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Evaluating undrained shear strength and sensitivity in soft sensitive clay using piezocone and field vane tests

Évaluation de la résistance au cisaillement non drainé et de la sensibilité dans l'argile molle sensible en utilisant des essais au cône piézométrique et des essais au scissomètre sur le terrain

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ABSTRACT: Evaluating undrained shear strength in clayey soils, especially soft sensitive clays in Finland, is crucial for several geotechnical engineering applications. In-situ investigation methods, including field vane and piezocone testing, offer versatile methodologies to assess the soil parameters, overcoming issues related to undisturbed soil sampling. Challenges in using the field vane in soft sensitive clays are discussed, as well as the improvements offered by piezocone testing. However, evaluating cone factors to assess the undrained shear strength is not straightforward, owing to soil strength anisotropy and overconsolidation effects. The paper focuses on assessing the undrained and remoulded shear strength in Finnish soft sensitive clays based on an extensive experimental program conducted at four different test sites, comparing the results obtained from piezocone, field vane, and fall cone tests. Discrepancies among these methods are highlighted, as well as possible improvements in devices and test interpretation to assess the soil parameters correctly.

RÉSUMÉ: L'évaluation de la résistance au cisaillement non drainé dans les sols argileux, en particulier dans les argiles sensibles et molles de Finlande, revêt une importance cruciale pour plusieurs applications en génie géotechnique. Les méthodes d'investigation in situ, telles que le test de la gaine et le test de la piezocone, offrent des approches polyvalentes pour évaluer les paramètres du sol, surmontant ainsi les problèmes liés à l'échantillonnage non perturbé du sol. Les défis liés à l'utilisation du test de la gaine dans les argiles sensibles sont discutés, ainsi que les améliorations offertes par le test de la piezocone. Cependant, l'évaluation des facteurs de cône pour évaluer la résistance au cisaillement non drainé n'est pas aisée, en raison de l'anisotropie du sol et de la surconsolidation. L'article se concentre sur l'évaluation de la résistance au cisaillement non drainé et remaniée dans les argiles sensibles de Finlande, sur la base d'un vaste programme expérimental mené sur quatre sites d'essais différents, comparant les résultats obtenus à l'aide du piezocone, du test du scissomètre et du test du pénétromètre à cone tombant. Les divergences entre ces méthodes sont mises en évidence, de même que les améliorations possibles des dispositifs et de l'interprétation des essais pour évaluer correctement les paramètres du sol.

Keywords: Clays, cone penetration, fall cone, piezocone, sensitivity, shear strength, vane.

1 INTRODUCTION

The accurate determination of undrained shear strength (s_u) in clayey soils is a crucial aspect upon which critical decisions regarding foundation design, embankment stability, and overall geotechnical infrastructure depend. In the context of Finnish clays, undrained shear strength assessment has been a subject of particular interest, notably through the utilization of the Field Vane Shear Test (FVT) and the Cone Penetration Test with pore pressure measurements (CPTU) (Di Buò 2020; Selänpää 2021; Länsivaara et al. 2022). Furthermore, it is common practice to collect undisturbed samples for conducting the fall cone tests (FCT) to assess the intact and remoulded strength properties of soft sensitive clays in Finland.

FVT is established as a common practice for determining undrained shear strength. Recent research studies conducted at Tampere University of Technology (Selänpää et al. 2017) have revealed the potential underestimation of undrained shear strength in soft sensitive clays when using FVT due in part to soil disturbance caused during predrilling and vane insertion, strain rate effects, non-uniform shear stress distribution around the vane, uncertainties in soil-rod friction evaluations, waiting time between vane insertion and rotation, apparatus maintenance, and calibration, as well as measurement system accuracy and errors.

Moving beyond the traditional FVT, the CPTU offers a rapid and continuous in-situ approach to evaluate s_u, providing readings of cone tip resistance (q_c), sleeve friction (f_s), and porewater pressure measured behind the shoulder (u_2) (Lunne et al. 1997).

Nevertheless, the cone factors N_{kt} and $N_{\Delta u}$ are needed to evaluate s_u from CPTU data based on the correlations $s_u=(q_t-\sigma_{v0})/N_{kt}$ and $s_u=(q_t-\sigma_{v0})/N_{\Delta u}$, where q_t is the corrected cone tip resistance for unequal end area effects (Jamiolkowski et al. 1985; Robertson and Campanella 1988; Lunne et al. 1997), σ_{v0} is the total vertical stress, and u_0 is the in-situ water pressure.

In overconsolidated clays, characterized by dilative stress-strain behaviour, the cone-bearing factor N_{kt} determination is rather challenging due to the strain level at which laboratory undrained strength is defined and the noted decrease of overconsolidation ratio (OCR) with depth (D'Ignazio & Lehtonen 2021).

Moreover, further challenges arise when taking into account the s_u anisotropy in clay in stability analysis, specifically active ($s_{u,A}$), passive ($s_{u,P}$), and direct simple shear ($s_{u,DSS}$) modes. These differences in undrained shear strength behavior occur due to the unique stress paths, direction of loading, and strain levels associated with each loading mode (Bjerrum 1973).

In this scenario, the CPTU data can be employed to assess the s_u in compression, whereas the FVT is more directly associated with determining simple shear, $s_{u,DSS}$. Consequently, making a direct comparison between these two tests may yield different results.

In the study of soft sensitive clays, a critical focus lies in assessing remoulded shear strength ($s_{u,rem}$) and soil sensitivity (S_t). These clays exhibit a relatively stiff response in their undisturbed state but transform into a viscous liquid upon remoulding, as initially noted by Rosenqvist (1953). The S_t is a parameter defined as the ratio of peak s_u to the corresponding $s_{u,rem}$ at the same water content (w). The term 'quick clay' characterizes highly sensitive clays with S_t values exceeding 50 and $s_{u,rem}$ values below 0.4 kPa (Rankka et al., 2004). However, establishing an unambiguous definition of quick clays remains challenging, as various classification systems have been put forth, including those by Rosenqvist (1953), Bjerrum (1954), Holtz et al. (2011), and Rankka et al. (2004).

Traditionally, $s_{u,rem}$ and S_t are determined through fall cone tests on soil samples. However, this method can be costly and time-consuming, especially when faced with the challenges of obtaining high-quality undisturbed samples (Ladd and DeGroot, 2003; Di Buò et al., 2019). Consequently, the prospect of assessing soil sensitivity through field testing becomes increasingly attractive.

CPTU provides a promising solution for estimating remoulded strength, utilizing f_s that reflects the frictional resistance encountered as the sleeve penetrates the soil. It is important to note that several authors have addressed concerns about the accuracy and resolution of sleeve friction measurements in soft, sensitive clays, where measured friction values can dip below 1 kPa (Lunne et al. 1997). These challenges can be mitigated by employing piezocones with higher resolution and precision (Di Buò et al., 2022).

Additionally, $s_{u,rem}$ can be measured using FVT. In this approach, the vane's rotational speed is increased to 6°/s, and measurements are taken after a 3600° vane rotation. Selänpää et al. (2017) discussed issues related to inaccuracies in remoulded strength evaluation based on FVT, which may stem from device-related factors, such as loose connections between the vane axle and the rotating system, vane tilt movements causing a 'wave' effect, and potential variations in pore pressure distribution around the remoulded area.

One aim of this paper is to exploit data obtained from an extensive experimental program conducted on Finnish soft sensitive clays (Di Buò 2020, Selänpää 2021, Länsivaara et al. 2022) and evaluate profiles of s_u from CPTU, FVT, and FCT test with particular emphasis on the values of the factors N_{kt} and $N_{\Delta u}$. Moreover, a comparative analysis is conducted among CPTU, FVT, and FCT methods to assess the remoulded shear strength, aiming to explore disparities arising from the diverse approaches.

In the following sections, the raw, direct measurements of FVT and FCT are utilized. They have not been empirically corrected based on plasticity.

2 EXPERIMENTAL DATA FROM SITES

The data included in this paper are a part of an extensive research project conducted by the Research Centre Terra at Tampere University in collaboration with the Finnish Transport Agency. The primary objective of this study was to establish robust correlations for estimating s_u and the preconsolidation stress (σ'_p) in Finnish soft clays. Furthermore, this research aimed to promote the utilization of CPTU as a solution to address challenges associated with the traditional FVT method. For a more comprehensive understanding of this research and its findings, details are given by Di Buò (2020), Selänpää (2021), and Länsivaara et al. (2022).

The experimental program encompassed various test sites across Finland. However, the focus of this paper is on four specific sites within the country, namely Perniö, Masku, Paimio, and Sipoo. The main geotechnical properties of the investigated sites, including water content (w), plasticity index (PI), and soil sensitivity (S_t), are detailed in Table 1. The investigated clays are characterized by low OCR (1.2 – 1.50), high natural water content (40 – 120), and plasticity index, ranging between 20 and 70. The Masku and Sipoo clays are characterized by lower sensitivity compared to the Perniö and Paimio clays.

These sites have been investigated by using a low-capacity cone (7.5 MPa), which is suitable in sensitive clay deposits, and an innovative electric downhole FVT device equipped with a casing. Moreover, samples have been retrieved with a tube sampler to overcome the difficulties related to sample disturbance in soft sensitive clays. Details of the devices and testing procedure are discussed by Selänpää et al. (2017), Di Buò (2020), and Länsivaara et al. (2022).

3 EXPERIMENTAL PROGRAM RESULTS

3.1 Undrained shear strength evaluation

The undrained shear strength profiles, derived from CPTU, and the intact strength determined using the FVT and FCT are illustrated in Figures 1 and 2 using q_{net} and Δu_2, respectively, for each of the 4 sites. Notably, a single representative CPTU profile was selected for each site, specifically those characterized by the highest data quality.

The N_{kt} and $N_{\Delta u}$ factors were assumed to optimize the fit of the FVT and FCT data. It is evident that, across all the sites examined, the s_u values determined by the FCT consistently exceed those obtained from the FVT. In some instances, such as Paimio and Sipoo, it is possible that the FVT data may have been affected by inaccuracies related to device or testing issues, resulting in unrealistically low s_u values.

The calculated N_{kt} values range from 11 to 14, while $N_{\Delta u}$ values range from 8 to 11, with the lower values providing a better fit to the FCT data. The variability in the evaluation of s_u results from many variables: soil heterogeneity, device precision and accuracy, interpretation methods, and operator skills, to name a few.

Table 1. Geotechnical properties of the investigated clays.

Site	Depth	w (%)	PI (%)	S_t
Perniö	2.0 – 3.0	100 – 110	40	40 – 60
	3.0 – 4.0	70 – 100	30	50 – 70
	4.0 – 6.0	70 – 90	30	50 – 70
	6.0 – 8.0	90 – 110	40	70 – 90
Masku	3.0	80	40	20
	5.0	120	70	20
	7.0	60 – 80	50	20
Paimio	3.0 – 5.0	40 – 80	20	60 – 100
	6.0 – 7.0	90 – 110	40	80 – 90
	7.0 – 9.0	70 – 90	40	60 – 80
Sipoo	2.0 – 3.0	80 – 100	50	20 – 40
	5.0 – 7.0	90 – 110	60	20 – 30
	8.0 – 9.0	80 – 100	50	15

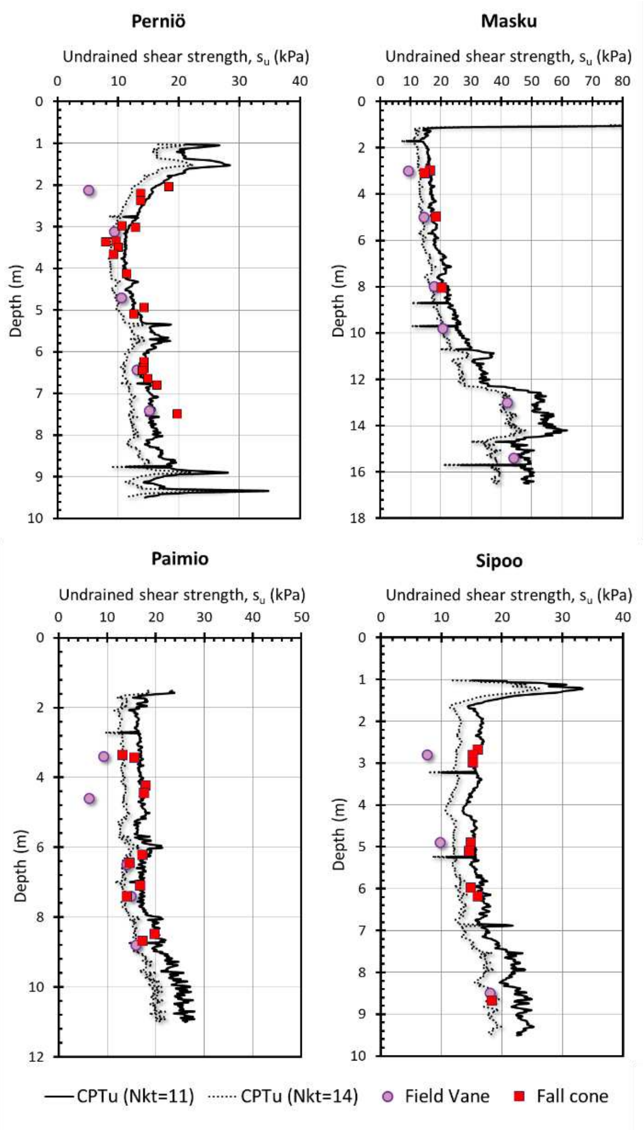

Figure 1. S_u profiles based on CPTU, FVT, and FCT with indications of the best-fit N_{kt} factor.

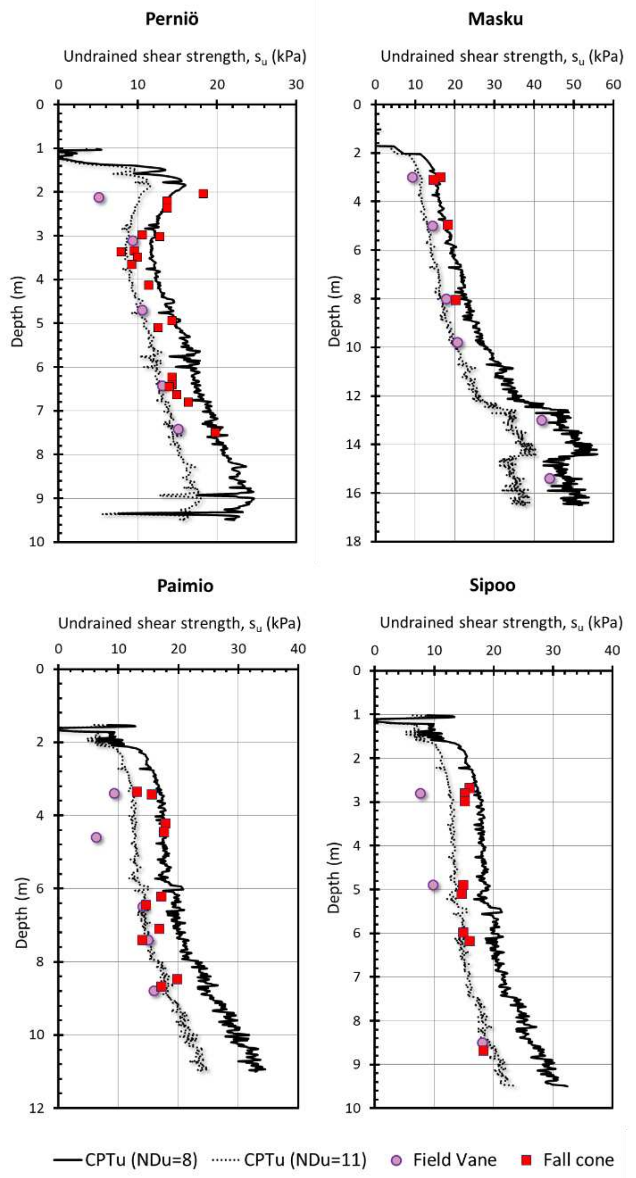

Figure 2. S_u profiles based on CPTU, FVT, and FCT with indications of the best-fit $N_{\Delta u}$ factor.

3.2 Evaluation of $s_{u,rem}$ and S_t

The assessment of $s_{u,rem,}$ and S_t in soft sensitive clays presents notable challenges stemming from the inaccuracies associated with field test devices, including CPTU and FVT, as well as considerations related to sample quality and laboratory test procedures in the case of FCT. In the case of the FVT, the value of $s_{u,rem}$ is obtained from the residual torque reading after 10 full revolutions of the rotated vane. For the FCT, after a peak s_u is obtained, the sample is remoulded and tested again using a free-fall drop cone weight to obtain $s_{u,rem}$. For the CPTU, the normal assumption is that the remoulded strength is equal to the measured sleeve friction, i.e., $s_{u,rem} = f_s$ (e.g., Lunne et al. 1997). However, a recent database study (Mayne et al. 2023) has shown that while f_s provides a reasonable value of $s_{u,rem}$ in a variety of clays having low-medium sensitivity, in fact, f_s in highly-sensitive to quick clays overpredicts the $s_{u,rem}$ by a factor of 2 to 10.

Figure 3 presents a comparison of field data on 16 clays in terms of remoulded vane strength (s_{ur}) versus measures of sleeve friction (f_s). The database included 11 clays of low-medium sensitivity ($S_t < 15$) and 5 clays that are of high sensitivity ($S_t > 15$).

Notwithstanding these challenges, it is evident that FCT stands out as the most reliable method for evaluating $s_{u,rem}$, provided that the natural water content (w) is maintained. The data collected from the surveyed sites in Finland are presented in Figure 4, illustrating that CPTU is incapable of accurately directly estimating $s_{u,rem}$ due to limitations in sleeve sensor resolution. In contrast, FVT yields closer agreement with the values measured via FCT, although the results consistently exhibit higher values. These observations have been previously discussed by Selänpää et al. (2017) and Di Buò et al. (2022).

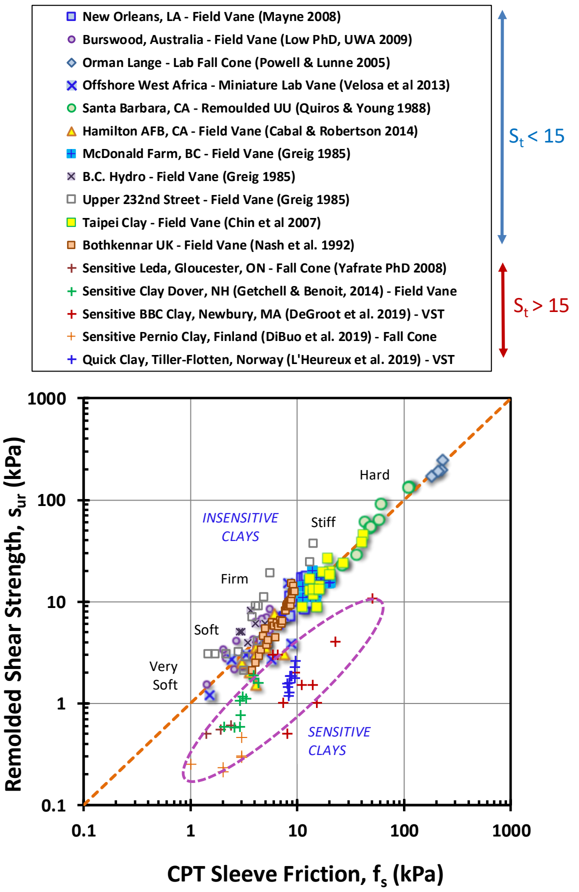

Figure 3. Measured values of remoulded undrained shear strength from FVT (s_{ur}) versus CPTU sleeve friction (f_s) for 16 clays (after Mayne et al. 2023).

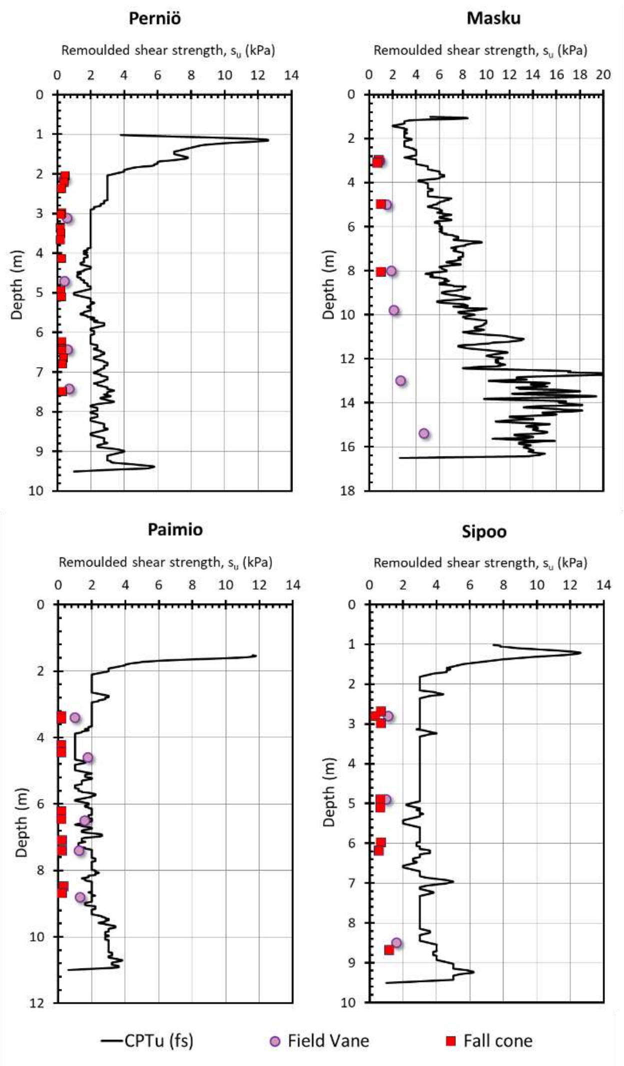

Figure 4. $S_{u,rem}$ profiles based on CPTU, FVT, and FCT.

4 CONCLUSIONS

Assessing the strength parameters s_u, $s_{u,rem}$, and S_t in soft sensitive clays is rather challenging, owing to several factors, including different devices, testing methodologies, interpretation methods, and soil properties variability. This paper reports findings obtained from 4 test sites located in soft sensitive clay deposits in Finland. The primary outcomes of this research study can be summarized as follows:

- The intact strength, as determined by the FCT, generally exceeds the s_u measured by the FVT.
- The best fit N_{kt} values fall within the range of 11 and 14, while $N_{\Delta u}$ values span from 8 to 11, with the lower value fits better the FCT data;
- The CPTU sleeve friction is not a suitable method to correctly estimate $s_{u,rem}$ due to the limited resolution of the load cell sensor, whereas the FVT provides comparable values to those measured through the FCT.

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