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Characteristic Shear Strength Parameters Derived from Cone Penetration Test

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Abstract: The interpretation and application of CPT (cone penetration test) results is characterized by considerable variability of data, either in measured or correlated parameters. According to the requirements of Eurocode 7 the existing variability in soil properties has to be taken into account statistically during the determination of the characteristic values of each parameter. This should be done by selecting a cautious estimate of the value affecting the limit state. Obtaining the characteristic values of CPT measurements is not an easy task and on this aspect nor clear neither unified guidelines exist. This paper focuses in several approaches to characterize the cone resistance and the sleeve friction using simple statistical analysis, in order for these parameters to be applicable in design. Similar procedures are then applied to determine the characteristic values of correlated parameters from CPT such as the effective friction angle for sands and the undrained shear strength for clays. The resulting characteristic values of the considered parameters emphasize the fact that the prediction and the interpretation of characteristic values of soil properties is a complicated and biased procedure.

Key words: Eurocode 7, CPTu (piezocone test), characteristic value, friction angle, undrained shear strength.

1. Introduction

The CPT (cone penetration test) has been widely used in geotechnical practice due to the many advantages that this test offers in gaining continuous profiling and also fast and reliable data. Typically the most common measured parameters are the corrected cone resistance (q_t) and the sleeve friction (f_s). Enhanced versions of CPT, e.g. CPTu (piezocone test) and SCPTu (seismic piezocone test), and other technological improvements provide much more data available in geotechnical design and for a wide variety of soils and sites. The main applicability of CPTu results is for soil profiling and soil type, but many correlations which estimate geotechnical parameters from CPTu results also exist [1]. The accuracy and applicability of these correlations depends highly on soil type and on the estimated parameter itself. On the other hand, direct application of CPTu results has been developed for a variety of geotechnical problems such as shallow and deep foundation bearing capacity, settlements calculation, and liquefaction potential prediction.

This paper focuses on the interpretation of CPTu measurements in order to select appropriate characteristic values of q_t and f_s. Selecting characteristic values is a crucial step in performing a design according to the partial factor method introduced in Eurocode 7. This procedure has to be done carefully in order to achieve the required confidence level and also to take into account the data variability and uncertainty. Similar procedures are also used for the characterization of two derived shear strength parameters, i.e. effective friction angle (ϕ') and undrained shear strength (s_u).

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2. Available Recordings and Interpretation

2.1 Piezocone Measurement

Two CPTu sounding profiles, further referred to as CPTu1 and CPTu2, are analyzed in the following. Values of q_t, f_s, and pore pressure measured just behind the cone (u_2) are plotted in Figs. 1 and 2.

The value of q_t represents the corrected cone resistance for pore water effects:

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

where: q_c is the measured cone resistance; a is the net area ratio with typical values between 0.7 and 0.85 [1].

Recordings are taken every 1.52 cm (0.05 feet) thus making it possible to have a large number of available data, averagely 65 readings for each meter of sounding. The GWT (ground water table) is located 2 m below existing ground level for CPTu1 and 1.5 m for CPTu2. GWT is used as a base to calculate the hydrostatic pore pressure (u_0). Table 1 makes a summary of the basic descriptive statistical parameters for the available CPTu recordings.

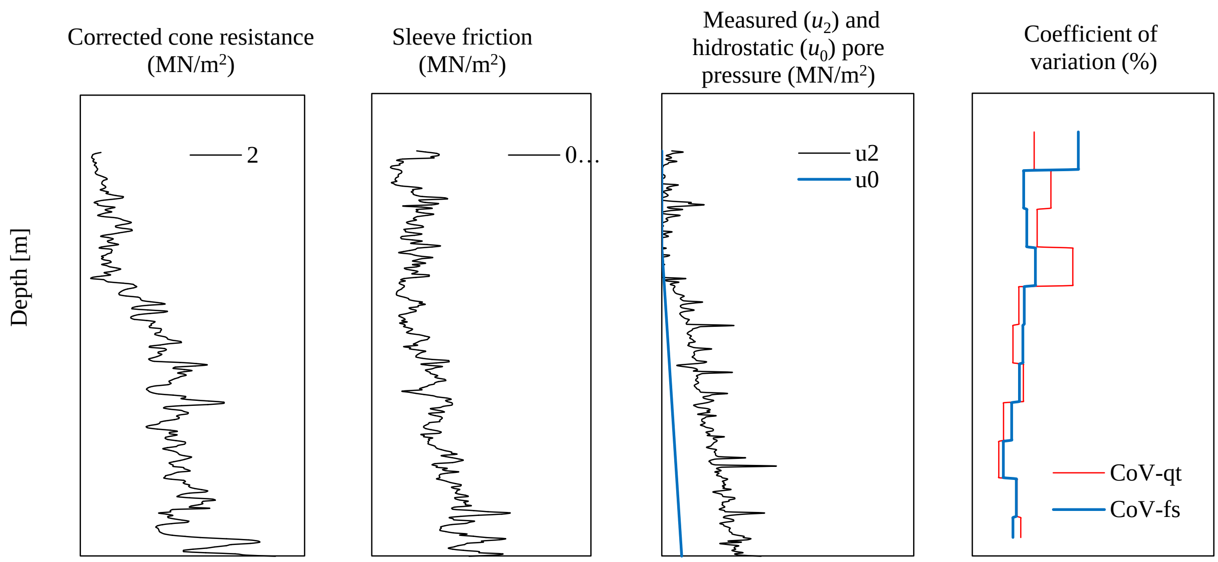

Fig. 1 Measurements of basic parameters and calculation of CoV (coefficient of variation) for CPTu1.

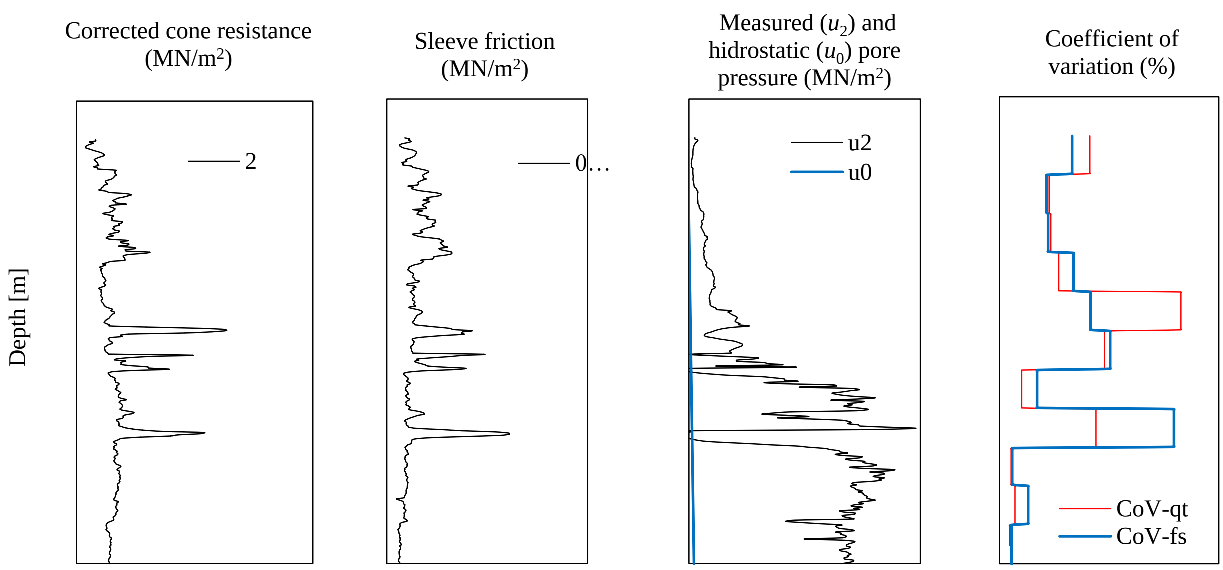

Fig. 2 Measurements of basic parameters and calculation of CoV for CPTu2.

Table 1 Descriptive statistical parameters for CPTu1 and CPTu2.

Statistical parameter	CPTu1		CPTu2	
	Corrected cone resistance	Sleeve friction	Corrected cone resistance	Sleeve friction
Depth (m)	0.75-6	0.75-6	0.5-6	0.5-6
Mean value (MN/m^2)	6.34	0.02637	3.32	0.11795
Standard deviation (MN/m^2)	3.37	0.01068	1.51	0.06848
CoV (%)	40.5	53.2	45.6	58.1

As it is characteristic of geotechnical parameters, a relatively high variability and uncertainty is present in all available data. In order to quantify this variability, the CoV is calculated and plotted in Figs. 1 and 2. CoV is defined as the ratio between the standard deviation and the mean for a given set of data. CoV is calculated for every 0.5 m of the profile, having thereby at least 30 data for each set and as a consequence a representative value of CoV [2]. In CPTu1 the CoV has values between 10% and 40%, which are quite familiar values for geotechnical parameters. On the other hand, for CPTu2 we have values of CoV up to 85%. These extreme values can be attributed to the presence of some very thin layers with relatively higher values of q_t and f_s.

2.2 SBT (Soil Behavior Type) Determination

Despite the measured ones, other normalized parameters are calculated and used for SBT identification and for correlation purposes. Since all available correlations are strongly connected to soil type, SBT evaluation is a necessary and helpful procedure. It must be emphasized that SBT provides a prediction regarding the mechanical characteristics of the soil, such strength and stiffness, and not about physical characteristics. Here, the normalized CPTu SBT$_N$ chart introduced by Robertson and Cabal [1] in 1990 and updated in 2010 is used.

This chart uses two basic CPTu normalized parameters, i.e. normalized cone resistance (Q_t) and normalized friction ratio (F_r), defined as below:

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

$$F_r = \frac{f_s}{(q_t - \sigma_{v0})} \times 100\% \tag{3}$$

where: σ_{vo} is the total in-situ vertical stress; σ'_{vo} is the effective in-situ vertical stress.

Fig. 3 shows the results of SBT$_N$ chart for CPTu1 and CPTu2. CPTu1 profile consists mostly in sandy soils (zone 6: clean sand to silty sand) and less in sand mixtures (zone 5: silty sand to sandy silt). CPTu2 profile consists in a combination of very stiff clay (zone 9: very stiff fine grained) and mixtures of silt and sand (zone 4 and 5).

The Eslami-Fellenius soil classification chart [3] is also plotted in Fig. 4 for CPTu1 and CPTu2 and the results emphasize the difference in soil types. Further, the effective friction angle is derived from CPTu1 and the undrained shear strength is derived from CPTu2.

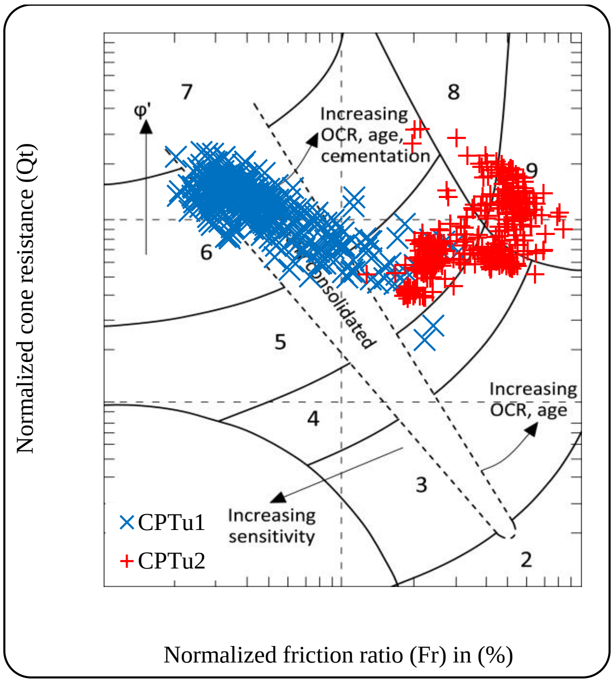

Fig. 3 Normalized SBT chart.

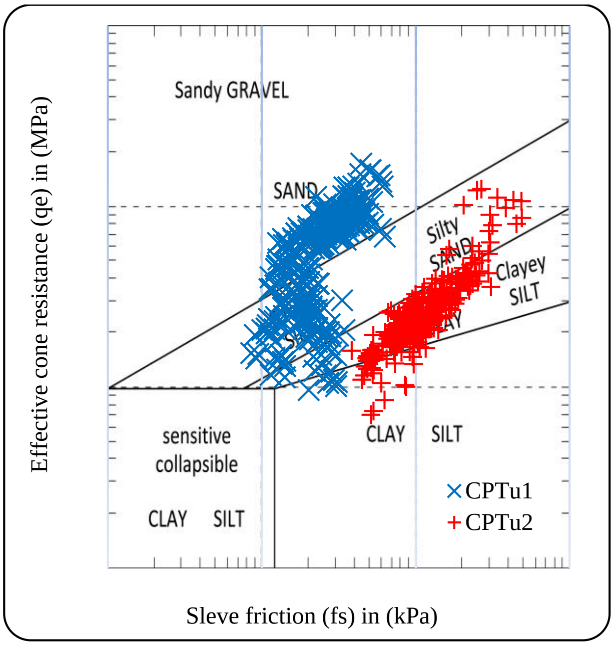

Fig. 4 Eslami-Fellenius soil classification chart.

3. Characteristic Values of Cone Resistance and Sleeve Friction

3.1 Characteristic Value Definition

Selecting characteristic values, for both loads and resistances, is a crucial step in performing a design according to the semi-probabilistic method (partial factor method) introduced in Eurocode 7. The code despite giving a definition for what a characteristic value is does not indicate a procedure to calculate it and this has led to several interpretations. The big range of selected characteristic values has been shown by some authors and also from several conducted design examples, where practicing engineers are asked to select characteristic values from field and laboratory tests data [4-6].

Eurocode 1990 "Basis of design" defines the characteristic value as a 5% fractile value, when a low value of the material is unfavorable [7]. This definition works well for man-made materials, with relatively low variability of their properties, and fails when applied to geotechnical parameters, due to the high variability that they have. This has led to a different interpretation of characteristic values in the Eurocode 7 "Geotechnical design", which states "the characteristic value of a geotechnical parameter shall be selected as a cautious estimate of the value affecting the occurrence of the limit state" [8].

A key aspect in geotechnical design is that the occurrence of a limit state is dependent on the average value of the governing parameter in a relatively large zone, much larger than the sample size. From this point of view it is important to assess how much ground is involved or is relevant to the occurrence of a specific limit state [5]. The occurrence of limit state is also related to different aspects such as the structural system, foundations type, and building functions. The above specifics make the determination of characteristic values a complex and case dependent procedure. Other factors affecting the selection of characteristic soil properties are: the existing background information of the site, required level of probability, type and number of samples and extension of investigation, calculation model, etc. [9].

3.2 Calculation and Plots of Characteristic Values

As the Eurocode 7 requires, the characteristic value (x_k) should be selected as a cautious estimate of the spatially averaged value of a property for a relevant soil volume. Statistically, the 95% confident assessment of that mean value is required. The confidence level has to do with the cautious estimate (degree of caution) of the mean (or selected best fit line between data) and is quantitatively expressed in a simplified way by the below equation:

$$x_k = x_{mean} \pm K \cdot s \tag{4}$$

where: x_{mean} represents the mean value of the parameter for a specific depth (or the value in the best fit line); s is the standard deviation of the data for all the soil profile or for a selected set (any of profile layers if several layers are identified); K is a statistical coefficient that takes into account the sample size (n), the confidence level (α), and the chosen probability distribution. The applied approaches for selecting x_k are presented in Table 2.

Table 2 Applied approaches for characteristic values selection [10].

Approach	Characteristic value, x_k
Simple mean/best fit line values	x_{mean}
50% fractile at 95% confidence level	$x_{mean} - t_{n-1}^{95\%} \cdot \sqrt{(1/n)} \cdot s$
5% fractile at 95% confidence level	$x_{mean} - 1.645 \cdot s$
Shchneider's equation	$x_{mean} - 0.5 \cdot s$

Here: *n* represents the degrees of freedom (number of samples or measurements); $t^{n-1}_{95\%}$ represents the Student's *t*-value for *n*-1 degrees of freedom and confidence level of 95% for a normal distribution [11].

The first step in plotting the characteristic line is to plot an initial line (below referred as best fit line) that represents somehow the averaging or trend of the measured data. Such best fit lines have to fit well with the trend of the data versus the depth and in the same time have to be appropriately simple, in order to be easily used during calculations. In this aspect, we have used the best fit line computed by linear regression analysis available in Excel, using regression tool in Data Analysis Pack [11]. The above described best fit line is plotted for q_t and f_s data for both CPTu recordings (Figs. 5 and 6).

Then, the residuals are calculated for each best fit line and are also plotted in Figs. 5 and 6. The residuals are expressed as the difference between the measured value and the predicted value by the best fit line. The histograms and the fitting normal distribution for the residuals of q_t are shown in Fig. 7 and on this basis, the respective standard deviations are calculated. The residuals of q_t show a good compliance with the theoretical normal distribution, arguing in this way the applicability of the relationships described in Table 2. Using these relationships and the standard deviations of each residual set, the characteristic lines for each approach are established and plotted (Figs. 5 and 6).

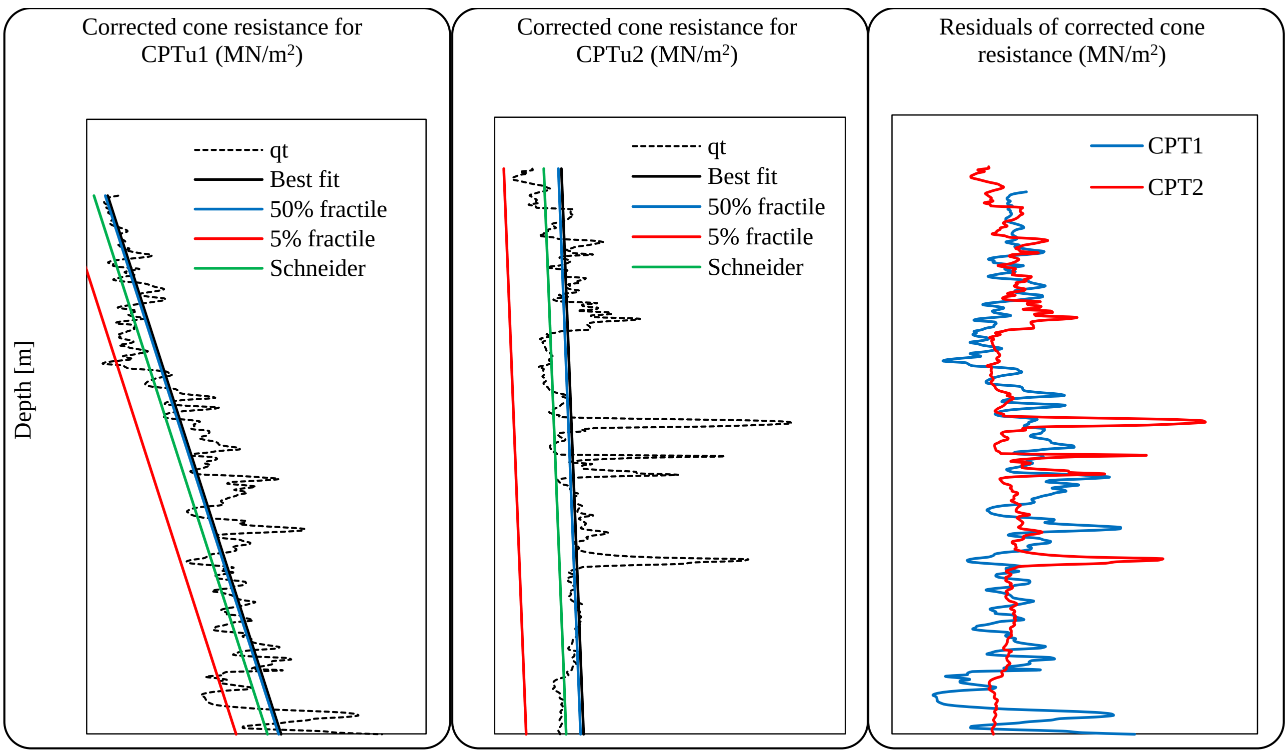

Fig. 5 Characteristic values of corrected cone resistance for CPTu1 and CPTu2 and respective residuals.

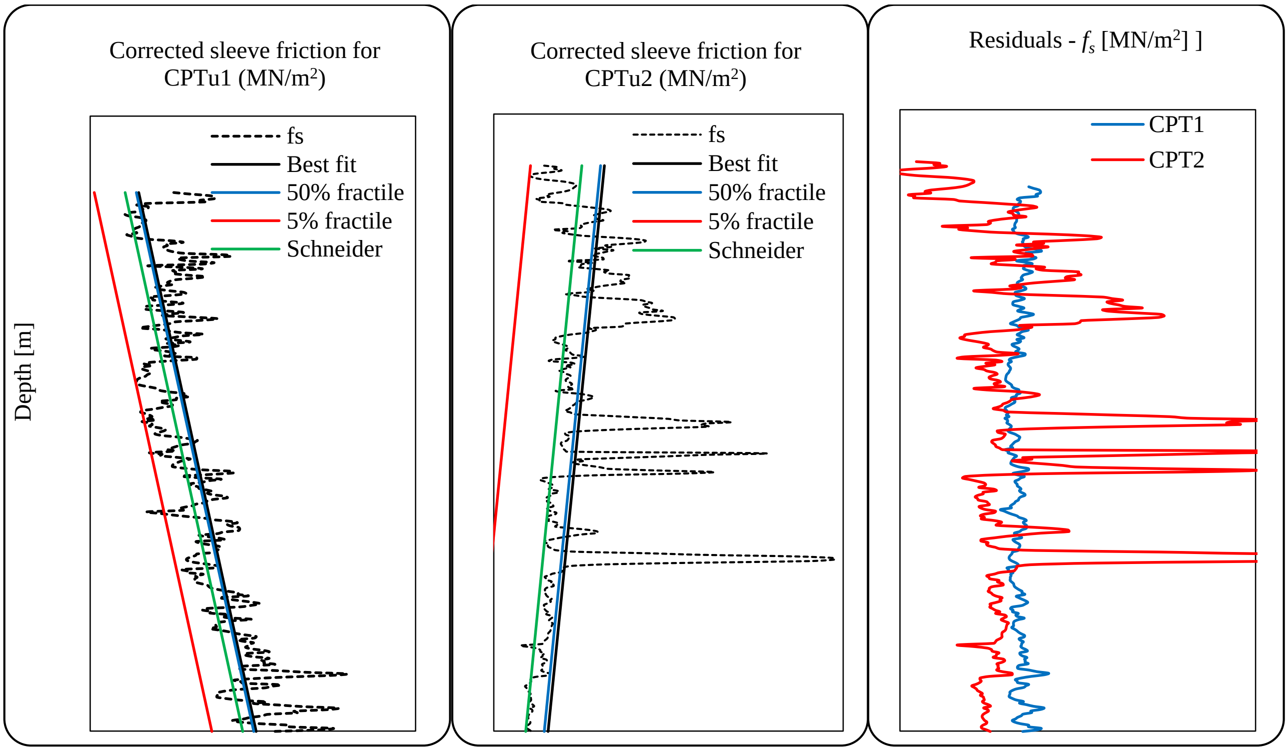

Fig. 6 **Characteristic values of sleeve friction for CPTu1 and CPTu2 and respective residuals.**

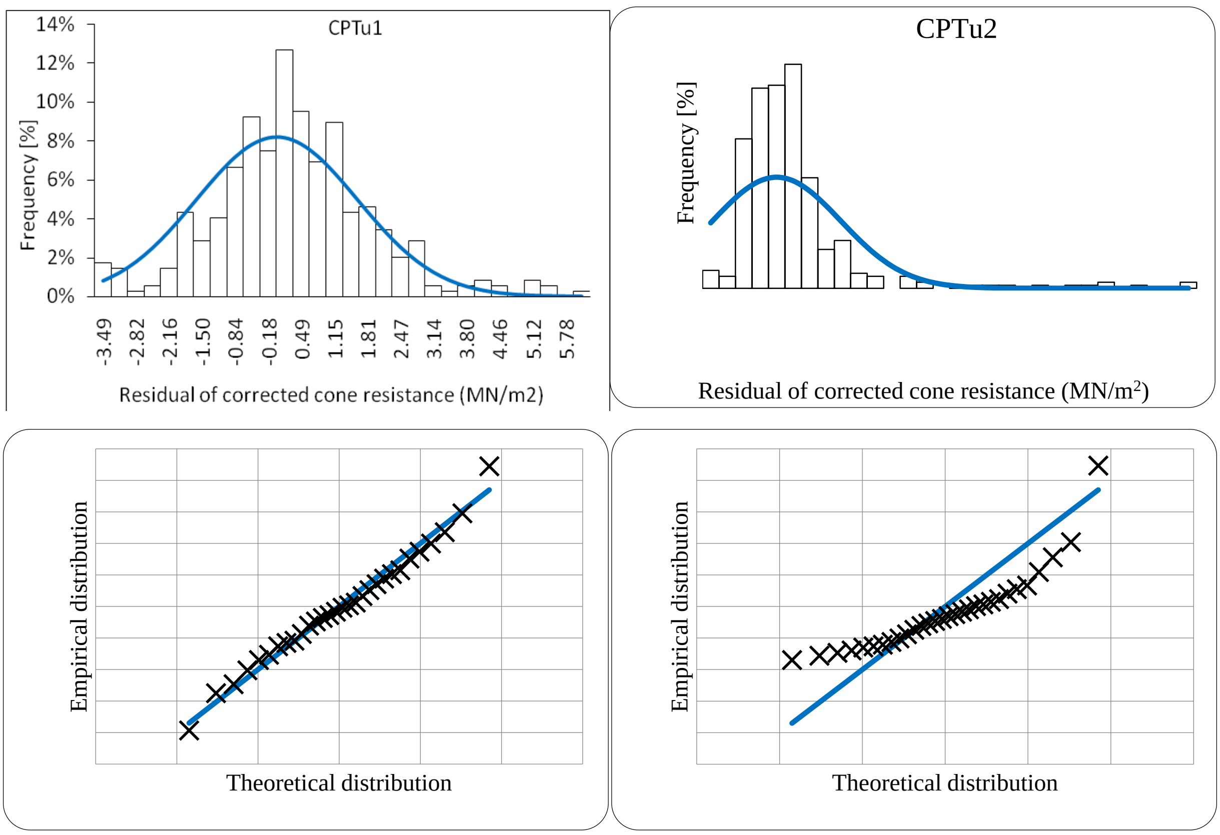

Fig. 7 **Histograms and Q-Q plots of the residuals of q_t for CPTu1 and CPTu2.**

4. Characteristic Values of Correlated Parameters

A large number of correlations are available in order to estimate soil properties from CPTu data for a wide range of soil types. The applicability and reliability of these correlations vary on soil type and on the estimated parameter [1]. Regarding the soil shear strength parameters (ϕ' and s_u) the perceived applicability ranges from high to moderate. Correlations for ϕ' and s_u are applied to the available CPTu registrations and the respective characteristic values are selected. For CPTu1 φ' is derived, since it is mainly composed of sands and for CPTu2 s_u is derived, since it consists mostly in clays.

Several methods have been used for the assessment of effective friction angle for sands from CPTu. The most used are the empirical correlations based on calibration chamber test and field results. Table 3 presents the two used relationships between ϕ' and CPTu measured parameters. The derived ϕ' values are plotted in Fig. 8.

Estimating the undrained shear strength is very important in short-term loading conditions of clays or clayey silts. The main difficulty in this task is the fact that s_u does not have a unique value, but it depends on the used testing apparatus and procedure. The main affecting factors are the direction of loading, boundary conditions, stress level, and sample disturbance [12]. All applied theories result in this relationship between q_t and s_u [1].

Table 3 Used relationships for effective friction angle correlation.

Author	Relationship	Reference
Robertson & Campanella (1983)	$\tan\phi' = \frac{1}{2.68}\left[\log\left(\frac{q_c}{\sigma'_{v0}}\right) + 0.29\right]$	[1]
Kulhawy & Mayne (1990)	$\phi' = 17.6^o + 11.0^o \cdot \log\left(\sqrt{\frac{(q_t/\sigma_{atm})}{(\sigma'_{v0}/\sigma_{atm})}}\right)$	[12]

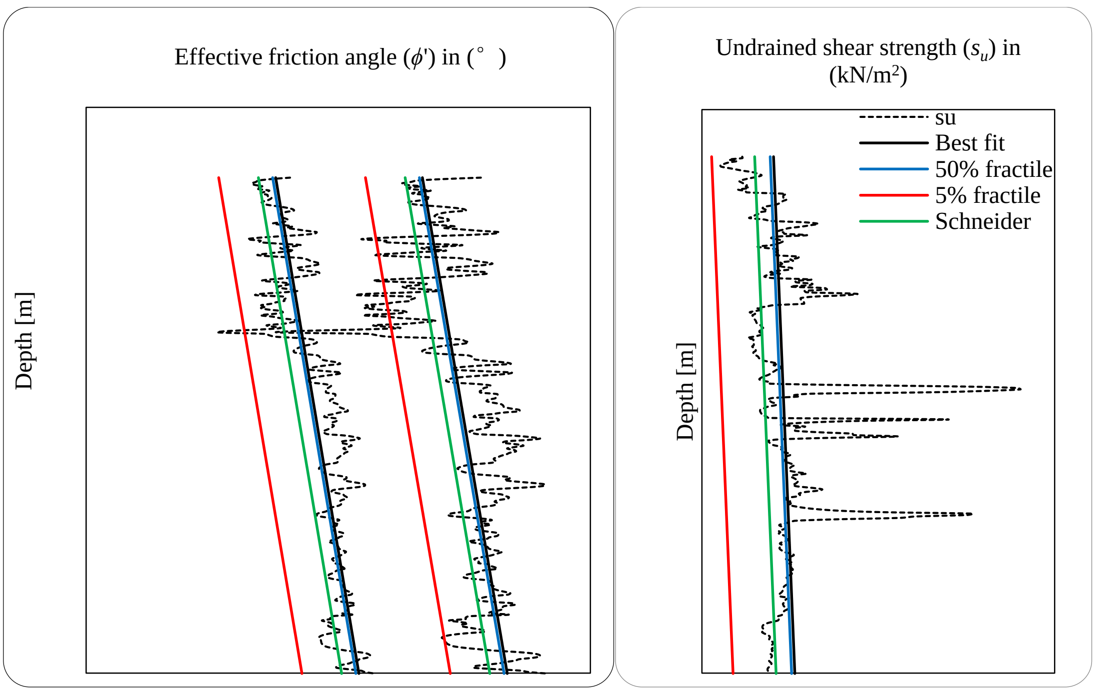

Fig. 8 Characteristic values of effective friction angle and undrained shear strength.

$$s_u = \frac{q_t - \sigma_{vo}}{N_{kt}} \tag{5}$$

N_{kt} is a bearing factor and its assessment has been the main research focus during years, without reaching any agreement. In literature [1, 13, 14] it is advised that the range of N_{kt} values is from 10 to 20, with an average of 14. The value of N_{kt} has been calculated using two approaches. Firstly, an average value of N_{kt} = 14 is used and secondly, N_{kt} is calculated by using the normalized friction ratio [1]

$$N_{kt} = 10.5 + 7 \cdot \log F_r \tag{6}$$

The two used approaches result in very similar values of s_u and those calculated using N_{kt} = 14 are plotted in Fig. 8. Regarding the characteristic values of ϕ' and s_u (Fig. 8), they are calculated using the same approaches described previously for q_t and f_s.

5. Conclusions

As can be seen from the graphs in Figs. 5, 6 and 8, it is very difficult to get a single line for characteristic values of the discussed parameters. This comes firstly due to subjectivity during the cautious estimating process, e.g. the difference between 50% fractile and 5% fractile approach. The other cause that influences directly the outcome of characterization is the large variability in recorded and estimated values. For q_t and f_s we have values of CoV up to 85%. It is very visible the conservationism of the 5% fractile approach enhanced once again the non-applicability of this method for properties with very large variability (i.e. as most nature made materials are). In some cases (Figs. 5 and 6) the 5% fractile approach predicts even negative characteristic values of q_t and f_s. On the other hand, the 50% fractile approach derives a characteristic line relatively close to the initial best fit line, i.e. there is very low conservationism. Most probably this is due to the very large available number of data, since the characteristic value according to this approach (Table 2) depends highly on the sample size. Schneider's equation gives an intermediate line which refers to 5% and 50% approach lines. Visually it looks a very appropriate line but is difficult to quantify or to judge on this aspect.

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