Using SHANSEP for verification of unreliable piezocone data in clays

M D'Ignazio¹², V Lehtonen²

¹ Department of Civil Engineering, Tampere University, Korkeakoulunkatu 5, 33720, Tampere, Finland
² Ramboll Finland Oy, Pakkahuoneenaukio 2, 33100, Tampere, Finland

marco.dignazio@tuni.fi; marco.dignazio@ramboll.fi

Abstract. The evaluation of the undrained stability of old embankments on soft clays relies upon the accurate modelling of undrained shear strength in the subsoil. It is vital to account for the effects of consolidation to determine the increased shear strength below the embankment. The CPTU test is a fast in-situ test that provides continuous measurements with depth and can be easily performed through the embankment to evaluate the strength increase. The interpretation of undrained shear strength from CPTU requires the selection of cone factors, which are normally based on laboratory or in-situ (e.g. field vane) tests or empirical correlations. However, CPTU measurements can be negatively affected if the test is poorly executed or if the apparatus lacks proper calibration. This paper discusses how the SHANSEP empirical model for clays can be used to verify the reliability of the available CPTU measurements in a given site investigation case. Further, the paper attempts to provide insights into the selection of empirical cone factors for modelling undrained shear strength for embankment stability. The SHANSEP 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 applicability of the method is presented for a case study from Western Finland, where CPTU testing was carried out both on the side and underneath an old railway embankment. The results of the study are exploited to suggest recommendations for engineering practice.

1. Introduction
The undrained shear strength ($s_u$) governs the short-term stability of embankments built on soft clay deposits. An accurate modeling of $s_u$ below old embankments, which accounts for the effects of consolidation in terms of strength increase with time, is likely to result in higher safety factors compared to the conditions prior to construction and will allow for increased traffic loads on the already existing infrastructure. Therefore, it may reduce or, for some cases, avoid costly solutions to improve stability under upgraded design loads.

The undrained shear strength can be evaluated from both in-situ, e.g. field vane (FVT), piezocone (CPTU), and laboratory tests, e.g. triaxial, direct simple shear, fall cone. CPTU testing can be carried out relatively easily and quickly through the embankment and used as the basis to evaluate strength increase after a certain period of time. Among others, one of the main advantages of CPTU is that it provides continuous readings of cone penetration resistance ($q_c$), pore pressure above tip ($u_2$) and sleeve friction ($f_s$) with depth. However, CPTU requires laboratory or in-situ (e.g. FVT) tests to interpret $s_u$. Therefore, the reliability of the $s_u$ from CPTU will depend upon the quality of the calibration tests.
Laboratory test results are known to be affected by the sampling technique ([1],[2]) and specimen handling prior to testing, while FVT may suffer from inaccuracies related to testing apparatus and procedure ([3]). In addition, CPTU measurements can be negatively affected by poor test execution or if the apparatus is not properly calibrated. For instance, if proper saturation of the porous filter is not ensured, \( u_2 \) will likely be underestimated ([4]). This will, in turn, underestimate \( s_u \) and may result in costly design solutions.

One well-established and reliable ([5],[6],[7]) model for \( s_u \) is the SHANSEP empirical model for clays ([8]). It describes the relationship between the normalized \( s_u \) and the overconsolidation ratio (OCR) by means of empirical material coefficients that are defined from laboratory test results.

The use of SHANSEP in CPTU interpretation has been discussed in the literature (e.g. [9],[7],[10]). However, it is seldom applied in practice since it requires the determination of OCR and a laboratory calibration of material coefficients. Nevertheless, SHANSEP parameters for clays have been widely investigated by several authors and collected in both global as well as regional databases ([5],[11],[12],[13],[14],[15]). Therefore, in absence of laboratory data, calibration parameters can be established from these databases and used for preliminary analyses.

This paper attempts to use SHANSEP to model \( s_u \) and detect unreliable CPTU measurements in clays. The framework is exploited to define equations to determine empirical cone factors, where model parameters are selected from databases. The method is applied to a case study from Western Finland, where CPTU measurements are available from both the side and the centerline of an old railway embankment founded on a soft normally consolidated clay. Field vane test data are used to verify the applicability of the method to Finnish soil conditions.

2. SHANSEP empirical model for clays

Ladd and Fott ([8]) first introduced the SHANSEP concept, which describes the normalized \( s_u \) with respect to the vertical effective consolidation stress \( (s_u / \sigma'_w) \) as a function of the OCR \( (=\sigma'_p / \sigma'_w) \), following equation (1):

\[
\frac{s_u}{\sigma'_w} = \left( \frac{s_u}{\sigma'_w} \right)_{NC} OCR^m = S OCR^m
\]

where \( S \) is the \( (s_u / \sigma'_w) \) for 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 (TXC), extension (TXE) and DSS tests yield to different values of \( S \) ([12],[16]). Typical values of \( S \) are 0.28-0.35 for TXC ([16],[17]) and 0.20-0.27 for DSS ([5],[12],[16],[17],[18]). Furthermore, some Authors 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 TXE ([11],[16]). Other studies suggested \( m \) to be fairly constant and equal to \( \approx \)0.8 ([5],[13]). D’Ignazio et al. ([5]) found \( m = 0.76 \) for Finnish clays based on FVT data from 24 sites and OCR = 1-4.

For Swedish clays, [13] reported a dependency of DSS and TXE strength on the liquid limit (LL), while [7] and [14] observed a dependency of \( s_u \) on the natural water content \( w \). No dependency of \( S \) and \( m \) on index parameters was observed from FVT on Finnish clays ([5]).

Interpretation of piezocene results using a SHANSEP-CPTU model

The determination of the monotonic \( s_u \) from CPTU is generally based on the cone factors \( N_{kt} \) and \( N_{sw} \) that reflect the laboratory test data, as follows:

\[
s_u = \frac{q_t - \sigma'_{so}}{N_{kt}} \quad (2)
\]

\[
s_u = \frac{u_2 - u_{eq}}{N_{sw}} \quad (3)
\]

where \( q_t \) is the corrected cone tip resistance, \( \sigma'_{so} \) the total overburden in-situ vertical stress, \( u_2 \) the pore pressure measured above the cone and \( u_{eq} \) the equilibrium pore water pressure. For low OCR offshore and onshore clays, [19] reported \( N_{kt} = 8.6-15.3 \) and \( N_{sw} = 3.3-8.8 \) for TXC and \( N_{kt} = 11-20 \) and
$N_{kt}=4.8-11.9$ for FVT. [7] found $N_{kt}=5-16$ and $N_{kt}=5-10$ for TXC in onshore Norwegian clays with OCR less than 6.

Equation (1) requires the determination of OCR and two empirical coefficients. The OCR can be evaluated from the CPTU results as suggested by e.g. [21] as follows:

$$\sigma'_p = \alpha(q_t - \sigma'_v)$$  \hspace{1cm} (4)
$$\sigma'_p = k(u_2 - u_0) = k\Delta u$$  \hspace{1cm} (5)

where $\alpha$ and $k$ are a site- or layer-specific empirical coefficient that for OCR $< 5$ vary in the range 0.15-0.5 and 0.3-0.8, respectively ([20]). Mean values of $\alpha = 0.3$ and $k = 0.53$ are reported by [21] for clays worldwide. [22] suggested $\alpha = 0.3$ and $k = 0.39$ for slightly overconsolidated Finnish soft clays.

Simple expressions for $N_{kt}, N_{hu}$ can be established from the combination of equations (1), (2), (4) and (1), (3), (5) with $OCR = \sigma'_p / \sigma'_v$, resulting in equations (6) and (7).

$$N_{kt} = \frac{(q_2 - \sigma'_v) / \sigma'_v}{s_u / \sigma'_v} = \frac{(q_t - \sigma'_v_0) / \sigma'_v}{OCR} = \frac{OCR^{1-m}}{as}$$  \hspace{1cm} (6)
$$N_{hu} = \frac{(u_2 - u_0) / \sigma'_v}{s_u / \sigma'_v} = \frac{(u_2 - u_0) / \sigma'_v}{OCR} = \frac{OCR^{1-m}}{ks}$$  \hspace{1cm} (7)

Equations (6) and (7) suggest the empirical cone factors to increase with increasing OCR. For normally consolidated state (OCR=1) and assuming typical values of $\alpha = 0.3$, and $S = 0.22$ for DSS, $N_{kt} \approx 15$. This is in line with the recommendation by [23] for DSS shearing. For $k = 0.53$ and $S = 0.22$, $N_{hu} \approx 8.6$. This agrees with the mean value in [19] for FVT. For triaxial compression, assuming $\alpha = 0.3$, $k = 0.53$ and $S = 0.33$, $N_{kt} \approx 10$ and $N_{hu} \approx 5.7$, in agreement with [7] and [19].

3. Applicability of the SHANSEP-CPTU model

3.1 Site description

The SHANSEP-CPTU model is applied to a case study of an old railway bridge site in a soft clay area. The site is located in Mynämäki, in Southwestern Finland, about 5 km from the Baltic coast. An old railway bridge across a small river is to be replaced, and the stability and stiffness of the approach embankments is to be improved with sheet pile walls installed around the embankment. The new bridge abutments will be founded on large diameter driven steel piles.

A site investigation was conducted in 2018. Test locations are presented in Figure 1. CPTU measurements (among other site investigations) were collected from the embankment centreline (CPTU 272, 275) and approximately 2…5 m off the embankment toe (CPTU 271, 273, 274, 276). The aim of the CPTU measurements and additional FVT was to determine the $s_u$ versus depth profile.

The old approach embankment is approximately 2 m high measured from the surrounding ground level. The structural layers and coarse fill are altogether about 3 m thick. Below the fill layers there is a 18-20 m thick (organic) clay layer. Below the clay layer there is a 6-12 m thick layer of glacial moraine, with bedrock below. At the side of the embankment there is a ca. 1 m thick dry crust above the clay layer. A cross-section from one abutment is given in Figure 2.

The top part of the clay layer has a very high sulphate content. Next to the embankment at 2-3 m depth, the water-soluble sulphate content is 11 000 mg/kg, from dried soil material. At 4-5 m and 13-14 m depths the values are 960 mg/kg and 260 mg/kg, respectively.

The water content, liquid limit (determined as fineness number from fall cone testing of disturbed samples) and organic content are presented in Figure 3. The liquid limit is generally close to the water content, except for the very topmost, quite organic part of the clay layer where the liquid limit is notably higher. The sensitivity measured from fall cone on samples taken underneath the embankment is in the range 5-8. A noteworthy observation is that the measured FVT strength ($s_u/FVT$ in Figure 3) correlates with water content and liquid limit. This is in line with the findings of [5] for Finnish clays. The FVT
strength corrected as a function of liquid limit according to the Finnish embankment stability guidelines ([24]) (hereinafter referred to as $s_u (mob)$) indicates that the clay is nearly normally consolidated.

**Figure 1.** Site investigation layout.

**Figure 2.** Investigated cross-section at Mynämäki.
Undisturbed samples were taken from under the embankment centerline with a ca. 50 mm piston sampler for oedometer testing. Unfortunately, the undisturbed samples turned out to be completely disturbed, possibly due to too fast retraction of the sampler from the soil. Absolutely no indication of a preconsolidation pressure could be observed from the CRS oedometer results.

Figure 3. (a) water content (w) and fineness number (F), (b) organic content and (c) FVT strength from the embankment sides (free field).

3.2 Evaluation and interpretation of CPTU measurements

Measurements of cone tip resistance $q_t$ showed unusual noise and the results were about one order of magnitude higher than expected. This was possibly due to errors in the apparatus calibration. Therefore, the results for $q_t$ are not presented. This study then focuses on the interpretation of $s_u$ based on pore pressure readings.

Pore pressure measurements from CPTU 272 suggest $\Delta u$ under the embankment ($\Delta u_e$) to be consistently lower than $\Delta u$ from the side ($\Delta u_s$) down to ca. -7 m elevation as shown in Figure 4. This would then imply that $s_u$ has decreased with time according to equation (3). On the other hand, CPTU 275 indicated $\Delta u_e > \Delta u_s$. For comparison, CPTU measurements taken 20 years after construction at Murro test embankment in Southwest Finland, showed increased $\Delta u$ along with $s_u$ increase ([25],[26]). The Murro test embankment is 2 m high and is founded on a sulphide normally consolidated clay deposit as the Mynämäki embankment. Further, CPTU 274 shows $u_2$ much lower than the surrounding CPTUs down to ca. +2 m elevation. Therefore, CPTU 272 and 274 seems to have suffered from inaccuracies.

One possible reason for inaccurate measurements may be related to loss of piezocone saturation. CPTU testing requires saturation of the piezocone for a reliable evaluation of $u_2$. Saturation fluids that are commonly used are either de-aired water, silicon oil or glycerine ([4]). As reported by [4], saturation loss can occur when penetrating non-saturated surface deposits, overconsolidated clay layers or very dense coarse layers. For the Mynämäki case, cone penetration through the embankment and/or drycrust may have induced loss of saturation. Some of the pore pressure measurements in Figure 4 show distinct steps in the profile with little definition, particularly at shallow depths. According to [4], this is evidence of poor saturation. The degree of response seems to improve at greater depths, where the profiles reach similar values of pore pressure.
Figure 4. Pore water pressure $u_2$ at Mynämäki site.

Figure 5 shows $N_{3d}$ vs OCR from equation (7) for $k = 0.39$ and $S = 0.22$, $m = 1$ ([27]) and $S = 0.24$, $m = 0.76$, recommended by [5] for $s_u(mob)$ of Finnish clays. Note that the assumption $m = 1$ implies $s_u = S\sigma'_p$ and $N_{3d}$ = constant and independent of OCR. The plot in Figure 4 suggests $N_{3d} \sim 10.7-11.7$ for normally consolidated state. Nevertheless, OCR needs to be defined in order to select the most appropriate $N_{3d}$ value.

Figure 5. $N_{3d}$ vs OCR for $s_u(mob)$. 
The OCR is modelled from equation (5) as $\sigma'_p/\sigma'_v$, with $k = 0.39$ ([22]), as shown in Figure 6. OCR values less than the unity are found from CPTUs 272, 273, 274, 275; while the highest OCR values in the clay (OCR = 1.2-1.5) are found from CPTU 271. An OCR of such a magnitude is in line with Murro test embankment ([28]) and may be an indicator of soil ageing due to secondary consolidation and chemical phenomena ([29]). Unrealistic OCR < 1 values are likely to be the result of inaccurate pore pressure measurements, besides the uncertainties associated with the empirical factor $k$. Further, OCR = 1.2-1.5 next to the embankment suggests that the clay under the embankment is normally consolidated.

![Figure 6. OCR vs depth for $k = 0.39$.](image)

For $k = 0.39$ and OCR = 1.2-1.5, $N_{du} = 11.2-11.6$ according to equation (7) and Figure 5. As illustrated in Figure 7, the $s_{u(mob)}$ from CPTU 271, 273 and 276 based on equation (7) appears to be in line with the FVT results. CPTU 274 matches the FVT behavior only below +2 m elevation; while CPTU 276 seems to slightly overestimate the FVT results. Equation (7) was used assuming that when OCR < 1 $N_{du}$ is taken at the minimum value of OCR = 1. Under these assumptions, $s_{u(mob)}$ from CPTU 275 is higher than the FVT results, suggesting that strength increase occurred under the embankment. This is consistent with the pore pressure measurements in Figure 4. However, it is not straightforward to conclude whether the inferred strength is realistic, given that OCR from CPTU 275 is less than 1 (Figure 6). A proper validation would require actual FVT measurements below the embankment. For the estimated $N_{du}$ values, CPTU 272 would indicate that $s_{u(mob)}$ under the embankment is lower than $s_{u(mob)}$ from the side. In order to fit CPTU 272 to CPTU 275, $N_{du} \approx 5$ would be required to match $s_{u(mob)}$ at ~5 m elevation. Such a $N_{du}$ value could not be justified by equation (7), which was already demonstrated to provide a good fit to the FVT measurements.
Figure 7. $s_u(mob)$ vs depth.

4. Summary and conclusions
This paper discussed the applicability of SHANSEP method for piezocone interpretation in clays and to evaluate possible inaccuracies in CPTU measurements. The SHANSEP method describes the variation of normalized undrained shear strength with overconsolidation ratio. Equations for empirical cone factors $N_{kt}$ and $N_{\Delta u}$ were derived based on SHANSEP. These equations require input parameters from laboratory tests, which are representative of the $s_u$ shearing mode considered in the analysis. When laboratory data is not available, coefficients can be derived from literature on relevant soil types and, possibly, from regional databases.

The applicability of the proposed method was evaluated for a case study of an old railway embankment resting over soft organic sulphate rich normally to slightly overconsolidated clay. The site investigation consisted of CPTU and field vane (FVT) testing, besides the basic index tests. Some of the pore pressure readings showed suspicious measurements, suggesting that the undrained shear strength had decreased with time under the embankment. This could be attributed to the loss of piezocone saturation while penetrating coarse and unsaturated layers above the soft clay. The SHANSEP based interpretation was not only capable of accurately modelling FVT strength measured at the embankment side but could also be used to prove the inaccuracy of pore pressure measurements that would have led to a severe underestimation of undrained shear strength.

Even though this method requires a more extensive validation, the results of this study seem to be promising, considered that the mean values of the empirical coefficients for the determination of OCR and cone factors were selected from literature. At the same time, the need for a thoughtful selection of empirical calibration coefficients from literature may constitute a limitation of the method. It is therefore recommended to select those from high-quality regional databases where possible or, needless to say, from actual test results.
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