

On the interpretation of piezocone tests in natural silt and sand mixtures

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Abstract – This paper presents the results of a number of variable rate piezocone tests (CPTU) carried out in the context of three independent site investigation campaigns on intermediate soil deposits. Attention is focused on the analysis of CPTU measurements in relation to the different penetration rates so as to identify drainage conditions during standard tests. Indeed, intermediate soils, typically including a large variety of mixed soil types, are generally characterized by permeability values within the range in which partial drainage is likely to occur during cone penetration and a non-identification of this effect may result in invalid CPTU-based estimates of soil parameters.

I. INTRODUCTION

Over the last decades cone penetration testing, with or without pore pressure measurements (CPTU/CPT), has become the most widely used in-situ testing technique for stratigraphic profiling and site characterization. The amount of knowledge so far gained on the interpretation of CPT/CPTU in sands and clays, in terms of fundamental mechanics of cone penetration, soil classification charts and both theoretical and empirical correlations for the estimate of soil parameters, is undoubtedly wide.

Only in recent years research efforts have been focused on other natural soils (silts, mixed soil types, volcanic and residual soils) that are still relatively poorly understood, and the applicability to such *unusual geomaterials* [1] of the existing interpretation approaches, typically developed for *standard* sands and clays, has come into question [2, 3]. A crucial point at issue is undoubtedly represented by the idealized assumption of a stiff distinction between drained and undrained testing conditions, which is very likely to be unsuitable for interpretation of CPT/CPTU data in silts, sandy silts, clayey sands or other sedimentary soils having very scattered grain size distributions and thus falling in the so called intermediate permeability range (i.e. 10^{-5} to 10^{-8} m/s). Indeed, cone penetration test response in similar deposits is, in all probability, affected by partial drainage effects and the preliminary identification of this condition is a key step in order to avoid misinterpretation of field measurements and, consequentially, invalid estimates of

soil parameters [4].

The matter is at present far from being satisfactorily solved. This may explain why there is a substantial lack of standardized recommendations providing engineers with some guidance on both testing procedures and data interpretation in intermediate soils. Nevertheless, geotechnical research has yielded a few key results on probable consolidation patterns during cone penetration. In particular, following the pioneering work of Randolph and Hope [5], piezocone tests (CPTU) carried out at non-standard penetration rates are now widely recognized as a simple and effective way to analyse the effect of partial drainage on penetrometer measurements and to detect the transition point from undrained to partially drained and drained responses.

So far, most of the relevant experimental studies on velocity effects have been mainly based on centrifuge physical models and laboratory reconstituted specimens of normally consolidated kaolin clay or silty clay (e.g. [5, 6, 7, 8]), whilst only a limited number of research contributions [9, 10, 11] have discussed results obtained from field scale tests and full size penetrometers.

This paper presents the results of a number of variable rate piezocone tests carried out in the context of three independent site investigation campaigns in intermediate soil deposits, with the aim of gathering a wide, coherent experience in rate effects on cone penetration response and thus obtaining some insight on the different degrees of partial drainage during the tests. Attention is also focused on the analysis of field measurements during dissipation tests, and the reliability of conventional approaches for the estimate of the coefficient of consolidation in such deposits is discussed.

II. THE TREPORTI TEST SITE DATABASE (VENETIAN LAGOON)

The set of piezocone tests described in this section is part of a comprehensive database collected at the Treporti Test Site (Venice, Italy) from 2001 to 2008, in the context of an ambitious research project aimed at better understanding the mechanical behaviour of the heterogeneous and highly stratified normally consolidated silty sediments forming the upper 100 m of the Venetian lagoon basin. The whole site investigation campaign, extensively described in Tonni and Gottardi [3] and also

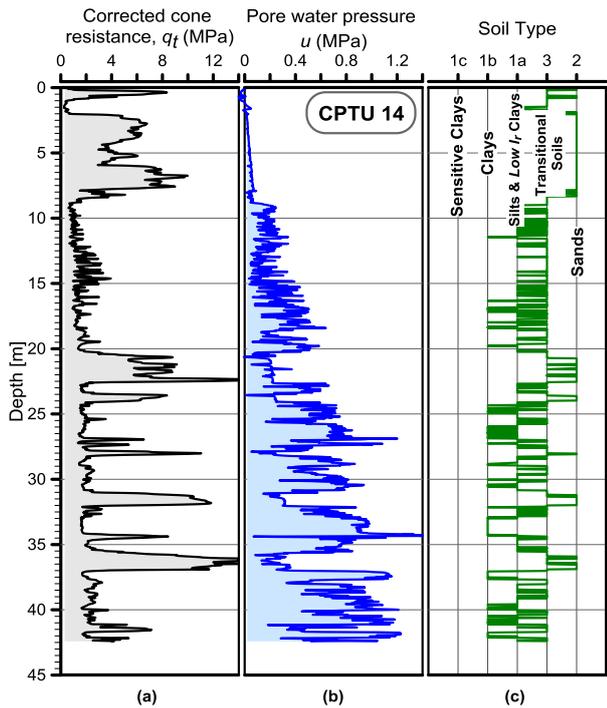


Fig. 1. CPTU 14 log profiles (a-b) and CPTU-based soil classification using the Schneider et al. [13] method.

in Tonni and Simonini [12], consisted of a large number of piezocone and flat dilatometer tests, together with continuous coring boreholes with sample extraction and high quality laboratory tests. The research programme included the construction of a full scale, vertical-walled cylindrical test bank which was continuously monitored during approximately 6 years with regard to a number of relevant parameters.

A typical piezocone response of Venetian subsoil, described in terms of the corrected cone resistance q_t and the pore pressure u , is provided in Figure 1 along with results from the application to such data of the rather sophisticated classification procedure developed by Schneider et al. [13]. Field measurements, in this case, refer to a standard-rate (20 mm/s) piezocone test (CPTU 14) carried out prior to the bank construction and located in the centre of the circular area later loaded by the bank itself. The classification profile plotted in column (c) provides immediate evidence of the general intermediate nature of Venetian sediments: indeed, most of the experimental points from 8 to 20 m in depth fall in the domain of silts (1a) or transitional soils (3), these latter including a wide variety of soil mixtures, such as clayey sands, silty sands, silty sands with clay, clayey sands with silt, whereas a complex assortment of fine (1b) to coarse (2) sediments, without any evident specific trend, can be observed below 22 m.

In such stratigraphic conditions, partial drainage during cone penetration is very likely to occur. This is also confirmed by the simple interpretation procedure

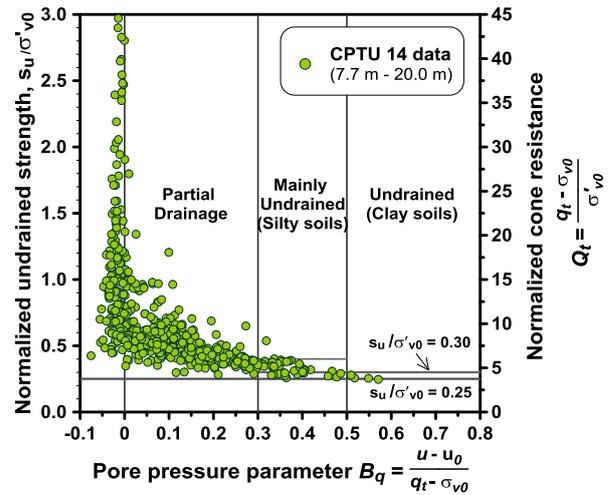


Fig. 2. Assessment of drainage conditions on CPTU14 data. Modified from Tonni and Gottardi [14].

proposed by Schnaid et al. [1], based on plotting the normalized cone resistance Q_t vs. the pore pressure parameter B_q , in combination with the undrained strength ratio s_u/σ'_{v0} . As shown in Figure 2, the method assumes that in normally consolidated silty soils partial drainage prevails when $B_q < 0.3$, and in such case the resultant estimated undrained strength ratio turns out to be significantly higher than values commonly accepted for NC or slightly OC soils.

The set of adjacent, variable rate piezocone tests (labelled as 34, 34_{min}, 34_{max}), carried out after the complete removal of the test bank, provided some fundamental insights into the consolidation pattern of Venetian sediments, with special attention to the predominantly silty unit detected from 7.5 to 20 m in depth.

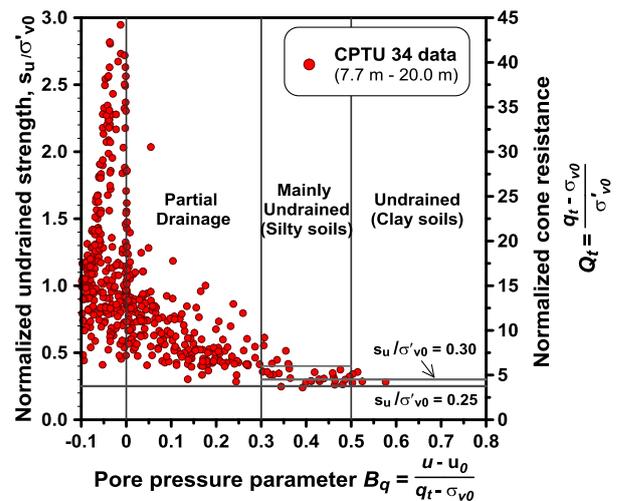


Fig. 3. Assessment of drainage conditions on CPTU34 data. Modified from Tonni and Gottardi [14].

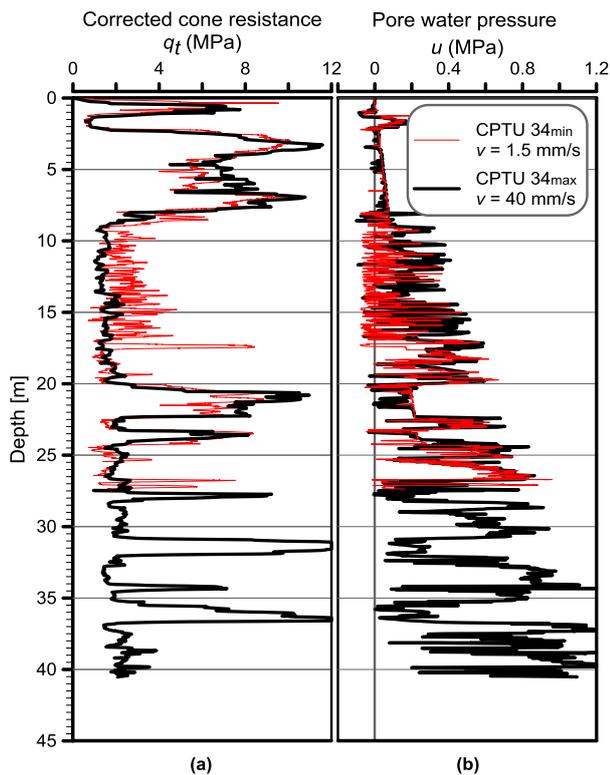


Fig. 4. Comparison between cone resistance and pore pressures of adjacent CPTU tests performed at two different penetration rates.

By comparing data plotted in Figure 3 with those of Figure 2, both obtained from adjacent standard cone penetration tests, a more pronounced dilative behavior of silty sediments, with very low or even negative excess pore pressures ($B_q < 0$), can be observed in CPTU 34, as a consequence of the undergone compression and overconsolidation.

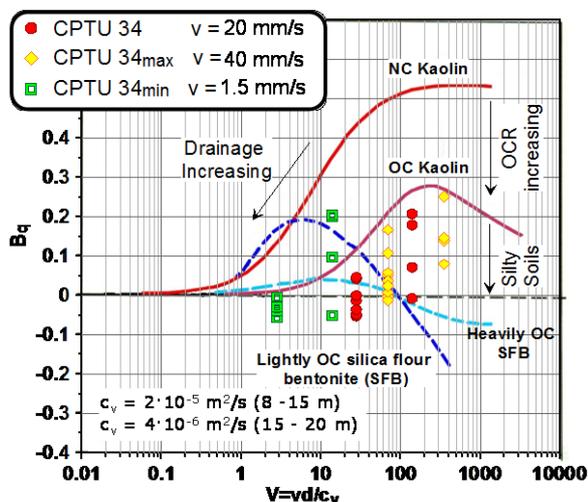


Fig. 5. Effect of normalized penetration rate V on excess pore pressure ratio B_q .

Besides, according to profiles of CPTU 34_{min} ($v = 1.5$ mm/s) and CPTU 34_{max} ($v = 40$ mm/s) provided in Figure 4, it can be easily observed that a reduction in the penetration rate results in a general increase in corrected cone resistance q_t and a decrease in pore water pressures u . More importantly, interpretation of these “pioneering” data on natural silts in terms of the excess pore pressure ratio B_q vs. the dimensionless velocity $V = v \cdot d / c_v$ (being the cone diameter $d = 35,7$ mm) provided a clear indication that, due to a variety of factors such as viscosity, silt content and stress history, the pore pressure response of these sediments seems to follow a complex trend, significantly different from the *backbone curve* [4] obtained by Schneider et al. [6] from centrifuge tests in normally consolidated kaolin clay (Figure 5).

It is worth observing that the above interpretation may have partly suffered from the uncertainties surrounding the evaluation of the relevant vertical coefficient of consolidation c_v , which was estimated from a few available pore pressure dissipations collected during standard piezocone tests, using the well-established method of Teh and Houlsby [15]. Indeed, the method is based on the assumption of undrained behaviour during penetration, which turns out to be questionable in such intermediate soils.

In conclusion, on the basis of the experimental points depicted in Figure 5, it is evident that additional piezocone tests, performed over a wider penetration rate interval, would be required in order to identify a well-defined trend line for the quantitative assessment of drainage degrees around the advancing cone.

III. VARIABLE RATE CPTU IN LIQUEFACTION-PRONE SILTY SANDS

This section presents results of a set of adjacent piezocone tests [16] carried out at different, non-standard penetration rates in the silty sand deposits forming the subsoil of the small village of Mirabello, located in the eastern part of the river Po alluvial plain, which experienced extensive liquefaction-induced ground effects after the seismic sequence occurred in May 2012.

The effect of penetration rate v on cone resistance q_t , pore pressure u and sleeve friction f_s , is shown in Figure 6, the attention being here focused on a thin homogeneous soil layer of sandy silt at 5.3 to 6.6 m in depth. A general slight decrease of q_t , together with an increase of u can be observed when the penetration rate v varies from 10 mm/s to 80 mm/s; by contrast, a gain in cone resistance occurs when the penetration velocity is equal to the maximum value $v_{max} = 130$ mm/s, thus following a trend similar to those reported in other studies from field as well as calibration chamber CPTs or centrifuge tests performed on fine soils, under undrained conditions.

According to the experimental results presented in Figure 6, it seems reasonable to assume that a penetration

rate equal to 80 mm/s, where q_t is minimum, corresponds to a fully undrained behaviour, with negligible viscous effects. Additional tests, performed at cone velocities in

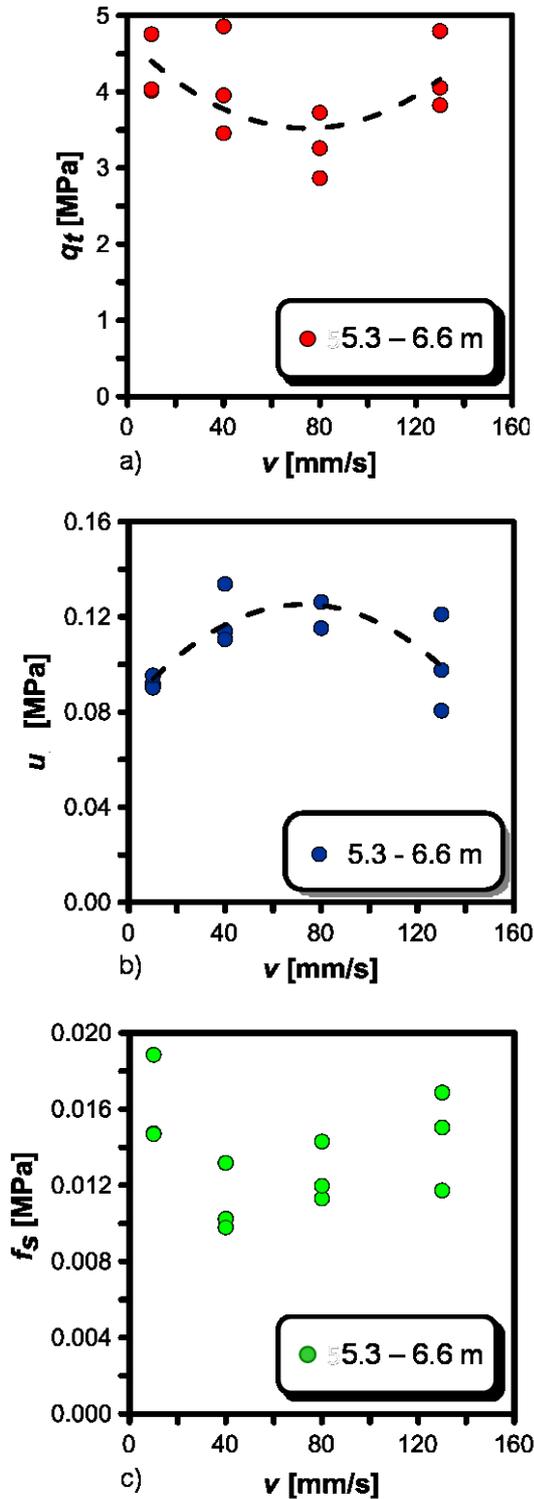


Fig. 6. Effect of penetration rate on piezocone measurements.

the range 80-130 mm/s, could undoubtedly help in identifying more accurately the transition point to fully undrained conditions.

Despite this, the application to the above data of the mathematical approach discussed in DeJong and Randolph [17] allowed predicting possible trend curves of both cone resistance and pore pressure vs. normalized velocity V , thus providing a preliminary estimate of the value of V at which drained penetration is likely to occur: the computed value turned out to be $V \approx 0.3$, i.e. well below the value of V corresponding to a standard rate of penetration.

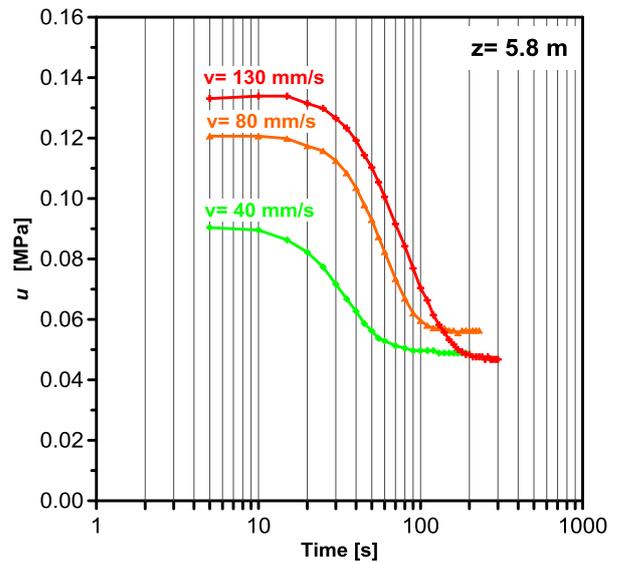


Fig. 7. Dissipation curves obtained for different penetration rate tests.

Table 1. Estimates of c_h from dissipation tests.

Test	Depth (m)	v (mm/s)	t_{50} (s)	c_h (m^2/s)
CPTU 4	5.86	40	32	$4.8 \cdot 10^{-5}$
CPTU 8	5.84	80	57	$2.7 \cdot 10^{-5}$
CPTU 13	5.82	130	71	$2.2 \cdot 10^{-5}$

Finally, Figure 7 shows three pore pressure dissipation curves, referred to the same depth $z = 5.8$ m. Estimates of the horizontal coefficient of consolidation c_h , obtained by interpreting the above dissipation data through the method of Teh and Houlsby [17], have been reported in Table 1. In the application of this procedure, a rigidity index I_r equal to 380 has been adopted. As expected, the method results in similar values of c_h for tests at $v = 80$ mm/s and $v = 130$ mm/s, when fully undrained conditions are very likely to apply, in accordance with the assumptions of the method. Hence, in intermediate soils,

the routine interpretation of dissipation curves obtained from standard penetration rate tests must be treated with a great deal of uncertainty.

IV. VARIABLE RATE CPTU IN CLAYEY SILTS

The third group of variable rate CPTU was recently carried out in a test site located in the southern margin of the river Po valley (Forlì). The stratigraphy of this area, as detected from a deep borehole as well as from a number of preliminary standard CPTUs, mainly consists of silty-clayey materials up to 28.5 – 29 m in depth, followed by gravels. Locally, from 8 to 9 m, 12 to 16 m and 19 to 21 m below ground level, interbedded silty sand levels are detected.

The application of the well-known CPTU-based classification chart proposed by Robertson [18] to the test performed at a standard penetration rate (i.e. CPTU 1) is shown in Figure 8(a). It turns out that the upper 4 meters mainly consist of silt mixtures (Soil Behaviour Type, $SBT = 4$) with occasional presence of silty sands/sandy silts ($SBT = 5$), whereas sediments below 4 m consist of an alternation of silt mixtures ($SBT = 4$) and clays ($SBT = 3$) with two main interbedded layers, 1 to 3 m thick, of sand mixtures ($SBT = 5$ and $SBT = 6$). This SBT profile is in substantial agreement with the soil lithology detected by an adjacent borehole, also reported in Figure 8(a).

The dataset collected in this site includes No. 8 adjacent piezocone tests performed at penetration rates from 1 mm/s to 62 mm/s, all pushed over 15 m in depth. Lower and upper values of cone velocity were necessarily defined by the technical limits of the equipment in use.

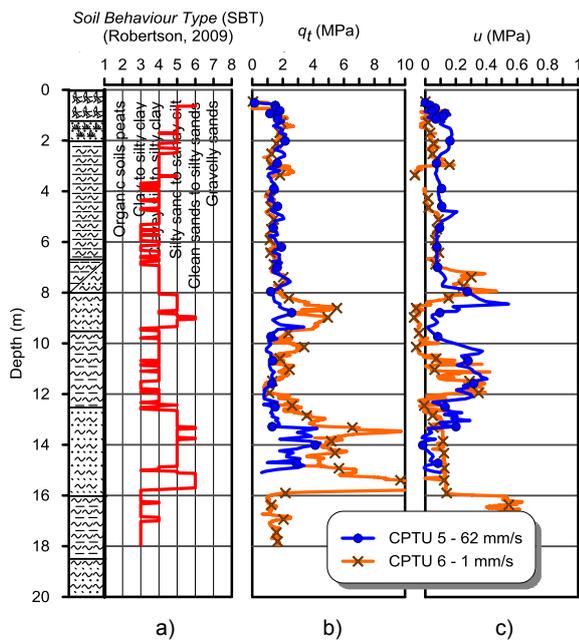


Fig. 8. CPTU-based classification results (a) and log profiles of two representative piezocone tests (b-c).

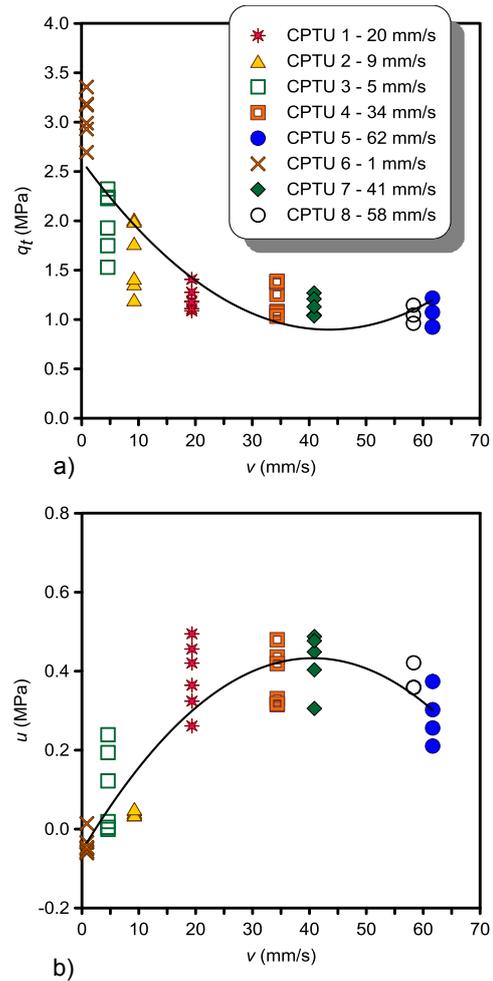


Fig. 9. Effect of penetration rate on piezocone measurements.

Figure 8(b) shows the q_t and u profiles obtained from tests CPTU 5 and CPTU6, carried out at the maximum and minimum penetration rates, respectively. By comparing the cone resistance profiles, it can be observed that the effect of a variation in cone velocity is more evident below 8 m depth; by contrast, the response in terms of pore pressures seems to be more sensitive to the different testing conditions over the whole investigated length.

According to the procedure already applied in section 3, the piezocone data collected within the clayey silt unit, at the representative depth interval 10-10.3 m below ground level, have been represented in terms of cone velocity (Figure 9), by considering the average values of both q_t and u within thin sublayers. Again, a rather saddle-shaped trend can be observed in the $q_t - v$ plot: due to partial consolidation, tip resistance increases as the penetration rate reduces from about 40 mm/s to 1 mm/s, whereas it slightly increases at $v > 40$ mm/s, as a consequence of viscous effects. A consistent response can be observed in the $u - v$ plot. According to such results,

fully undrained conditions are very likely to occur at a cone velocity close to 40 mm/s. A more in depth interpretation of the data collected in the Forli site is still under way.

V. CONCLUDING REMARKS

The paper has presented results of a number of variable rate piezocone tests carried out in the context of three independent site investigation campaigns on intermediate soil deposits. The effect of penetration rate on cone resistance and pore pressure measurements has been investigated with the aim of identifying drainage conditions when CPTU are performed at a standard velocity. Indeed, partial drainage is very likely to occur during conventional CPTU in intermediate soils and the preliminary identification of such effect is of paramount importance in order to properly interpret field data and thus obtain reliable geotechnical parameters.

Compared to some typical consolidation patterns of clays, provided by variable rate CPTU in physical models, the piezocone data presented in this paper generally show a more complex response, primarily due to the essentially silty nature of the investigated sediments as well as to their potentially dilative behaviour.

Although the occurrence of partial drainage during standard tests was confirmed in all cases, larger velocity intervals are generally required in order to capture the actual degree of drainage around the cone.

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