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Published in:

Cone Penetration Testing 2018 : Proceedings of the 4th International Symposium on Cone Penetration Testing

Publication date:

2018

Document Version

Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):

Martínez, M. F. G., Tonni, L., Gottardi, G., & Rocchi, I. (2018). Analysis of CPTU data for the geotechnical characterization of intermediate sediments. In *Cone Penetration Testing 2018 : Proceedings of the 4th International Symposium on Cone Penetration Testing* (pp. 281-287). CRC Press.

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Analysis of CPTU data for the geotechnical characterization of intermediate sediments

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ABSTRACT: The intermediate soil (e.g. silt, sandy silt, clayey silt) response at the standard cone penetration (CPT) velocity of 20 mm/s is generally partially drained, falling between that of sand and clay. As a result, a proper interpretation of CPT (or CPTU) in such mixed soils is not always straightforward. In order to properly analyse the in situ soil response and avoid incorrect estimates of soil parameters, the preliminary assessment of drainage conditions is essential. In this paper, changes in normalized CPTU measurements caused by changes in cone velocity are analysed. Penetration rate effects are assessed by means of No. 8 piezocone tests, with penetration rates ranging from about 0.9 to 61.7 mm/s. Tests were performed at a site located at the southern margin of the Po river valley (Northern Italy), where the sub-soil mainly consists in a clayey silt deposit. Limitations on the applicability of some widely used empirical correlations, proposed for sands, are investigated and some preliminary results are shown.

1 INTRODUCTION

Cone penetration testing, with or without pore water pressure measurements (CPTU/CPT), is the most widely used in-situ technique for stratigraphic profiling and evaluation of soil parameters. Compared to sampling and laboratory testing, it allows fast and economical data acquisition and interpretation.

It is generally accepted that the soil response to the standard penetration rate (20 mm/s) is fully drained in sands and fully undrained in clays. By contrast, partially drained response is very likely to occur in silts and other natural soil mixtures (i.e. silty or clayey sands, sandy silts), with significant implications on the appropriate interpretation of field measurements for geotechnical characterization. Current engineering practice lacks of standardized recommendations concerning both testing procedures and data interpretation in such intermediate soils, whilst a significant amount of knowledge is nowadays available for sands and clays.

Over the last years, a number of studies (e.g. Randolph 2004, Schnaid et al. 2004) have stressed the crucial importance of a preliminary assessment of the actual drainage conditions around the advancing cone in order to suitably interpret CPTU data in silty sediments. In this regard, according to the experience of various Authors (e.g. Randolph & Hope 2004, Schneider et al. 2007), cone penetration

tests carried out at variable rates are nowadays recognized as an effective way to identify the transition point from undrained to partially drained and drained responses. A dimensionless velocity V (Finnie & Randolph 1994), given by:

$$V = \frac{v \cdot d}{c_v} \quad (1)$$

is generally used to interpret field data, being v the cone penetration rate, d the cone diameter and c_v the vertical coefficient of consolidation. Some Authors have also observed that the horizontal coefficient of consolidation c_h should be used in Equation (1) instead of c_v , since the primary direction of pore water flow is horizontal (Chung et al. 2006).

Although the matter is at present far from being satisfactorily solved, the significant amount of experimental research carried out so far, including both laboratory studies with miniature penetrometers and field scale tests (e.g. Randolph & Hope 2004, Chung et al. 2006, Oliveira et al. 2011, Kim et al. 2008, Tonni & Gottardi 2009, Schnaid et al. 2010, Suzuki et al. 2013, Krage et al. 2014, García et al. 2014, García et al. 2016b), has led to the identification of probable consolidation patterns as function of cone penetration rate. However, the available research results seem to suggest that there is not a unique drained nor undrained transitional

value of V , being dependent on the fine content of soils (Suzuki & Lehane 2015).

Significant difficulties have been typically encountered in the interpretation of variable rate field scale tests, due to a variety of reasons, such as limitations in equipment capability to vary and control the penetration velocity, additional time and costs related to field testing (Suzuki & Lehane 2014) and, particularly, natural soil heterogeneity and the unavoidable spatial variability of soil deposits.

This paper presents the analysis of a set of variable rate CPTU tests carried out in a clayey silt deposit located in the southern margin of the Po river valley near Forlì, Italy. The identification of a probable consolidation trend as function of cone velocity is first examined in order to establish the actual drainage degree during a standard CPTU. Besides, based on a few available laboratory test results, limitations on the applicability of some widely used empirical approaches for geotechnical characterization are discussed and a preliminary attempt to account for partial drainage effects in correlations for the estimate of the friction angle is presented.

2 SITE DETAILS AND FIELD TESTS

The dataset used in this study includes No. 8 adjacent CPTU tests, typically 1 to 2 m distant from each other, performed at penetration rates from 0.9 mm/s to 61.7 mm/s. All tests were pushed to over 15 m in depth. A 35.7 mm diameter cone with pore pressure recorded at the shoulder position (u_s) was employed. For further details on this campaign, readers may refer to García Martínez et al. (2016a, b).

The stratigraphic conditions of this site, as revealed by a deep borehole carried out in a previous investigation campaign as well as by standard CPTU results, mainly consist of a macro-unit of about 29 m of silty-clayey sediments, followed by gravels. Local interbedded silty sand/sandy silt levels, 1 to 3 m thick, are encountered from ground level to 29 m in depth.

Table 1 summarises some basic physical properties of such sediments, together with a few results from direct shear tests and oedometer tests carried out on undisturbed samples.

According to grading characteristics and Atterberg limits, the tested samples range from silty sands (15–15.5 m in depth) to silts-sandy silts (12.3–12.5 m) with approximately 10% of fine content and also high plasticity clays (6.2–6.7 m and 18.0–18.5 m in depth). According to both CPTU and borehole logs, a certain variability in fine content can be at times detected at decimetric level.

Table 1. Physical and mechanical properties.

Depth (m)	γ_n (kN/m ³)	w_n (%)	w_L (%)	w_p (%)	S (%)	M (%)	C (%)
6.2–6.7	19.8	25	57.6	21	–	65	35
12.2–12.3	19.2	31.3	25	17	25.6	59.4	15
12.3–12.5	19.2	31.3	20	19	41.1	48.9	10
15.0–15.5	20.6	22.2	–	–	68	32	–
18.0–18.5	19.2	31.5	50.8	23.1	–	60	40

Depth (m)	M^* (MPa)	c_v^* (m ² /s)	ϕ^{**} (°)
6.2–6.7	8.6	–	20.8
12.3–12.5	4.8	$3.1 \cdot 10^{-6}$	34.6
15.0–15.5	–	–	38.9
18.0–18.5	6.3	$1.5 \cdot 10^{-7}$	23.43

S: sand; M: silt; C: clay;

* from oedometer tests (stress interval 70–145 kPa);

** from direct shear tests.

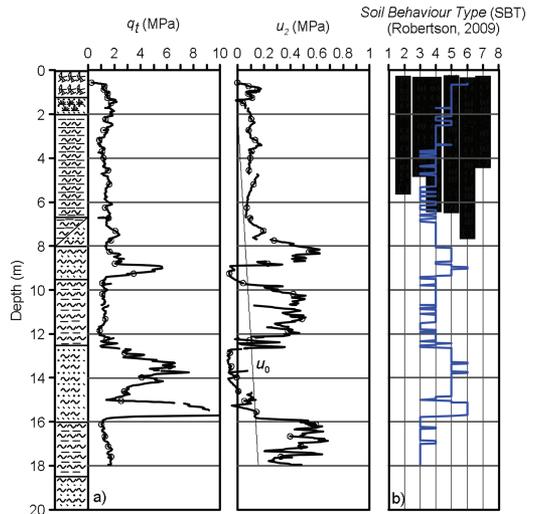


Figure 1. a) CPTU1 log profiles and b) SBT profile according to Robertson (2009).

Figure 1 shows the q_t and u_s profiles obtained from standard cone penetration test CPTU1. The equilibrium pore pressure profile, corresponding to a water table located at approximately 2 m in depth, has been also plotted in Figure 1 for useful comparison with u_s .

The Soil Behaviour Type (SBT) profile depicted in column (b) has been derived from the value of the material index I_{cr} , according to the well-known CPTU-based classification method proposed by Robertson (2009). Such classification results have been more extensively commented in García Martínez et al. (2016b). A reasonable agreement

between results in terms of Soil Behaviour Type and soil lithology from borehole BH1, also reported in Figure 1, can be appreciated.

The q_t and u_z profiles from the set of piezocone tests performed at various penetration rates have been plotted in Figure 2. Lower (0.9 mm/s) and upper (61.7 mm/s) values of test velocity were established based on the technical limits of the equipment.

The figure shows that in the upper 7 m, cone resistance remains almost unvaried, whereas pore pressure appears to be slightly more sensitive to penetration rate effects. In any case, such response seems to suggest that penetration in these shallow sediments, basically classified as SBT = 4 or SBT = 3, is predominantly undrained. At greater depth, q_t generally decreases and u_z increases as the rate of penetration is decreased. It is worth noting that the pore pressure at 0.9 mm/s follows a hydrostatic profile from 12.7 to 16 m, thus indicating fully drained penetration. Again, from 16 m up to the end of the tests, where almost all the sediments are classified as clay, q_t profiles are substantially coincident (García et al. 2016b).

Dissipation tests have been also carried out during the CPTU campaign. As an example, Figure 3 shows the dissipation curves obtained from tests CTPU1 (20 mm/s) and CPTU8 (58 mm/s) at about 12.2 m in depth. As it will be discussed later, test CPTU8 is likely to be ascribed to fully undrained initial conditions. Accordingly, the coefficient of consolidation for this silt has

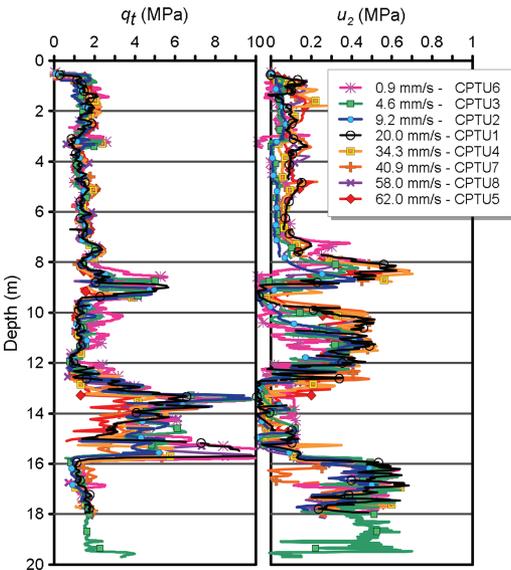


Figure 2. CPTU profiles from adjacent tests at variable rate.

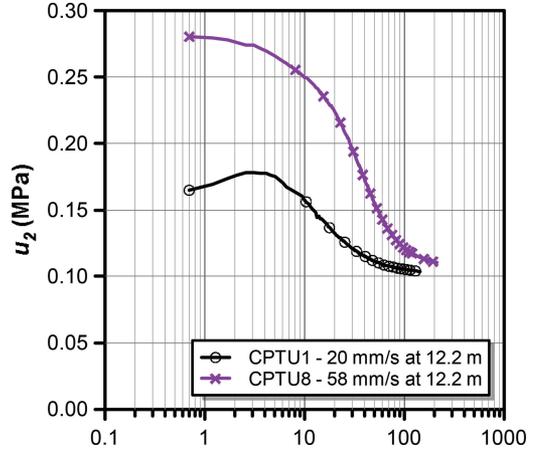


Figure 3. Dissipation tests at 12.2 m.

been determined by applying to CPTU8 dissipation data the well-known Teh & Houlsby (1991) method, this latter being based on the assumption of fully undrained penetration. Assuming the rigidity index $I_r (= G/s_u)$ equal to 130, c_h turned out to be equal to $2.9 \cdot 10^{-5} \text{ m}^2/\text{s}$.

Such estimate of the horizontal coefficient of consolidation is about one order of magnitude higher than the value of c_v obtained from the oedometer tests carried out on a soil sample taken at the same depth (see Table 1). As observed by various Authors, differences between c_v and c_h are basically due to anisotropy of soil permeability k in the vertical and horizontal directions, which may result in values of the ratio k_h/k_v , up to 10–15 in highly stratified deposits or silts with continuous permeable layers (Jamiołkowski et al. 1985, Mayne 2007). On the other hand, it is often considered as acceptable that accuracy in the estimate of the coefficient of consolidation may vary within one order of magnitude (Robertson 2015). It is worth remarking here that the application of the Teh & Houlsby (1991) method to the dissipation test carried out during standard CPTU1 (i.e. in partial drainage conditions) resulted in $c_h = 4.4 \cdot 10^{-5} \text{ m}^2/\text{s}$.

In what follows, the computed c_h from CPTU8 dissipation test has been used to normalize cone penetration velocities, according to DeJong & Randolph (2012).

3 ANALYSIS OF RATE EFFECTS

In order to perform a preliminary analysis of rate effects on the piezocone measurements, the variations with velocity of normalized tip resistance, $Q_t = ((q_t - \sigma_{v0})/\sigma'_{v0})$, and normalized excess pore pressure, $\Delta u/\sigma'_{v0}$, in a few selected thin

homogeneous layers of sandy silts to silty sands (8–8.5 m, 14.8–15.2 m) and clayey silts (10–10.3, 11.8–12.2 m) have been first examined. In Figure 4, the median and the first and third quartile of Q_t and $\Delta u_2/\sigma'_{v0}$ are plotted, for each velocity v . A rather pronounced scatter of data can be appreciated in sandy silts/silty sands, especially at 14.8–15.2 m in depth, suggesting a certain intrinsic heterogeneity of these soil layers. As it will be shown in the following, intrinsic heterogeneity, coupled with the unavoidable horizontal spatial variability, makes the interpretation of field data more complex to be performed and consolidation trends more difficult to be identified.

According to the plots of Figure 4, clayey silts from 10 to 10.3 m show increasing values of Q_t for $v < 20$ mm/s, whereas those from 11.8 to 12.2 m only show higher values of Q_t for $v < 4.6$ mm/s. Regarding the $\Delta u_2/\sigma'_{v0} - v$ plots, the trend is similar at both depths: a transition point from undrained to partially drained response seems to be close to 40.9 mm/s.

With regard to the sandy silt/silty sand layers, trends at 8–8.5 m are similar to those identified for the clayey silts, although normalized values are generally higher. By contrast, Q_t at 14.8–15.2 m decreases with velocity over the entire investigated range, whilst pore pressures remain almost uninfluenced. In this latter layer, it is very unlikely that fully undrained conditions might have been reached at the maximum cone velocity of 62 mm/s, whilst approximately fully drained penetration may have occurred at $v_{min} = 1$ mm/s.

Data from the selected intervals of clayey silts (10–10.3 and 11.8–12.2 m) have been also

interpreted in terms of the normalized velocity V , taking the consolidation trend proposed by DeJong & Randolph (2012) as a base. According to such approach, the so-called “backbone curve” is given by:

$$\frac{Q}{Q_{ref}} \approx 1 + \left(\frac{Q_{drained}/Q_{ref} - 1}{1 + (V/V_{50})^c} \right) \quad (2)$$

where the subscript ‘ref’ denotes normalized measurements in undrained conditions whilst the coefficients $Q_{drained}/Q_{ref}$, V_{50} and c are the normalized drained resistance, the normalized velocity at 50% degree of drainage and the maximum rate of change of Q/Q_{ref} with V , respectively. It is worth emphasizing that Equation (2) only describes the consolidation process during cone penetration and therefore ignores effects of viscosity on tip resistance, which are conversely included in other formulations of the backbone curves, such as the one proposed by Randolph (2004).

Interpretation of the available data in the framework described by Equation (2) is not straightforward, especially with regard to the evaluation of the ratio $Q_{drained}/Q_{ref}$. Indeed, extremely slow penetration tests, not performed in this experimental study, would be required in order to attain fully drained conditions around the advancing cone and thus to obtain a value of $Q_{drained}$ which might be considered as representative of this deposit. Furthermore, according to the data shown in Figure 5, the consolidation trend exhibited by sediments at 10–10.3 m seems to differ notably from that observed at 11.8–12.2 m. In any case, $Q_{drained}$ would

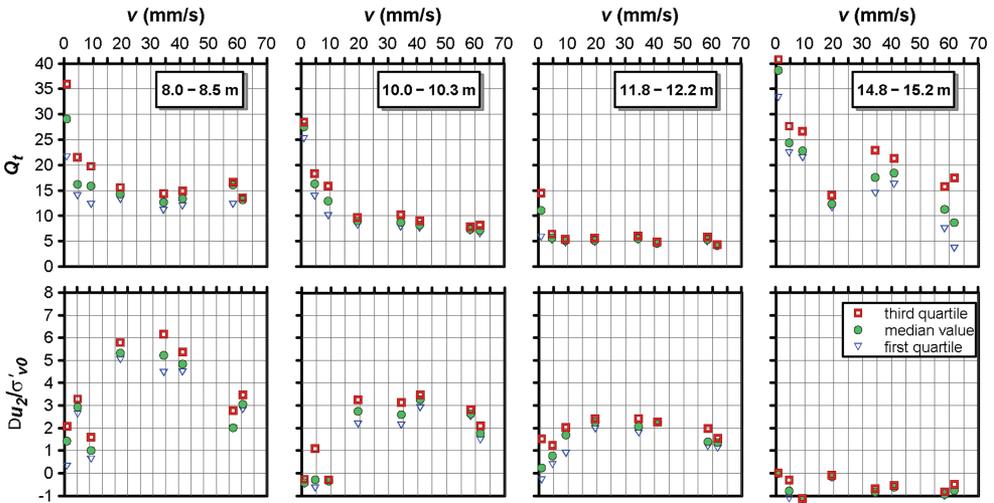


Figure 4. Q_t and $\Delta u_2/\sigma'_{v0}$ variations with penetration velocity within thin homogeneous layers.

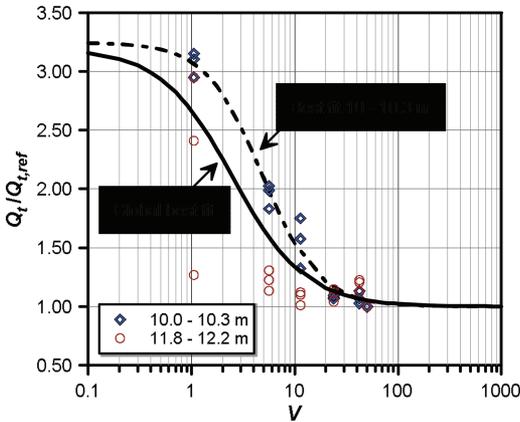


Figure 5. Normalised resistance variations with V within thin homogeneous clayey silt layers and fitted backbone curves.

be certainly located at $V < 1$, while the transition point from partially drained to fully undrained cone penetration has been assumed at $V = 50$.

It is worth remarking here that if c_h obtained from the dissipation test following standard penetration ($c_p = 4.4 \cdot 10^{-5} \text{ m}^2/\text{s}$) had been used, the consolidation trend would have shifted to the left, thus giving lower velocity transition points.

The best fit to data collected in the shallowest clayey silt has been attained by assuming $V_{50} = 4.82$, $c = 1.60$ and $Q_{drained}/Q_{ref} = 3.25$. This latter turns out to be consistent with the values obtained in other experimental studies, both in the laboratory (Oliveira et al. 2011) and in the field (Krage & DeJong 2016, Suzuki et al. 2013), where $Q_{drained}/Q_{ref}$ was found to vary approximately between 2.5 and 4, though higher values have been also detected in a few non-standard soils (DeJong et al., 2013).

At the same time, the regression analysis on the only cone resistance data at 11.8–12.2 has resulted in a significantly high, and thus rather questionable value of $Q_{drained}/Q_{ref}$ (≈ 28). More data would be probably required in order to identify a reliable consolidation trend. A global consolidation curve, matching all data points, has been obtained for $Q_{drained}/Q_{ref} = 3.20$, $V_{50} = 2.51$ and $c = 1.24$.

4 ASSESSMENT OF PEAK FRICTION ANGLE FROM CPTU-BASED CORRELATIONS

Most of the CPTU-based empirical correlations for the assessment of peak friction angle ϕ'_p have been calibrated on sands, thus potentially resulting in invalid estimates when applied to silts and sandy silts, due to potential partially drained conditions

in standard CPT. In what follows, different correlations for the estimate of the effective shear resistance in granular soils are examined and the computed values of ϕ'_p are compared with a few available laboratory results.

Figure 6 shows the peak friction angle profiles obtained from the application to piezocone data in silts-sandy silts of the well-known correlations described by Equation (3) and Equation (4), as proposed by Robertson & Campanella (1983) and Kulhawy & Mayne (1990) respectively:

$$\phi'_p (\text{°}) = \frac{180}{\pi} \arctan \left[\log \left(\frac{q_c}{\sigma'_{v0}} \right) + 0.29 \right] \quad (3)$$

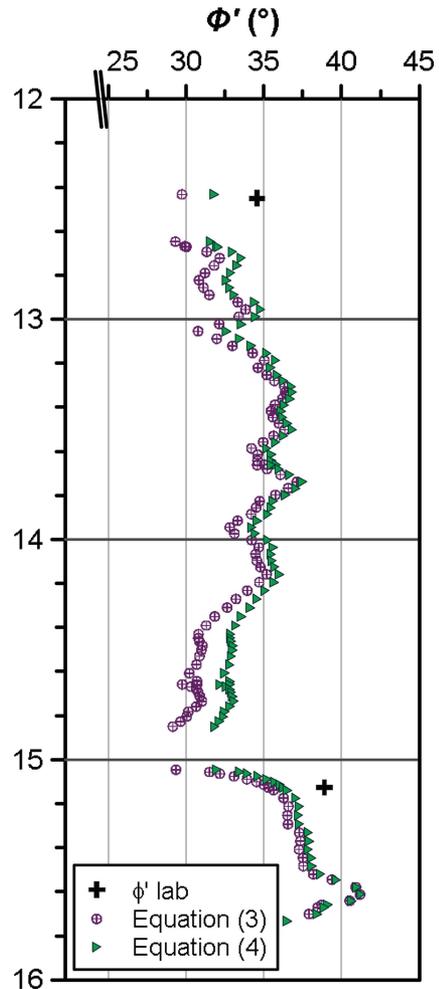


Figure 6. CPTU-based estimates of ϕ' and results from laboratory tests.

$$\phi'_p (\circ) = 17.6 + 11.0 \cdot \log \left[\frac{(q_t / \sigma_{atm})}{(\sigma'_{v0} / \sigma_{atm})^{0.5}} \right] \quad (4)$$

Profiles are shown for the depth interval 12.4–15.7 m, where a predominance of SBT = 5 has been found. Both correlations appear to be in good agreement. A certain variability of the computed values over the soil layer can be appreciated, as a consequence of its intrinsic heterogeneity.

By comparing such estimates with values of ϕ'_p obtained from direct shear tests (Table 1), also plotted in the figure at 12.4 and 15.1 m in depth, Equations (3) and (4) seem to underestimate the effective shear resistance of these intermediate sediments.

Following the approach recently proposed by Holmsgaard et al. (2016), the laboratory values of ϕ' have been used to adjust the cone resistance at the standard rate $v = 20$ mm/s and thus to obtain the $q_{t,dr}$ and the stress-normalized $Q_{t,dr}$, corresponding to fully drained conditions. The resulting normalized resistance assumed to apply at fully drained penetration, Q_{dr} , has been found to be ~ 32 at 12.4 m and ~ 70 at 15.1 m. Consequently, the ratio between the normalized drained resistance and that at standard velocity, Q_{dr}/Q_s , turned out to be 3.2 and 1.3 respectively. Holmsgaard et al. (2016) expressed such ratio in terms of non-normalized cone resistances $q_{t,dr}$ and $q_{t,20mm/s}$, obtaining $q_{t,dr}/q_{t,20mm/s} = 1.4$ for some silty soils of a test site in Dronninglund (Denmark).

It is obvious that such combined interpretation of field data and direct shear test results must be considered as a first attempt to account for partial drainage in geotechnical characterization and that a larger database from the laboratory would be necessary in order to confirm such preliminary analysis.

At the same time, the above interpretation has been also used to help in identifying a more reliable value of the normalized drained resistance $Q_{drained}/Q_{ref}$ in silt mixtures at 11.8–12.2 m and thus overcome uncertainties mentioned in section 3. Indeed, assuming a $Q_{drained}$ equal to 32, the ratio $Q_{drained}/Q_{ref}$ has turned out to be on average 6.8, Q_{ref} (~ 4.7) being obtained from field data (see Fig. 4). This outcome confirms that the value ($Q_{drained}/Q_{ref} = 28$) previously obtained from regression analysis is probably overestimated.

5 CONCLUSIONS

This paper has presented the results of a set of variable rate CPTUs conducted in a silty deposit located at a site in Northern Italy, with the aim of

having a better insight into the drainage degree during testing and its effect on field measurement and geotechnical characterization. Indeed, partial drainage may prevail in intermediate soils when CPTU are performed at the standard rate (20 mm/s).

Despite difficulties in interpreting field data, comparisons between the available tests revealed that decreasing penetration velocity generally results in increasing tip resistance, whereas pore pressure tends to decrease.

From the analysis in terms of normalised CPTU measurements within selected depth intervals of the clayey silt layer, a consolidation trend has been identified. The transition point from undrained to partially drained conditions is likely to occur at a normalised velocity $V/50$. By contrast, significant difficulties have been encountered in detecting fully drained conditions. According to the analyses, also relying on laboratory data, $Q_{drained}/Q_{ref}$ has been found to vary from 3.25 to approximately 6.8 in the predominantly silty layer. The amplitude of such range is presumably due to intrinsic heterogeneity of the soil unit. On the other hand, the estimated values turn out to be in substantial agreement with results from similar experimental studies.

As a consequence of partial drainage, careful attention should be paid when empirical CPTU correlations, developed for sands or clays, are used to estimate geotechnical parameters in intermediate soils. In particular, peak friction angle ϕ' in silts to sandy silts appears to be underestimated when some well-known expressions are applied to the standard test. Comparisons between the estimated and the measured ϕ' have suggested a ratio between the drained normalized and the standard resistance, Q_{dr}/Q_s , ranging between 3.2 and 1.3. Additional laboratory results would be required to confirm such preliminary results and to update empirical correlations.

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