Cone Penetration Testing 2022 – Gottardi & Tonni (eds)

Issues related to piezocone sleeve friction measurement accuracy in soft sensitive clays

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ABSTRACT: Over the past decades, the piezocone testing has been increasingly adopted for field investigation as it offers a quick and cost-effective methodology for subsoil profiling and geotechnical parameters estimation. Although the piezocone testing has revealed good applicability worldwide, difficulties are encountered in complex soil conditions, such as soft sensitive clays. One of the key issues in such soils is represented by the poor quality of the sleeve friction (f_s) measurement due to inaccuracy and poor resolution of the sleeve sensor. This paper investigates the influence of f_s data quality on soil parameters determination with particular emphasis on the soil behavior type (SBT) chart classification. The field investigation was conducted in a soft sensitive clay site located in Finland using two different penetrometers: a standard piezocone and an advanced piezocone characterized by enhance accuracy sleeve friction sensor. Results show that the use of high-resolution piezocone plays a key role in soft clays to avoid misleading soil type classification.

1 INTRODUCTION

1.1 *Cone penetration testing (CPT)*

Cone Penetration Testing (CPT) is a fast and reliable means of conducting subsurface investigation for soil profiling, site characterization and geotechnical parameters evaluation. Since the first introduction of the mechanical probe in 1930s, the equipment has been significantly improved by adding porous filters and transducers, obtaining the modern electronic piezocones (CPTu). Nowadays, the traditional piezocone testing provides three independent readings with depth: the cone tip resistance (q_c), the sleeve friction (f_s), and the excess pore water pressure (u_2) measured behind the cone tip (u_2). The q_c value should be corrected (q_t) to consider the pore pressure acting behind the shoulder. This correction is significant in soft to stiff clayey soils (Jamiolkowski et al. 1985, Robertson and Campanella 1988, Lunne et al. 1997).

The data provided by piezocone test is generally characterized by high precision and accuracy. The sensor accuracy is the difference between the target and the measured value while the precision refers to the degree of reproducibility of a measurement. These aspects are summarized in Figure 1.

Another aspect that plays a key role in data quality is the sensor resolution which is the smallest detectable incremental change that can be measured.

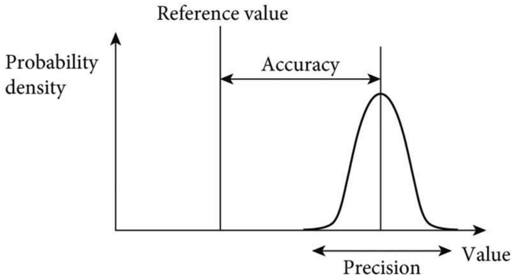

Figure 1. Accuracy and precision definition (source Wikipedia).

This is crucial in soft sensitive clays as the value of f_s is generally very low (<1 kPa).

The equipment available on the market are characterized by different features such as dimensions, tolerances, and sensor accuracy. However, all the specifications, technical requirements, and test procedures are outlined in the European Standards (EN-ISO 22476-1) and American Standards (ASTM D5778 - 20). All these aspects are extensively discussed by (Lunne at al. 1997). Although several piezocones can be employed for CPTu testing, it is fundamental to choose the appropriate equipment to obtain high-quality and reliable data, especially in soft sensitive clays. As an example, studies conducted by

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Tampere University (Di Buò et al. 2016, Di Buò 2020) have revealed that standard penetrometers are not suitable to correctly measure f_s in Finnish soft soil, which negatively affects the data interpretation and the accuracy of soil profiling as the small variability of f_s throughout the entire deposit cannot be detected. Moreover, the f_s is fundamental for the soil classification based on the Soil Behavior Type (SBT) chart proposed by Robertson (1990) or for the assessment of a number of geotechnical parameters, such as the soil sensitivity (Mayne 2014). Despite the importance of the f_s data, its correct measurement is still considered one of the main challenges in soft sensitive clays.

This paper presents the CPTu test results obtained from a soft sensitive clay test site located in Pohja, Southern Finland. The soundings have been performed using a "standard" probe and a penetrometer characterized by enhanced sensor accuracy and resolution, herein after referred to as "advanced". The results are analyzed and compared, pointing out the influence of f_s measurement on the SBT classification and the improvements that can be obtained using high accuracy sensors. The main goal of the study is to investigate the influence of the piezocone sensor accuracy on the soil interpretation, rather than a comparison between cone manufacturers.

1.2 *Equipment*

The two penetrometers adopted in this study were provided by two different manufacturers. Both cones are characterized by 60° apex angle, 10 cm^2 base and 150 cm^2 sleeve area. The first one, referred to as "standard", has been largely used for site investigation in Finnish soft clays as detailed by Di Buò et al. (2020): it consists of an electronic instrumented probe with a nominal range of 7.5 MPa, which is particularly suitable for soft soils investigation. The second, referred herein after as "advanced", is characterized by a nominal range of 50 MPa and higher accuracy compared to the previous cone. This cone has been used at the Pohja site as an attempt to overcome the issues related to the f_s measurement previously discussed. The technical features of both piezocones are summarized in Table 1. The enhanced accuracy of the advanced penetrometer is the result of the embedded sensors type and their configurations. In particular, the q_c and f_s load cells are characterized by four strain gauges wired into a Wheatstone bridge configuration. The bridge is compensated with four modules: two for the material elastic modulus temperature compensation, one for the zero-offset correction and the last one for zero-offset temperature compensation. The Wheatstone Bridge circuit consists of two simple series-parallel arrangements of resistances connected between a voltage supply terminal and ground producing zero voltage difference between the two parallel branches when balanced. It has two input terminals and two output terminals consisting of four resistors configured in a diamond-like arrangement. This configuration allows for high accuracy in the parameter measurement. Similarly, the u_2 sensor consists of a silicon piezoresistive load cell in Wheatstone bridge configuration.

Table 1. Technical features of the piezocones.

Standard penetrometer				
	q_c	f_s	u_2	Inclination
Maximum capacity	7.5 MPa	0.15 MPa	2 MPa	20°
Accuracy	0.2% (15 kPa)	0.7% (1 kPa)	0.25% (5 kPa)	0.5°
Advanced penetrometer				
	q_c	f_s	u_2	Inclination
Maximum capacity	50 MPa	1.6 MPa	2.5 MPa	20°
Accuracy	0.01% (5 kPa)	0.0025% (0.04 kPa)	0.0015% (0.04 kPa)	0.5°

1.3 *Test site*

The Pohja site locates on the southern coast of Finland along the railway line connecting the cities of Helsinki and Turku. The ground elevation is around 9 m above current sea level and the overall topography is flat. However, on a wider scale, the site locates in a valley surrounded by shallow hills with bedrock outcrops. The Pohja site subsoil consists of about 1.5 m thick dry crust layer overlaying a soft slightly consolidated clay layer. Below. silty and sandy layers are encountered. The bedrock is located at depth of 14 m. The water content decreases with depth, from 130% between 2m and 4m till reach 60% at about 7.5 m depth. The natural water content exceeds the liquid limit throughout the entire deposit. Plasticity index is 30–60 and sensitivity, defined as the ratio between intact (s_u) and remoulded undrained shear strength ($s_{u,rem}$), varies between 40 and 60 below the dry crust layer. The undrained shear strength evaluated by the fall cone (FC) test is 7 kPa under the dry crust layer and increases linearly with depth reaching 12 kPa at the depth of 7.5 m. The geotechnical properties of Pohja clay are shown in Figure 2.

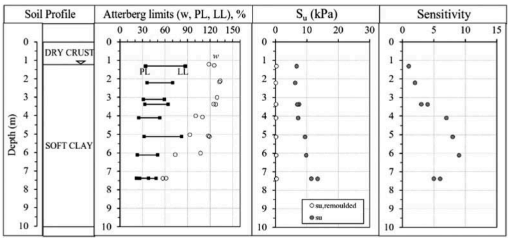

Figure 2. Index properties of Pohja clay.

2 CPTU DATA ANALYSIS

2.1 *CPTu soundings*

A total of three CPTu soundings are performed, two of them obtained from the advanced piezocone and one representative vertical from the standard cone. The main purpose herein is to investigate the impact of the sensor accuracy in the measurement readings. The same testing procedure has been adopted for both penetrometers. An initial pre-drilling is made to avoid pushing the cone into the dry crust layer which may cause the desaturation of the porous stone. Prior to CPTu sounding, the cone is placed into the hole filled with water for temperature balancing. Then, the apparatus is pushed into the soil at a standard rate of penetration of 20 mm/s till reaching the coarse layer (≈ 7 m). The measured q_c has been further corrected to account for the pore water pressure acting behind the cone as follows:

$$q_t = q_c + u_2(1 - a) \quad (1)$$

where *a* is the net cone area ratio provided by the manufacturer after the calibration process. The soundings are conducted using a ceramic filter element replaced after each test. The saturation is ensured by submerging the cone tip into a silicon oil bath in a vacuum device.

Results illustrated in Figure 3 indicate the presence of a homogeneous clay layer from 1 m to 7 m depth followed by interlayers of silts and sands. It is worth observing that both piezocones provide nearly identical response in terms of q_t and u_2 while f_s measurements made using the standard cone are characterized by poor accuracy and low resolution. In particular, higher f_s values are measured by the standard cone (>4 kPa) while the advanced cone indicates f_s values lower than 1 kPa. Even though this difference may seem neglectable, the total error is significant, and it has a great impact in the SBT classification as soil parameter estimation as discussed later.

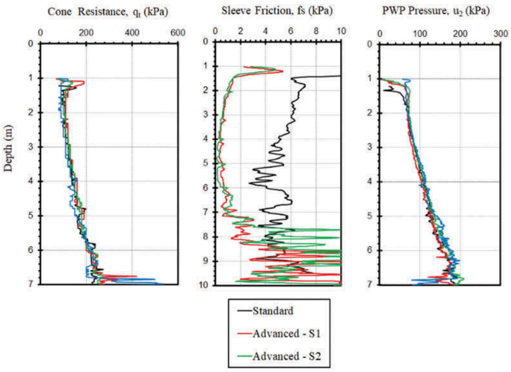

Figure 3. CPTu soundings at Pohja site.

2.2 *Soil Behavior Type (SBT) chart*

Since its first introduction, the CPT has been widely used for soil profiling and classification. Several authors have proposed classification charts that link the CPT parameters (q_t and f_s) to the soil type (Begemann 1965, Robertson et al. 1986, Robertson 1990). Among them, the soil behavior type (SBT) chart proposed by Robertson et al. 1986 has become quite popular. It identifies 12 types of soil based on the qt and fs values. This approach is mainly based on classifying the soil based on the in-situ behavior which depends on the strength, stiffness and compressibility. In contrast, the unified soil classification system (USCS) does not provide any information on the mechanical behavior as it is based on the grain-size distribution and plasticity. However, in most cases, both approaches agree fairly well as detailed by Molle (2005). The SBT chart has been further improved introducing the normalized parameters:

$$Q_t = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \quad (2)$$

$$F_r = \frac{f_s}{q_t - \sigma_{v0}} \text{x}100 \quad (3)$$

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}} \quad (4)$$

where Q_t is the normalized cone tip resistance, F_r is the normalized friction ratio, σ_{v0} is the total overburden vertical stress, σ'_{v0} is the vertical effective stress, u_0 is the hydrostatic pore water pressure. The normalized SBT (SBTn) chart is more reliable as it takes into account the influence of the in-situ stress in the soil classification which is particularly important when the sounding is performed at great depths. The charts are illustrated in Figure 4.

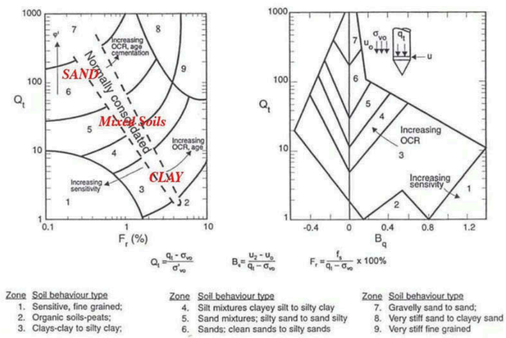

Figure 4. Normalized SBT chart proposed by Robertson 1990.

More recently, Robertson et al. (1998) introduced a normalized cone parameter with a variable stress exponent (n), defined as:

$$Q_{tn} = \left[\frac{q_t - \sigma_{v0}}{p_a}\right]\left(\frac{p_a}{\sigma'_{v0}}\right)^n \quad (5)$$

$$n = 0.38(I_c) + 0.05\left(\frac{\sigma'_{v0}}{p_a}\right) - 0.15 \quad (6)$$

where p_a is the atmospheric pressure (≈100 kPa) and I_c is the SBT index first introduced by Jeffries and Davies (1993) and further modified by Robertson (1990) as:

$$I_c = \sqrt{(3.47 - logQ_t)^2 + (logF_r + 1.22)^2} \quad (7)$$

The normalized SBT chart is shown in Figure 5 with the indication of the I_c values for the different soil type regions.

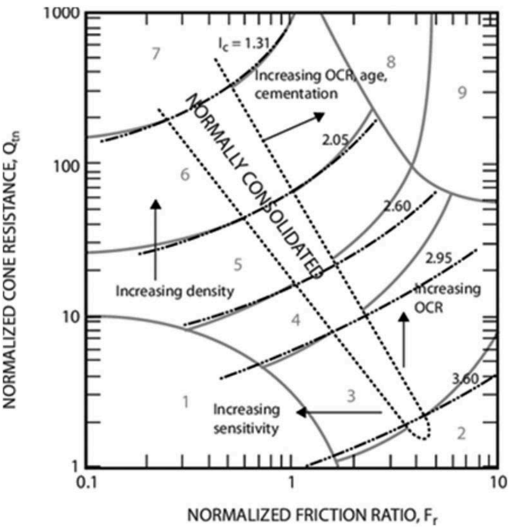

Figure 5. Contours of I_c on a normalized soil behavior type (SBTn) chart (Robertson 1990).

Recently, Robertson (2016) proposed an updated version of the SBT chart to capture the contractive-dilative soil behavior (Figure 6).

In this study, the original SBT chart proposed by Robertson (1990) is taken into account as the main purpose is to evaluate the soil sensitivity instead of the contractive-dilative soil behavior. It is worth observing that soft sensitive clay region is located at the bottom left of the Q_{tn} and F_r chart, or in the bottom right of the $Q_t - B_q$ chart (Figures 7, 8, and 9). Clearly, the correct evaluation of the f_s is fundamental for a correct evaluation of the SBT. To investigate this aspect, the CPTu soundings performed with the two penetrometers have been assessed separately for soil classification by using

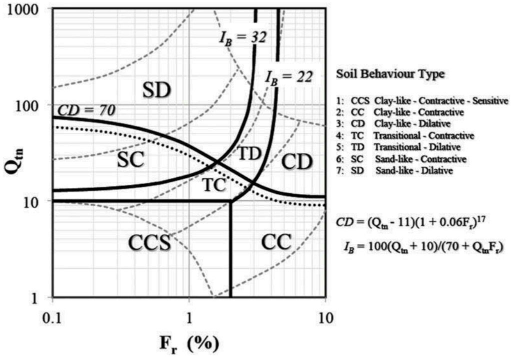

Figure 6. Proposed updated SBTn chart based on Q_{tn}–F_r (Robertson 2016).

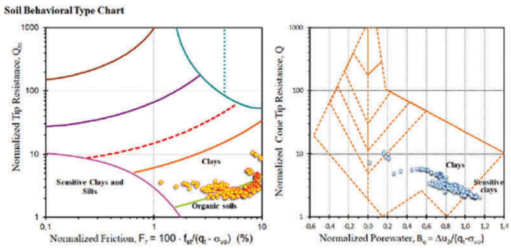

Figure 7. Soil behavior type (SBTn) chart based on standard CPTu cone data.

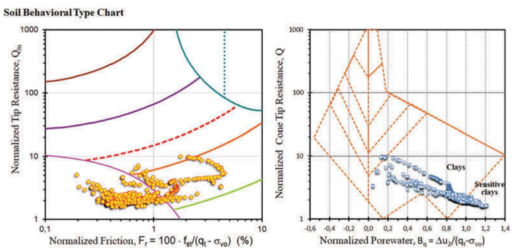

Figure 8. Soil behavior type (SBTn) chart based on the S-1 sounding (advanced cone).

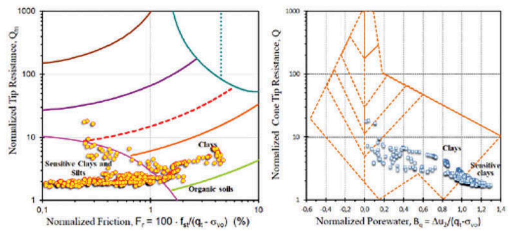

Figure 9. Soil behavior type (SBTn) chart based on the S-2 sounding (advanced cone).

the SBTn charts. Results are presented in Figures 7,8, and 9. As expected, in the Q_{tn}- F_r chart, the data obtained using the advanced cone fall almost entirely in the sensitive clay region while the data points provided by the standard cone fall between the clay and organic clay regions. The reason for this lies obviously in the overestimation of f_s from the standard cone which negatively affected the SBT evaluation. In contrast, the Q_{tn} – B_q chart provides more reliable SBT classification in both cases, even though most of the standard cone data points appear to fall in the clay region.

3 SENSITIVITY EVALUATION BASED ON CPTU DATA

In addition to the SBT classification, the f_s is used in a number of correlations for soil parameters estimation. Several authors (Schmertmann 1978, Robertson and Campanella 1988, Lunne et al. 1997, Robertson 2006) tried to obtain the soil sensitivity based on f_s or the normalized friction ratio (FR). From a theoretical point of view, it is reasonable to correlate the f_s data with the remoulded shear strength ($s_{u,rem}$) obtained from the fall cone test. As shown in Figure 10, the f_s measurement provided by the advanced cone fits fairly well with the $s_{u,rem}$ data (Figure 10) while the standard cone does not catch the trend.

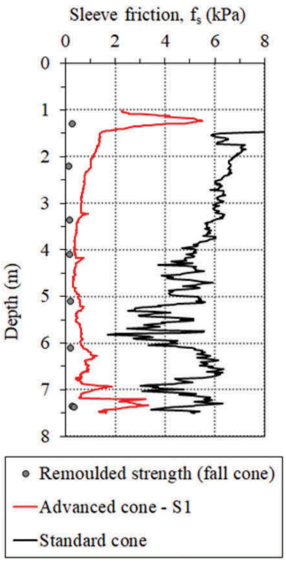

Figure 10. Comparison between the remoulded shear strength (su,rem) measured from the fall cone test and the sleeve friction from CPTu soundings.

4 DISCUSSION AND CONCLUSIONS

The presented study investigated the influence of the sleeve friction f_s measurement accuracy and resolution on the interpretation of piezocone data in soft sensitive clays. The study is limited to a single test site located in Pohja, Southern Finland. It has been shown that in these soils f_s values are significantly low (<1 kPa) and, therefore, the sleeve sensor should have sufficient resolution to perform accurate measurements. As shown for the Pohja site, traditional piezocones with f_s resolution >1 kPa may provide misleading results, thus inducing to an incorrect classification of the soil type based on the SBT charts. Moreover, the f_s appears to be a key parameter for a reliable estimation of the soil remoulded strength and sensitivity. Therefore, when performing CPTu soundings in soft sensitive clays, it is highly suggested to adopt suitable piezocone equipment with accurate and precise sleeve friction sensor for a reliable and robust data interpretation

The use of high-accuracy site investigation equipment is a key aspect for geotechnical risk assessment in soft sensitive clay areas. This aspect is relevant in relation to detection of sensitive clay layers that may trigger progressive failure during e.g. excavation works, or, as often observed in Norway or Canada, may induce large landslides because of human activity in the area or by other natural phenomena.

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