previous sites, giving a value of $a_q = 0.49$. Assuming $\phi' = 36°$, the operational rigidity index is calculated as $I_R = 124$. Assuming this set of parameters together with $\Lambda = 1$, a good agreement is observed when comparing the estimated values with the laboratory measured σ'_p (Fig. 11). In particular, the coefficient of determination varies between $0.67 < R^2 < 0.96$ (Table 2), thus indicating reliable estimation provided by the analytical model. Here, the amount of laboratory data available from Masku site is relatively small and further considerations cannot be made.

Paimio

Results from CIUC tests on Paimio clay are presented in Fig. 12. The effective stress paths suggest $\phi'_{peak} = 27.5°$ and $\phi'_{MO} = 33.7°$. The latter is comparable with the value provided by eq. (14): $\phi' = 33.7°$. The plot of (U*-1) versus the normalized cone resistance (Q) gives a slope parameter $a_q = 0.54$. Adopting $\phi'_{peak} = 31°$ and $\phi'_{MO} = 34°$ with $\Lambda = 1$, a value $I_R = 138$ is obtained. The implementation of the modified SCE-CSSM analytical solution using these operational values provides a relative good agreement between the laboratory measured σ'_p and OCR results and the estimated values as shown in Fig 13 and Table 2.

Sipoo

Three triaxial CIUC tests have been carried out on undisturbed samples at 5.85 m depth. Stress paths are shown in Fig. 14, indicating a mobilized effective friction angle $\phi'_{peak} = 25.4°$ and $\phi'_{MO} = 33.7°$, while a higher value is given by the NTH solution ($\phi' = 36.3°$). However, as observed for Masku clay, the best fitting is provided by the original SCE-CSSM solution, assuming $\phi' = 34°$. The value of the rigidity index is 332, with a slope parameter $a_q = 0.54$. This set of parameters and the plastic volumetric strain potential $\Lambda = 1$ are input into the SCE-CSSM solution resulting in a rather good estimation of σ'_p and OCR of Sipoo clay (Fig. 15), with R^2 ranging between 0.78 and 0.91 (Table 2).

SIMPLIFIED CPTu-BASED CORRELATIONS FOR FINNISH CLAYS

The SCE-CSSM framework provides a methodology to evaluate the soil yield stress σ'_p and OCR profiles which are in reasonable agreement with laboratory test data. Table 3 summarizes the effective friction angle and rigidity index values given by the different approaches previously discussed. For the investigated clays, the implementation of the SCE-CSSM solutions provided the best fitting by adopting the friction angle ratio (ϕ'_{peak}/ϕ'_{MO}) between 0.9 and 1. In contrast, lower values were observed for different worldwide sensitive soils, as detailed by Agaiby (2018). The reason that justifies this finding is apparently related to the magnitude of the slope parameter a_q: Finnish clays are characterized by a slope parameter ranging between 0.45 and 0.55 while data obtained from other sensitive clay test sites (e.g. Gloucester and Tiller-Flotten) indicate higher a_q values. Figure 16 shows the friction angle ratio ϕ'_{peak}/ϕ'_{MO} as a function of the slope parameter a_q, highlighting the aforementioned differences between Finnish clays and well-documented sensitive clays.

It is worth pointing out that the NTH solution gives a good estimation of the effective friction angle at maximum obliquity (ϕ'_{MO}). This value has been used to set the M_{c2} parameter in the analytical SCE-CSSM solution, while the M_{c1} is determined to match the experimental data. The principal objective of this study is to establish a set of CPTu based correlations for the yield stress evaluation of Finnish clays based on the SCE-CSSM solution. As such, representative values for effective friction angles and rigidity index are adopted as input of the SCE-CSSM analytical framework. In order to further investigate these parameters, available CIUC triaxial tests carried out at Tampere University on six additional Finnish sites were exploited. The interpretation of the effective stress paths yields the corresponding values of $\phi'_{peak} = 27°$ and $\phi'_{MO} = 36°$ (Fig. 17). This confirms that the ϕ'_{MO} estimated by the NTH solution matches the experimental data while the value of ϕ'_{peak} used in the SCE-CSSM solution is systematically higher. A plausible reason to justify this finding is that the measured values of ϕ'_{peak} are based on samples that were rendered normally consolidated before shearing, thus altering their initial structure. However, the use of "operational" best-fit values in the analytical model results in a reasonable estimation of the yield stress at the investigated sites. It is important to point out that the original SCE-CSSM framework is suitable for the estimation of the yield stress at Masku and Sipoo sites, which are characterized by the lowest sensitivities (S_t

< 30). On the other hand, the modified solution provides a better fit to the data for the high sensitive sites, where $S_t > 30$ (i.e., Perniö, Lempäälä and Paimio). That said, the boundary of $S_t = 30$ should not be regarded as a limit between low and high sensitive clays, but rather as an indicator that defines the range of applicability of the SCE-CSSM method in Finnish clays.

For the clays with $S_t < 30$ (e.g., Masku and Sipoo), simplified expressions can be derived from the original SCE-CSSM formulation assuming an average operational effective friction angle $\phi' = 35°$ (i.e., $M_{c1} = 1.42$), rigidity index $I_R = 230$, and $\Lambda = 1$. Using this set of parameters, equations (6), (7) and (8) can be simplified as:

$$\sigma'_p = 0.25\,(q_t - \sigma_{v0}) = 0.25\,q_{net} \tag{20}$$

$$\sigma'_p = 0.39\,(u_2 - u_0) = 0.39\,\Delta u_2 \tag{21}$$

$$\sigma'_p = 0.53\,(q_t - u_2) = 0.53\,q_{eff} \tag{22}$$

Similarly, for the clays with $S_t > 30$ (e.g., Perniö, Lempäälä, and Paimio), the following average parameters are assumed: $\phi'_{peak} = 31°$, $\phi'_{MO} = 34°$ (i.e., $M_{c1} = 1.24$, $M_{c2} = 1.37$), $I_R = 160$, and $\Lambda = 1$. Therefore, the yield stress can be estimated from equations (9), (10), (11) as:

$$\sigma'_p = 0.30\,(q_t - \sigma_{v0}) = 0.30\,q_{net} \tag{23}$$

$$\sigma'_p = 0.55\,(\Delta u_2 - \sigma'_{v0}) \tag{24}$$

$$\sigma'_p = 0.60\,(q_t - \sigma_{v0}) - 0.54\,(\Delta u_2 - \sigma'_{v0}) \tag{25}$$

where $\Delta u_2 = u_2 - u_0$.

For practical purposes, it may be convenient to rely on a single set of equations that are representative of the entire population of Finnish clays presented in this study, regardless of S_t. Moreover, as eqs. (24) and (25) appear to be more complex from a computational point of view, they are not further considered.

The equations were validated for the entire data set of Finnish clays consisting of n = 99 data points. The goodness of each correlation was evaluated by calculating the bias factor (b), coefficient of variation (COV), coefficient of determination (R^2) and standard error (SE) as detailed by Ching and Phoon (2014). The parameters b and COV are defined as the sample mean and the coefficient of variation of the ratio (measured target value)/(predicted target value). The prediction is considered to be unbiased when b = 1. The results of the statistical analysis are shown in Table 4. It is worth observing that the goodness of the model prediction based on the q_{net}, Δu_2 and q_{eff} is characterized by different values of R^2 ($0.65 < R^2 < 0.90$). In particular, equations based on a single parameter q_{net} and Δu_2 provide more reliable prediction than those based on q_{eff} as indicated by the R^2 in Fig. 17. Similar results were observed for equations (24) and (25). This finding can be explained by the fact that including two or more variables can negatively affect the model prediction. Therefore, it would be beneficial to rely on simple equations based on single parameter, i.e. equations (20) and (21).

The obtained equations have been further calibrated based on the b, thus obtaining:

$$\sigma'_p = 0.28\,(q_t - \sigma_{v0}) = 0.28\,q_{net} \tag{26}$$

$$\sigma'_p = 0.39\,(u_2 - u_0) = 0.39\,\Delta u_2 \tag{27}$$

$$\sigma'_p = 0.62\,(q_t - u_2) = 0.62\,q_{eff} \tag{28}$$

The calibrated equations are comparable with existing correlations for σ'_p from CPTu (e.g. Chen and Mayne 1996; Mesri 2001; Mayne 2017; D'Ignazio et al. 2019). In particular, the calibration coefficient 0.28 in Equation (26) is consistent with correlations proposed by Mesri (2001) for inorganic clays and silts and in line with those proposed by Chen and Mayne (1996) based on a large dataset of clays worldwide. This value is, however, lower than what Paniagua et al. (2019) found for Norwegian sensitive clays (0.44–0.47) from high-quality block samples. A summary of the calibrated equations, b and COVs is shown in Table 4, while the comparison between the experimental data and the correlation-based predictions is shown in Fig. 18. It is worth noting that all the correlations provide a reasonably good estimation of the yield stress, as the COV varies between 0.07–0.15. From an operational point of view, these equations can be reliably used for a preliminary evaluation of σ'_p in absence of site-specific data or when the available data is suspected to be unreliable.

CONCLUSIONS

The study presented in this paper investigates the validity of an established SCE-CSSM method for evaluating the yield stress of soft Finnish sensitive clays using in-situ piezocone tests. In particular, the analytical solution provides three expressions for effective yield stress (σ'_p) based on the cone tip resistance (q_t) and porewater pressure (u_2). Input geoparameters include the effective friction angle ϕ'_{peak}, defined at maximum deviatoric stress, the effective friction angle ϕ'_{MO} defined at maximum obliquity, and the undrained rigidity index I_R which is obtained directly by plotting (u_2 - σ_{vo}) versus q_{net}.

Overall, a good agreement between the yield stress profiles from CPTu and laboratory series of CRS consolidation tests is observed for all five tested sites, provided that model parameters are carefully selected. The original SCE-CSSM solution is more suitable in clays with $S_t < 30$, while the modified formulation provides a better estimation when $S_t > 30$. Both solutions require the definition of the effective friction angle and rigidity index of the soil. The "operational" friction angle values used in the analytical model do not always match the values interpreted from the laboratory test results, as shown in Table 3. The finding is possibly the result of sample disturbance as well as the fact that, in this study, the selection of the effective strength parameters was based on destructured clays samples. Moreover, it is important to highlight that the modified SCE-CSSM formulation is based on the assumption of effective cohesion c'=0. This will further affect the interpretation of the two friction angles (ϕ'_{peak} and ϕ'_{MO}) from tests that are used as input to the model.

Finally, simplified correlations have been derived using both the standard and the modified SCE-CSSM method for clays with $S_t < 30$ and $S_t > 30$, respectively. The equations derived have been compared with the experimental data and further calibrated to obtain the best fit to the entire data set of Finnish clays. The calibrated equations are in line with existing correlations for clays in the literature. The COV of the proposed correlations ranges between 0.07 and 0.15, thus suggesting that the predicted values are characterized by reasonably low uncertainty. Nevertheless, these correlations should only be used for a preliminary estimate of the yield stress of Finnish clays and be recalibrated when reliable site-specific data are available.

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FIGURES

Fig. 1: Location of the investigated test sites.

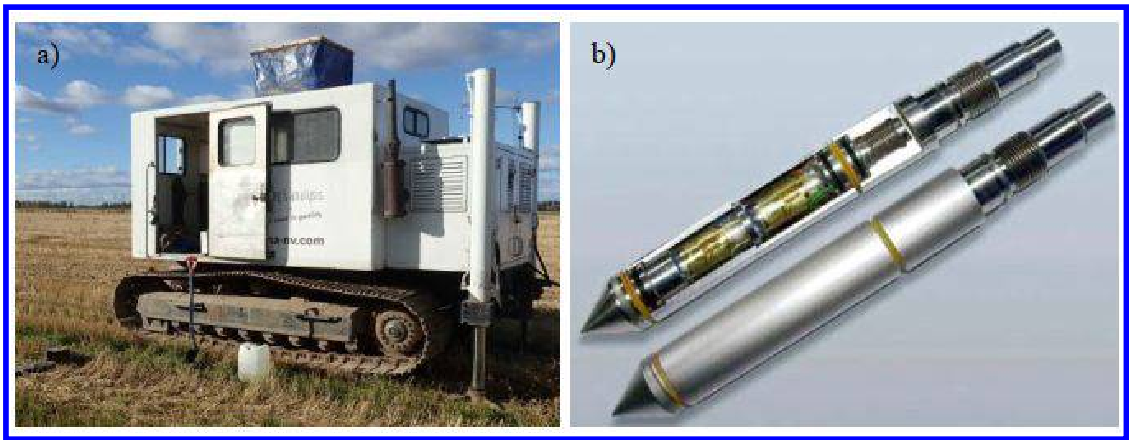

Fig. 2: AP van den Berg CPTu instrumentation: a) pushing equipment (on land CPT crawler); b) piezocones.

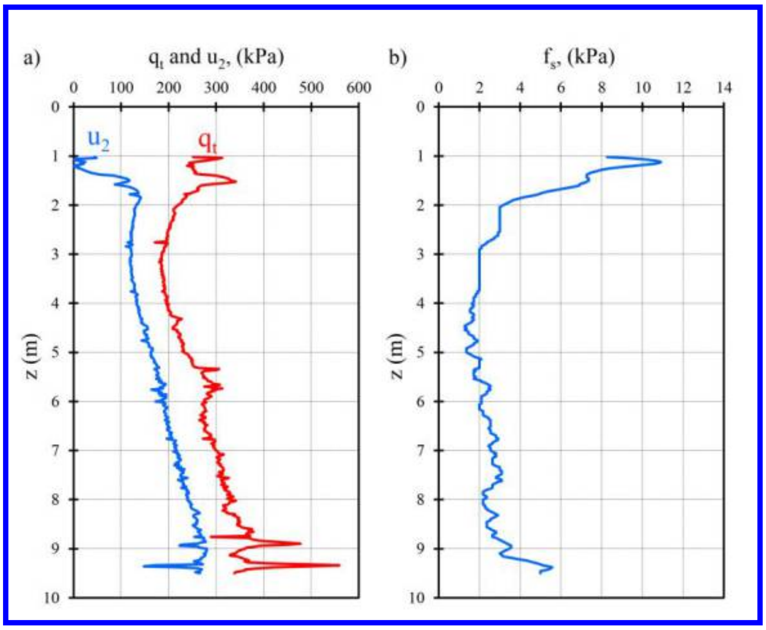

Fig. 3: Representative CPTu sounding conducted at Perniö site: (a) corrected cone tip resistance (q_t) and measured excess porewater pressure (u_2); (b) sleeve friction (f_s).

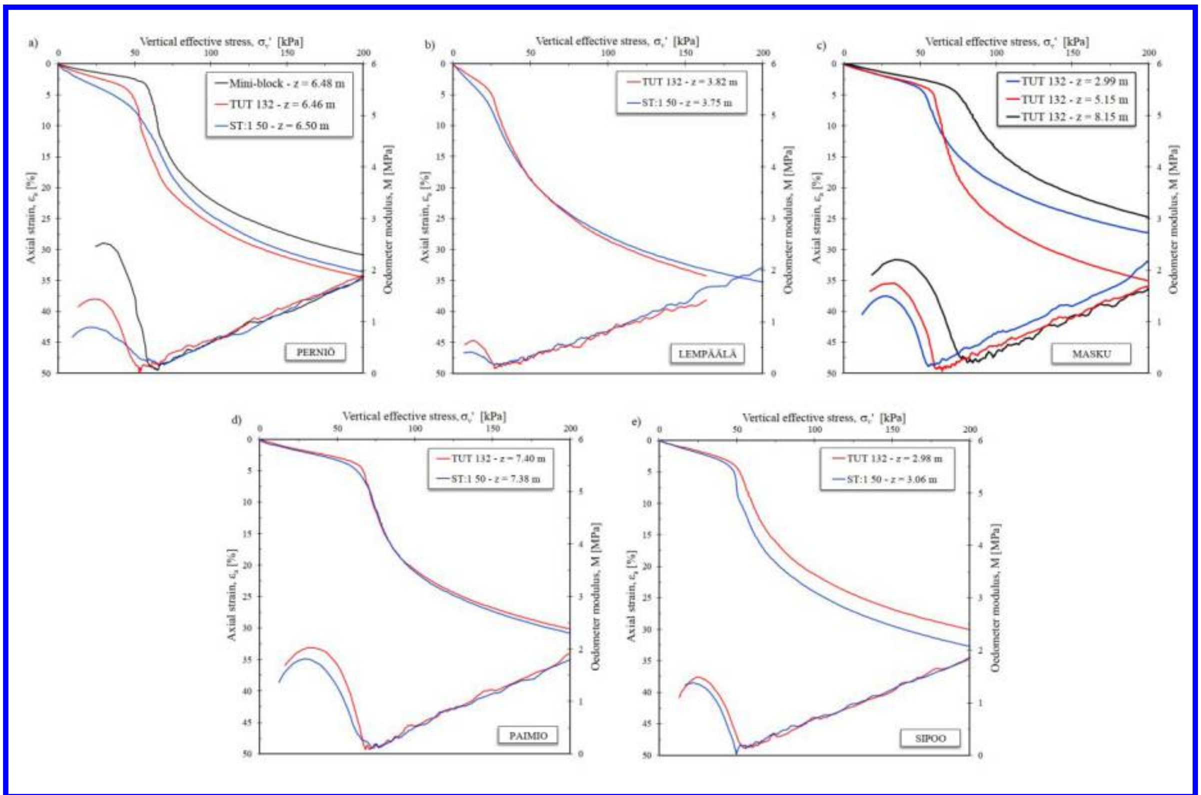

Fig. 4: Representative CRS consolidation test results from the investigated clays: a) Perniö; b) Lempäälä; c) Masku; d) Paimio; e) Sipoo.

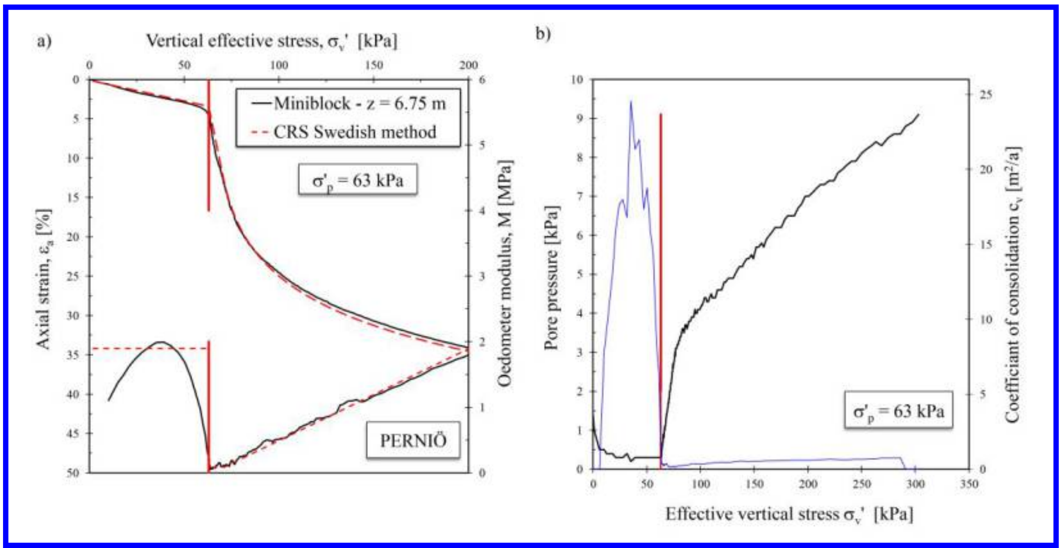

Fig. 5: Adopted procedure for evaluating σ'_p from CRS consolidation test: a) curve-fitting based on the CRS Swedish method; b) Pore water pressure response.

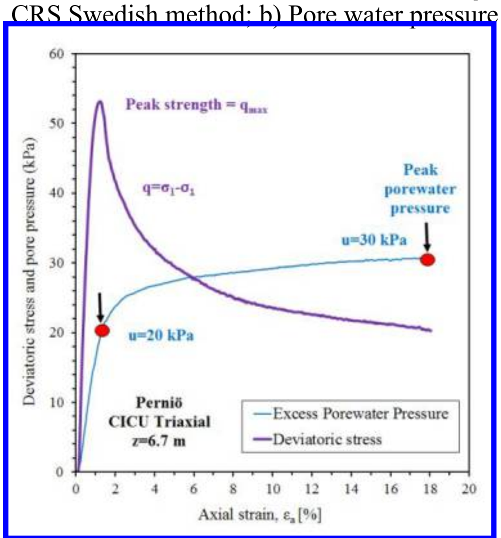

Fig. 6: Representative CIUC test result from Perniö soft clay showing the stress-strain and porewater pressure response.

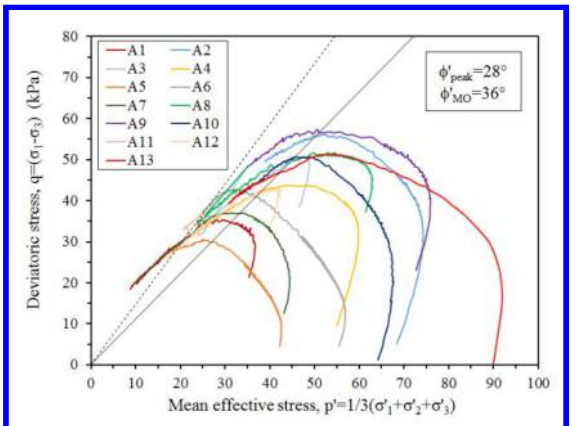

Fig. 7. Effective stress paths of TX compression tests for Perniö clay indicating mobilized friction angle at maximum stress q_{max} and maximum obliquity.

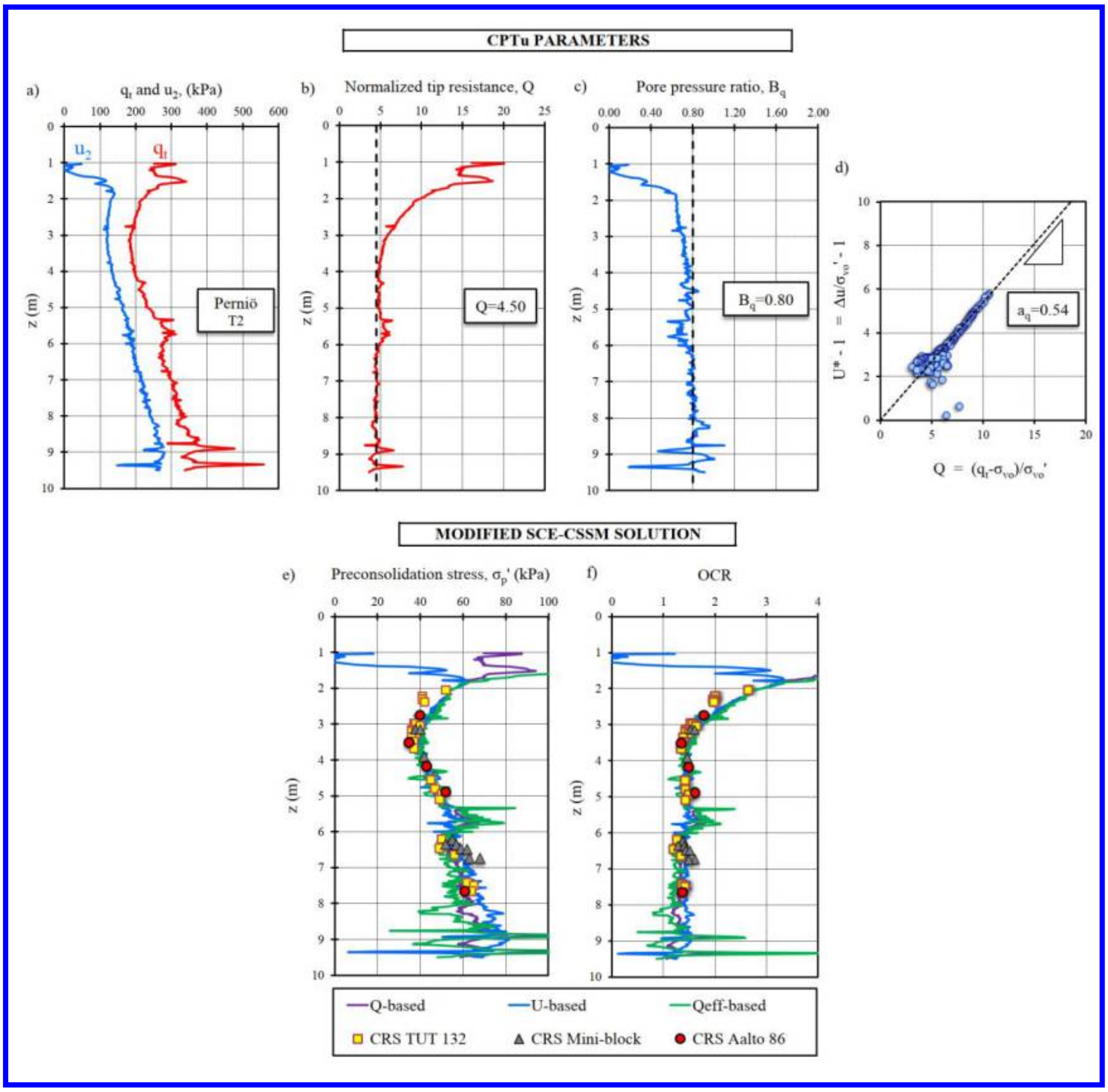

Fig. 8: Implementation of the modified SCE-CSSM analytical solution on Perniö clay: a) CPTu soundings; b) normalized tip resistance (Q) versus depth; c) normalized pore pressure ratio (B_q) versus depth; d) evaluation of the slope parameter a_q; e) implementation of the modified SCE-CSSM model for σ'_p prediction; f) implementation of the modified SCE-CSSM model for OCR prediction;

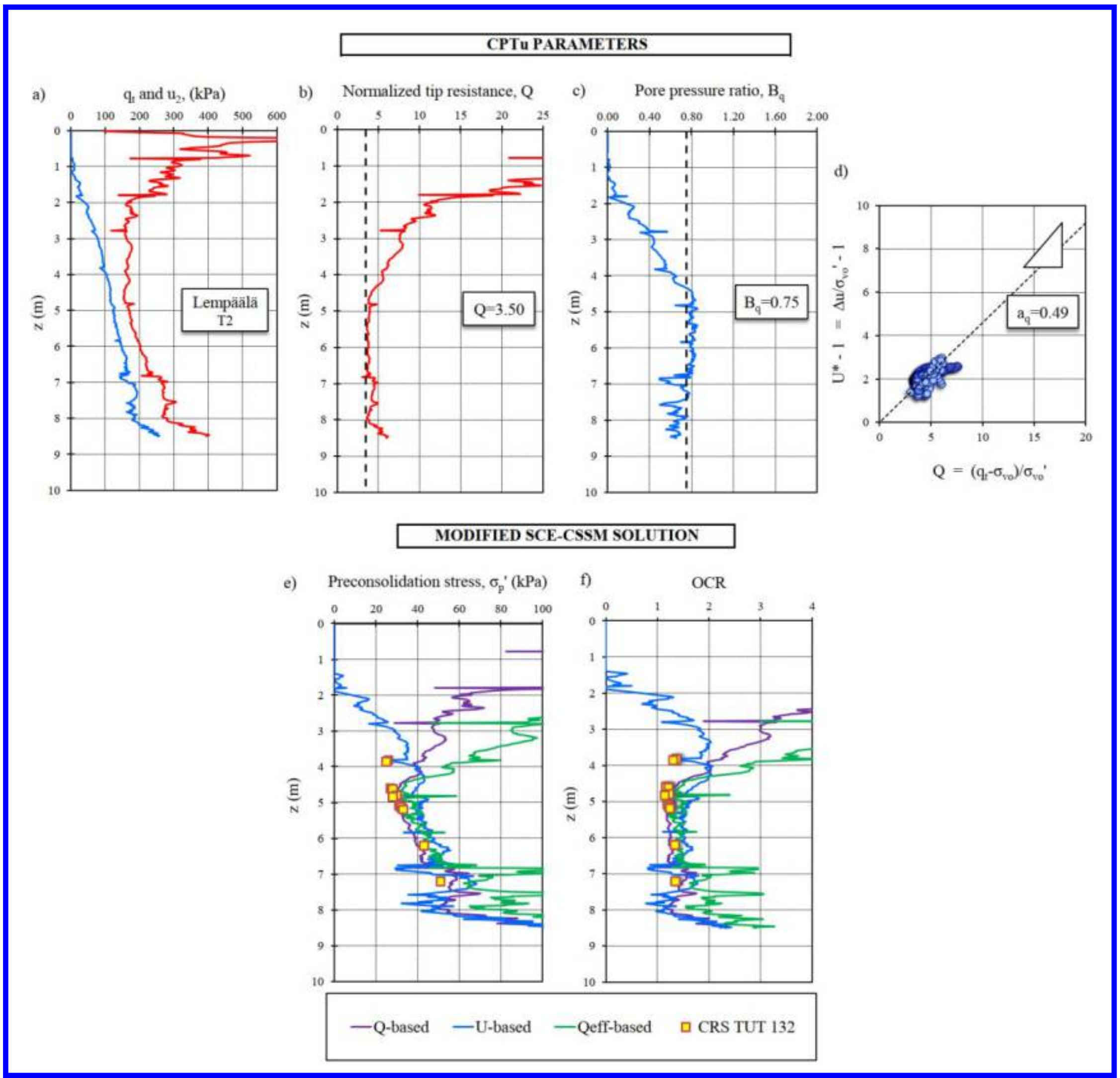

Fig. 9: Implementation of the modified SCE-CSSM analytical solution on Lempäälä clay: a) CPTu soundings; b) normalized tip resistance (Q) versus depth; c) normalized pore pressure ratio (B_q) versus depth; d) evaluation of the slope parameter a_q; e) implementation of the modified SCE-CSSM model for σ'_p prediction; f) implementation of the modified SCE-CSSM model for OCR prediction;

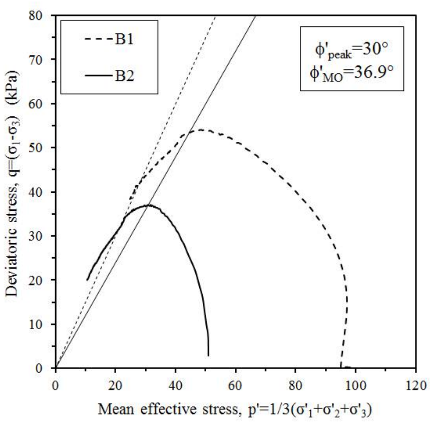

Fig. 10. Effective stress paths of TX compression tests in soft clay at Masku.

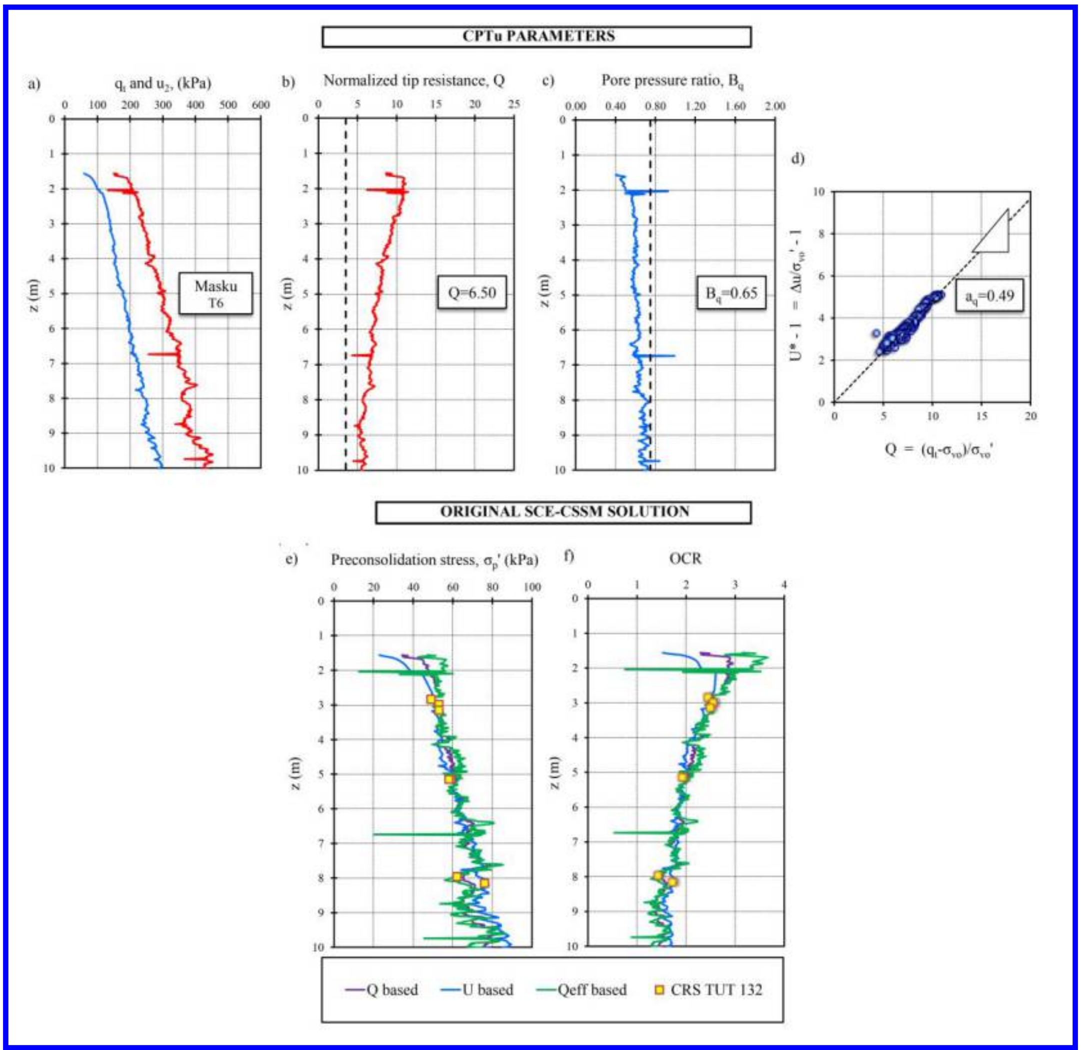

Fig. 11: Implementation of the original SCE-CSSM analytical solution on Masku clay: a) CPTu soundings; b) normalized tip resistance (Q) versus depth; c) normalized pore pressure ratio (B_q) versus depth; d) evaluation of the slope parameter a_q; e) implementation of the modified SCE-CSSM model for σ'_p prediction; f) implementation of the modified SCE-CSSM model for OCR prediction;

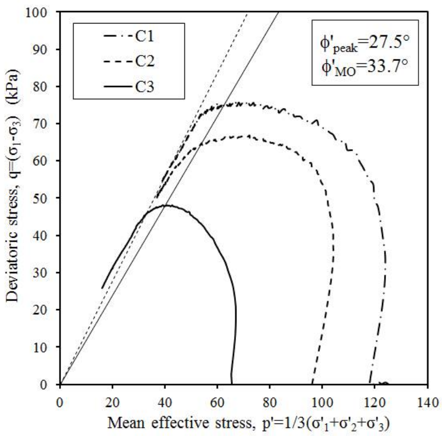

Fig. 12. Effective stress paths of TX compression tests in soft clay at Paimio.

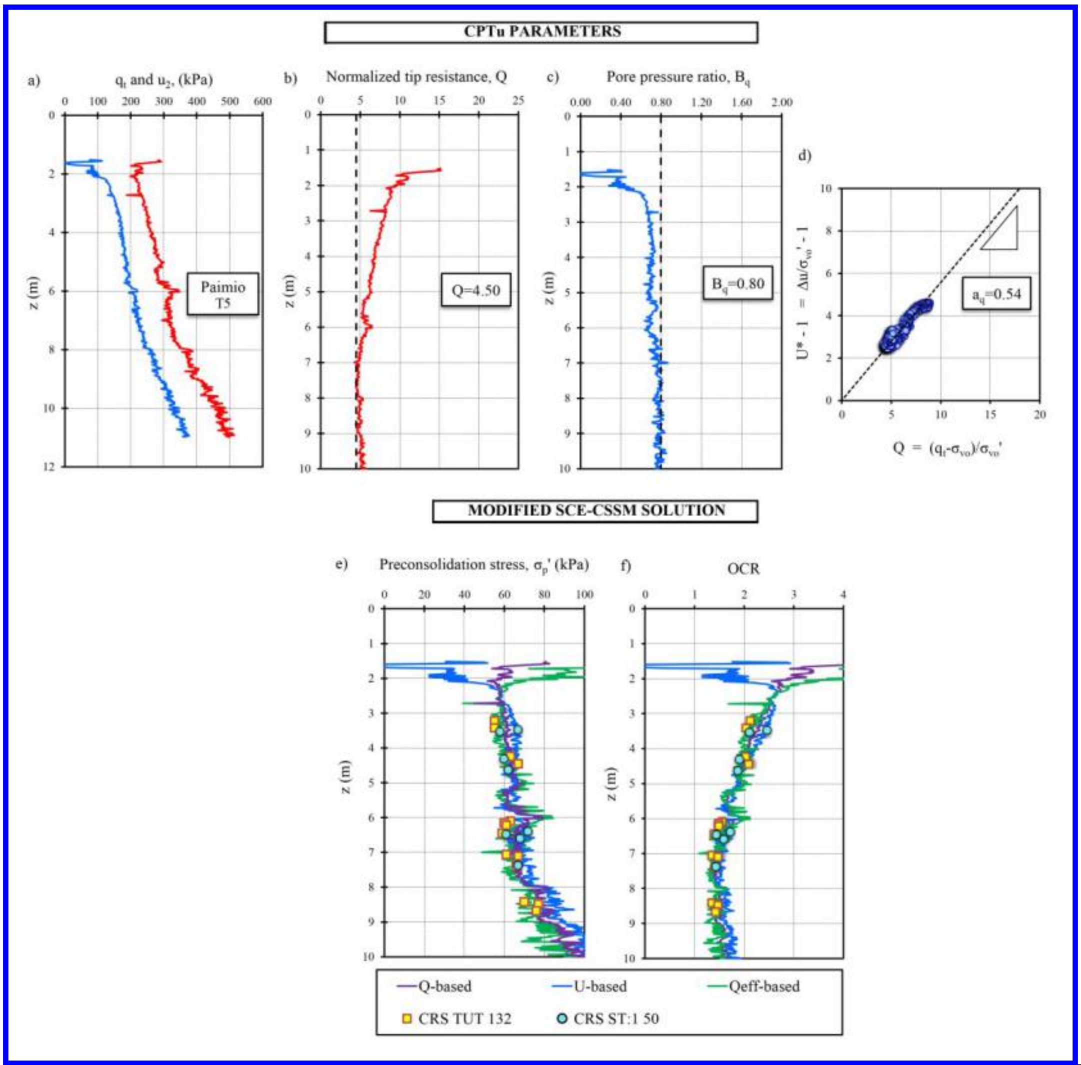

Fig. 13: Implementation of the modified SCE-CSSM analytical solution on Paimio clay: a) CPTu soundings; b) normalized tip resistance (Q) versus depth; c) normalized pore pressure ratio (B_q) versus depth; d) evaluation of the slope parameter a_q; e) implementation of the modified SCE-CSSM model for σ'_p prediction; f) implementation of the modified SCE-CSSM model for OCR prediction;

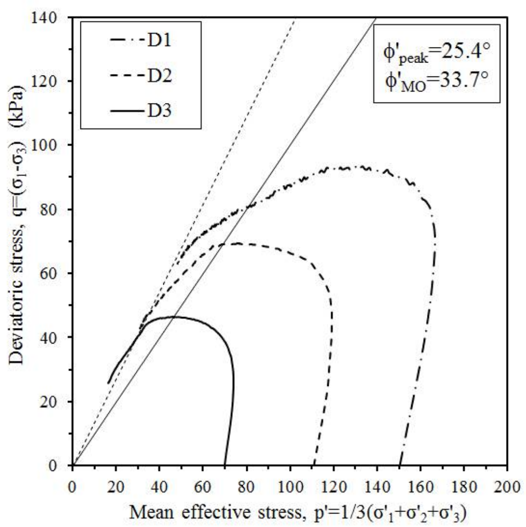

Fig. 14. Effective stress paths of TX compression tests on soft clay from Sipoo.

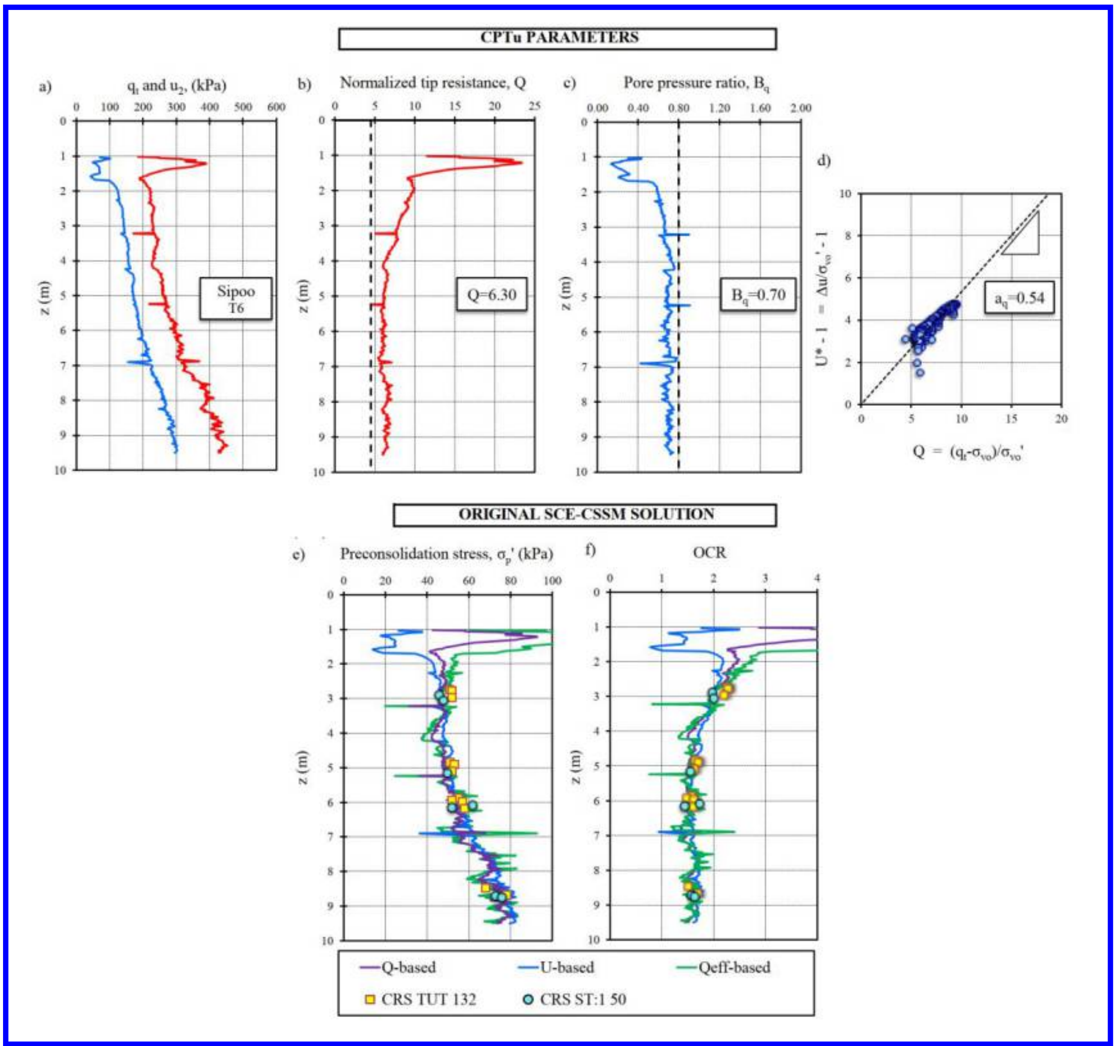

Fig. 15. Implementation of the simplified SCE-CSSM analytical solution on Sipoo clay: a) CPTu soundings; b) normalized tip resistance (Q) versus depth; c) normalized pore pressure ratio (B_q) versus depth; d) evaluation of the slope parameter a_q; e) implementation of the modified SCE-CSSM model for σ'_p prediction; f) implementation of the modified SCE-CSSM model for OCR prediction;

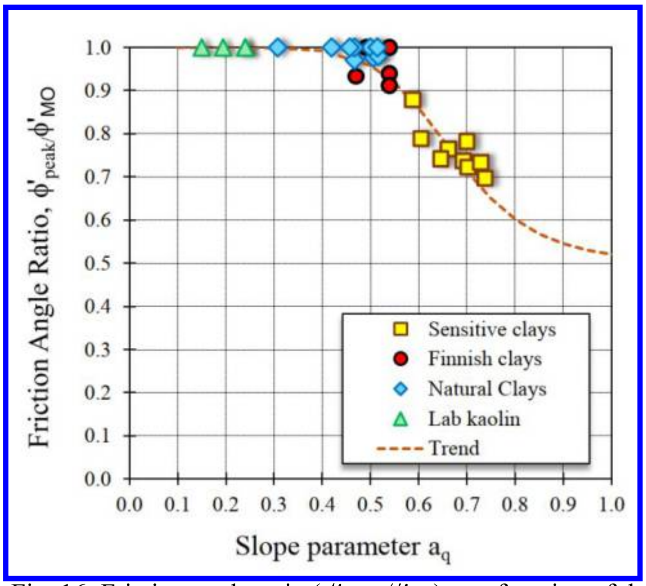

Fig. 16: Friction angle ratio (ϕ'_{peak}/ϕ'_{MO}) as a function of the slope parameter a_q for clays.

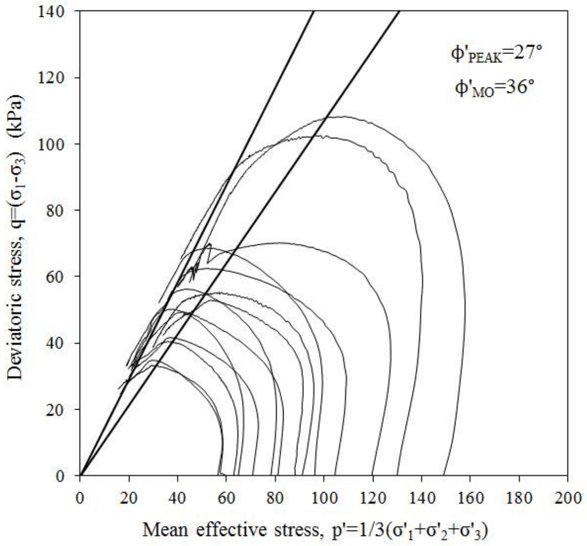

Fig. 17. Effective stress paths of TX compression tests from different Finnish clay sites.

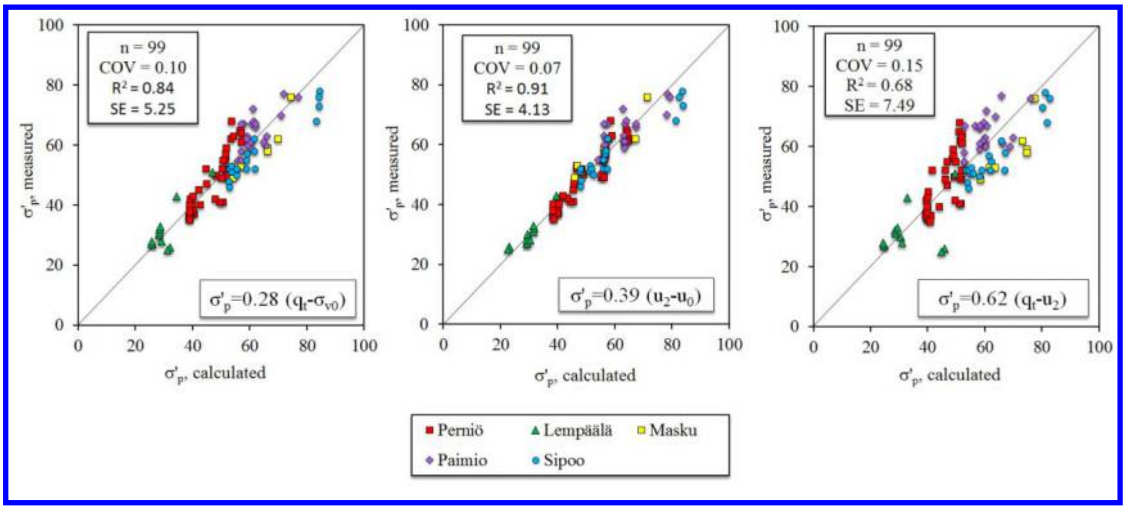

Fig. 18. Unbiased CPTu-based correlations for Finnish sensitive clays

TABLES

Table 1. Geotechnical properties of investigated sites.

SITE	*w* (%)	PI	OCR	S_t
Perniö	70 – 120	20 – 40	1.3 – 12	40 – 70
Lempäälä	40 – 130	20 – 40	1.2 – 1.5	30 – 40
Masku	70 – 120	40 – 70	1.2 – 1.7	20
Paimio	50 – 110	20 – 40	1.3 – 1.8	60 – 100
Sipoo	80 – 120	40 – 60	1.3 – 1.9	20 – 40

Table 2. Coefficient of determination (R^2) of the SCE-CSSM equations for deriving σ'_p and OCR.

SITE	SCE-CSSM MODEL	R^2: σ'_p based on q_{net}	R^2: σ'_p based on Δu_2	R^2: σ'_p based on q_{eff}	R^2: OCR based on Q	R^2: OCR based on U	R^2: OCR based on Q_{eff}
PERNIÖ	MODIFIED	0.80	0.85	0.64	0.80	0.83	0.75
LEMPÄÄLÄ	MODIFIED	0.52	0.90	0.32	0.41	0.77	0.31
MASKU	ORIGINAL	0.85	0.86	0.67	0.96	0.96	0.93
PAIMIO	MODIFIED	0.67	0.61	0.69	0.85	0.85	0.78
SIPOO	ORIGINAL	0.91	0.91	0.87	0.86	0.78	0.86

Table 3: Operational parameters for SCE-CSSM solution for Finnish sites.

SITE	NTH SOLUTION B_q	NTH SOLUTION Q	NTH SOLUTION ϕ'	TX TESTS ϕ'_{peak}	TX TESTS ϕ'_{MO}	SCE-CSSM SOLUTION TYPE	SCE-CSSM SOLUTION ϕ'_{peak}	SCE-CSSM SOLUTION ϕ'_{MO}	SCE-CSSM SOLUTION Λ	SCE-CSSM SOLUTION a_q	SCE-CSSM SOLUTION I_R
PERNIÖ	0.80	4.50	33.7	28	36	MOD.	31	33	1.00	0.54	191
LEMPÄÄLÄ	0.75	3.50	30	*n.a.*		MOD.	28	30	1.00	0.49	88
MASKU	0.65	6.50	35.9	30	36.9	ORIG.	36	-	1.00	0.49	124
PAIMIO	0.80	4.50	33.7	27.5	33.7	MOD.	31	34	1.00	0.54	138
SIPOO	0.70	6.30	36.3	25.4	33.7	ORIG.	34	-	1.00	0.54	332

Table 4: Proposed correlations for Finnish clays and calibration results

Equation	Correlation	n	Calibration results: b	Calibration results: COV	Calibrated Correlation
20	$\sigma'_p = 0.25\ (q_t - \sigma_{v0})$	99	1.12	0.10	$\sigma'_p = 0.28\ (q_t - \sigma'_{v0})$
23	$\sigma'_p = 0.30\ (q_t - \sigma_{v0})$	99	0.93	0.10	$\sigma'_p = 0.28\ (q_t - \sigma'_{v0})$
21	$\sigma'_p = 0.39\ (u_2 - u_0)$	99	0.99	0.07	$\sigma'_p = 0.39\ (u_2 - u_0)$
22	$\sigma'_p = 0.53\ (q_t - u_2)$	99	1.17	0.15	$\sigma'_p = 0.62\ (q_t - u_2)$