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Shear wave velocity as function of cone penetration test measurements in sand and silt mixtures

Laura Tonni [a,*], Paolo Simonini [b,1]

[a] Department of Civil, Chemical, Environmental and Materials Engineering, DICAM, Alma Mater Studiorum, University of Bologna, Bologna, Italy
[b] Dept. DICEA, University of Padova, Via Ognissanti 39, 35129 Padova, Italy

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ABSTRACT

A database of research-quality piezocone test (CPTU) results and shear wave velocity V_s measurements, assembled in the context of an ambitious research project carried out at the Treporti test site (Venice, Italy), has been interpreted in order to study the seismic response of the predominantly silty sediments forming the Venetian lagoon basin as well as to explore potential correlations for such intermediate soils. The experience gained so far with the Treporti database and other field data collected in the lagoon area has shown that the mechanical behavior of Venetian soils cannot be easily interpreted using the existing and well-established CPTU-based approaches, hence the interest in examining whether or not the seismic response of these sediments, expressed in terms of shear wave velocity, follows the framework published for other soils. The applicability to the available data of a number of existing correlations, originally developed either for sands or fine sediments, has been first investigated and updated relationships have been then suggested. Furthermore, the small-strain stiffness calculated from V_s measurements has been compared with the field stiffness derived from the observed performance of a full-scale test embankment built in the Treporti site, so as to verify common design assumptions. The verification and calibration of existing approaches are likely to constitute a useful contribution to the practice of geotechnics not only in the Venetian lagoon area, but also in the silty deposits usually present in the surrounding alluvial plain and other similar depositional environments, allowing rapid estimates of seismic soil classification as well as small-strain stiffness properties for preliminary design or at sites where only cone penetration data are available.

1. Introduction

In geotechnical problems, the evaluation of the shear wave velocity V_s is primarily important in defining the small-strain stiffness characteristics of soils, commonly expressed in terms of the low-amplitude shear modulus G_0. Shear wave velocity is also useful in earthquake site response analyses as well as in the evaluation of liquefaction potential, site classification, soil unit weight, soil stratigraphy and foundation settlements (e.g. Andrus and Stokoe, 2000; Schneider et al., 2001; Andrus et al., 2004; Mayne, 2007; Long and Donohue, 2010; Akin et al., 2011; Chang et al., 2011; Omar et al., 2011).

Over the last decades, a wide variety of in-situ seismic techniques, including cross-hole and down-hole methods, spectral analysis of surface waves and also advanced piezoelectric sensor-based devices, has been developed for direct measurement of shear wave velocity (Stokoe and Santamarina, 2000; Lee et al., 2010; Yoon and Lee, 2010). In the context of hybrid in-situ geotechnical tests (Mayne, 2000), the seismic cone penetration (SCPT-SCPTU) and seismic dilatometer (SDMT) tests have grown more popular worldwide since they provide an optimization of data collection by combining down-hole shear wave velocity profiles with either conventional penetration or dilatometer measurements. In any case, direct measurement of V_s requires specialized equipment and technical expertise in order to ensure that the data are properly obtained and evaluated. Thus, for low-risk projects or preliminary design, in-situ seismic measurements may not be economically feasible and empirical correlations between shear wave velocity and cone penetration test (CPT/CPTU) data turn out to be potentially useful at least for a first estimate of the small-strain stiffness of soils. Besides, due to the growing use of CPT/CPTU, huge amounts of data on diverse soil types have been collected worldwide, hence the possibility of deriving reliable values of the seismic properties of soils from conventional cone penetration readings provides an interesting and economical way of optimizing the existing measurements.

As a result, over the last years a significant number of correlations have been proposed to determine shear wave velocity from cone resistance, q_c. Most of them have been developed for relatively young

* Corresponding author at: Dept. DICAM, Viale Risorgimento 2, 40136 Bologna, Italy. Tel.: +39 051 2093526; fax: +39 051 2093527.
E-mail addresses: laura.tonni@unibo.it (L. Tonni), paolo.simonini@unipd.it (P. Simonini).
[1] Tel./fax: +39 049 8277904.

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deposits, with reference to two well-distinct soil categories, i.e. sands (drained behavior) and clays (undrained behavior).

In this paper, a database of research-quality piezocone test (CPTU) results and shear wave velocity measurements, assembled in the context of the Treporti test site (Venice) research project, is interpreted in order to identify possible trends between q_c and V_s for the highly heterogeneous, predominantly silty sediments forming the Venetian lagoon basin. The applicability of some existing relationships is examined and a refinement of the available approaches is suggested in order to gain better estimates of V_s in such intermediate sediments, whose mechanical behavior has been generally found not to fit easily into published frameworks and widely used CPT/CPTU-based correlations (Tonni and Gottardi, 2011). Taking this very well documented case study as a base, the idea is essentially to provide some guidance for practitioners working with these silt mixtures and other similar silty soils worldwide, for which little information can be generally found in the geotechnical literature.

Finally, the small-strain stiffness values derived from the seismic shear wave velocity profiles have been compared with the stiffness parameters obtained from back-analysis of a monitored test embankment built in the Treporti test site area, in order to have some insight into the subsoil deformation response in the elastic domain.

2. Basic state of knowledge

When considering V_s–q_c (or alternatively, G_0–q_c) correlations, the key question arises as to whether or not a small strain value (V_s, G_0) can be derived from an ultimate strength measurement (q_c). The issue was amply discussed by Mayne and Rix (1993), who observed that penetration resistance and initial tangent shear modulus, though reflecting soil behavioral responses at opposite ends of the strain spectrum, show a functional dependence on similar quantities (i.e., confining stress level, K_0 stress state, mineralogy, aging) and thus can be legitimately assumed to correlate. Such conclusion has been recently confirmed by Schneider et al. (2004), on the basis of a micro-scale interpretation of mechanisms governing wave propagation (Santamarina and Aloufi, 1999) and cone penetration in sands.

Following the pioneering studies of Jamiolkowski et al. (1988), Baldi et al. (1989), Bouckovalas et al. (1989), and Mayne and Rix (1993), a large number of empirical correlations between either G_0 or V_s and penetration test results have been proposed in the literature (e.g. Fear and Robertson, 1995; Hegazi and Mayne, 1995; Mayne and Rix, 1995; Simonini and Cola, 2000; Wride et al., 2000; Piratheepan and Andrus, 2002; Long and Donohue, 2010; Karray et al., 2011). The most recent studies have mainly focused on direct correlations between V_s and q_c, since shear wave velocity is a fundamental measurement, whereas G_0 $(=\rho \cdot V_s^2)$ is a calculated value obtained from V_s and either an assumed or measured value of mass density, ρ (Mayne and Rix, 1995). Besides, some of the empirical relationships use stress-corrected quantities for both V_s and q_c, so as to remove the effect of overburden pressure.

The experience gained so far on V_s–q_c correlations has clearly shown that fine and coarse soils generally follow different trends, hence the need of imposing particle-size limits on the validity of the majority of the available empirical formulations. A number of studies on granular soils have stressed the role of particle size distribution, suggesting the use of relations where the ratio between V_s and q_c is assumed to vary with the mean grain size D_{50} (e.g. Karray et al., 2011).

As regards fine-grained soils, a major issue with the most commonly used correlation by Mayne and Rix (1995) is that it relies on the in situ void ratio (e_0) as – input. This parameter is not often readily available, especially at an early stage of investigation, as it requires laboratory testing on undisturbed samples or advanced, non-routine in-situ testing devices (Kim et al., 2011). To overcome this drawback, Long and Donohue (2010) proposed a CPTU-based correlation which accounts for soil structure effects simply in terms of the pore pressure parameter B_q, as defined in Lunne et al. (1997):

$$B_q = \frac{u - u_0}{q_t - \sigma_{v0}} = \frac{\Delta u}{q_t - \sigma_{v0}} \tag{1}$$

where u is the measured pore pressure, u_0 is the equilibrium pore pressure, q_t is the corrected cone resistance from piezocone and σ_{v0} is the total vertical stress. The approach, also adopted in a recent study by Cai et al. (2010), can be considered a revision of the relationship proposed by Simonini and Cola (2000), who earlier explored a q_c–G_0 correlation including a dependence on the excess pore pressure Δu.

Despite the abundant literature, very few studies have considered global relationships between V_s and q_c, applicable to all soil types. One of the most interesting contributions is undoubtedly represented by the recent study of Robertson (2009), who proposed a general relationship developed in the framework of the well-known and newly revised CPT Soil Behaviour Type (*SBTn*) Chart, based on a variable, nonlinear stress normalization of cone tip resistance. In this approach, shear wave velocity is correlated to the corrected cone resistance q_t in conjunction with the Soil Behaviour Type index I_c. This latter depends, in turn, on the stress-normalized variables Q_{tn} and F_r, according to the following expressions (Robertson, 2009):

$$I_c = \sqrt{(3.47 - \log Q_{tn})^2 + (\log F_r + 1.22)^2} \tag{2}$$

$$Q_{tn} = \frac{q_t - \sigma_{v0}}{p_a} \cdot \left(\frac{p_a}{\sigma'_{v0}}\right)^n = \frac{q_{t,net}}{p_a} \cdot \left(\frac{p_a}{\sigma'_{v0}}\right)^n \tag{3}$$

$$F_r = 100 \cdot \frac{f_s}{q_t - \sigma_{v0}} \tag{4}$$

where f_s is the sleeve friction, p_a is the atmospheric pressure and σ'_{v0} is the effective vertical stress. The stress exponent n (≤ 1) in Eq. (3) depends on both the stress level and the *SBTn* index itself, hence the iterative nature of the method:

$$n = 0.38 I_c + 0.05 \cdot \left(\sigma'_{v0}/p_a\right) - 0.15. \tag{5}$$

The resulting correlation, deduced by approximating a series of stress-corrected shear wave velocity contours plotted on the *SBTn* Chart Q_{tn}–F_r, is given by:

$$V_s = \left[\alpha_{vs}\left(\frac{q_t - \sigma_v}{p_a}\right)\right]^{0.5} = \left[10^{(0.55 I_c + 1.68)}\left(\frac{q_t - \sigma_v}{p_a}\right)\right]^{0.5} (\text{in m/s}). \tag{6}$$

3. Overview of the venetian lagoon subsoil and the Treporti test site

The upper 100 m of the Venetian lagoon basin consist of a complex assortment of interbedded normally consolidated or slightly overconsolidated ($OCR = 1.1–1.3$) silts, medium-fine silty sands and silty clays. Such stratigraphic complexity is essentially due to the continental sedimentation process occurred during a marine regression in the last glacial Pleistocenic period (Würm). Only the shallowest, predominantly sandy deposits are referable to the current lagunar cycle (Holocene), while sediments below 100 m in depth derived from alternate continental and marine sedimentation phases associated with marine regressions and transgressions during the last 2 Ma.

An extensive overview of the geology of the lagoon area, together with a detailed description of the mineralogical characteristics of Venetian sediments, can be found elsewhere (e.g. Simonini et al., 2007). It is worth mentioning here that the coarse fraction of the upper 100 m sediments is predominantly composed of carbonates, with quartz and feldspar as other significant components. Silts and silty clays, resulting from mechanical degradation of sands, have a content of non-active, highly crystallized clay minerals (illite with minor quantities of chlorite, kaolinite and smectite) never exceeding 20% in weight. According to the Unified Soil Classification System, 95% of such sediments can be grouped into 3 classes: medium-fine sands (SP-SM) with sub-angular grains, silts (ML) and very silty clays (CL). The remaining 5%, most likely due to occasional lacustrine depositional environments, may be classified as organic clay and peat.

As recently observed by Long et al. (2010), the soils of the Venetian lagoon are perhaps the most well studied silt materials in the world. One of the significant findings from the extensive research on such sediments is that, as a direct consequence of their common mineralogical origin, the different soil classes show a similar mechanical behavior, mainly controlled by inter-granular friction (Cola and Simonini, 2002).

Based on the valuable experience gained from previous studies on Venetian soils, the Treporti test site (*TTS*) was set up within a major collaborative research project aimed at better understanding the stress-strain-time response of such heterogeneous sediments and similar intermediate soils. In this 15,000 m^2-large area, facing the North-Eastern lagoon, a full-scale 6.5 m high, 40 m diameter, vertical-walled cylindrical test bank was progressively built and continuously monitored for the following 6 years in terms of a number of relevant parameters (Simonini, 2004). Among the advanced and varied monitoring devices installed within the loaded area, a crucial role for the analysis of the subsoil deformation process and the consequent evaluation of soil stiffness parameters was played by the four sliding deformeters installed beneath the bank, providing subsoil vertical strains at 1 m intervals. A scheme of the construction history of the test bank, together with the associated settlement measured in the center of the loaded area, is reported in Fig. 1. The curve also shows the deformation occurred during the gradual removal of the bank, which was launched four years after the end of construction.

The accurate geotechnical characterization of the area mainly relied on extensive in situ testing, including a large number of piezocone and dilatometer (DMT) tests performed in three different phases, i.e. prior to the loading bank construction (I), after the bank construction (II) and at the end of its complete removal (III). In this way, a complete database of field data, related to a well-known stress history, has become available for interpretation. In addition to conventional CPTU and DMT, a few seismic piezocone tests (SCPTU) and seismic dilatometer tests (SDMT) were carried out in the first and third phases of the site investigation program (McGillivray and Mayne, 2004; Marchetti et al., 2004; Marchetti et al., 2008). Fig. 2 shows the location of a limited number of tests performed within the restricted area of the loading bank, with special emphasis given to a few SCPTU, CPTU and SDMT which are particularly relevant to the study described in this paper.

In last years, a significant amount of research (Tonni and Gottardi, 2010, 2011; Tonni et al., 2010; Tonni and Simonini, 2012) has been carried out on the analysis of the wide *TTS* database and a large subset of the available field measurements has been interpreted in terms of stress history and compressibility characteristics of Venetian soils. Results have shown that the empirical, CPTU-based correlations calibrated on the *TTS* data can be successfully applied to other sites of the Venetian lagoon (e.g. Tonni et al., 2013), thus confirming the potential of such exhaustive database for effectively representing the mechanical response of soils in the whole area.

4. Overview of the Treporti seismic data

As previously mentioned, the reference database adopted in this study consists of two sets of seismic tests, performed prior to and following the loading bank construction respectively.

The first set included three seismic piezocone tests (labeled as SCPTU14, SCPTU15, SCPTU19) and three adjacent seismic flat

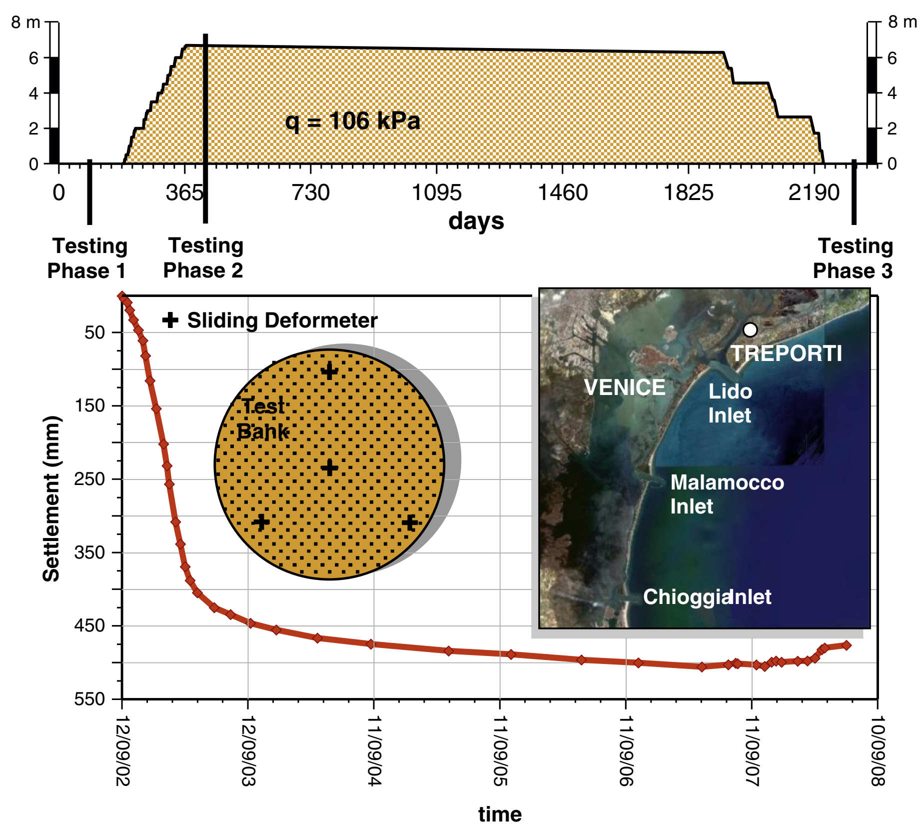

Fig. 1. Scheme of the construction history of the test bank and the associated settlement measured beneath the center of the loaded area. In the box: Satellite view of the Venetian lagoon.

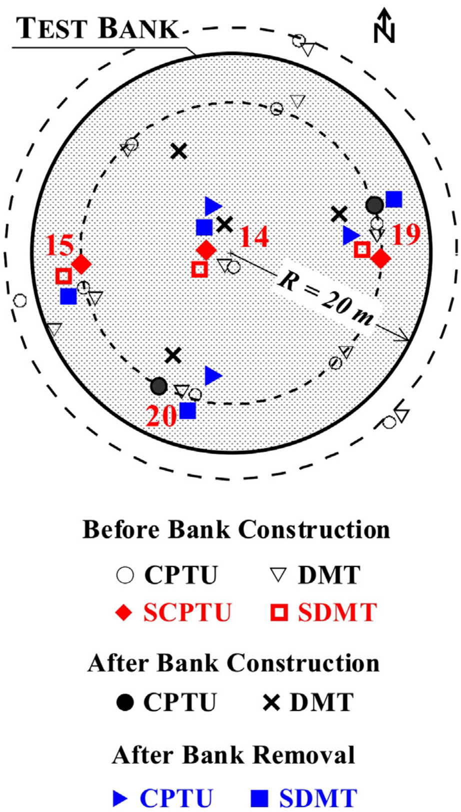

Fig. 2. Location of the in situ tests beneath the loaded area.

dilatometer tests (SDMT14, SDMT15, SDMT19). In SCPTU tests, seismic data were collected using a pseudo-interval method, while both the pseudo-interval and the true interval procedures were used in SDMT15 and SDMT19. In all cases, measurements of shear wave were made at 1 m intervals, during the pause at the end of each rod break. For the only SDMT14, V_s measurements were taken at frequent 20 cm increments, which is the same interval as for the conventional DMT readings. Details on the different acquisition methods as well as on the advantages or disadvantages associated with each testing procedure have been provided by McGillivray and Mayne (2004).

In the third phase of the site investigation campaign, three additional seismic dilatometer tests ($SDMT14_P$, $SDMT19_P$, $SDMT20_P$) and three conventional piezocone tests ($CPTU14_P$, $CPTU19_P$, $CPTU20_P$) were carried out approximately in the same testing locations of the first phase. In this way, the effect of a well-defined stress history condition on the in situ test measurements could be fully appreciated. For these SDMTs, seismic measurements were taken every 50 cm, using a true-interval method.

Fig. 3 shows the seismic piezocone profiles obtained from SCPTU14, in terms of corrected cone resistance q_t, sleeve friction f_s, pore pressure u, pore pressure parameter B_q and shear wave velocity V_s. The sounding details a well-defined top layer of sands followed by a silty unit with thin layers of sandy to clayey silts, from 8 to 20 m in depth. A dense and chaotic alternation of silty sands, silts, sandy and clayey silts with occasional presence of peat, can be detected at depths greater than 22 m. The pore water pressure profile rarely follows up the hydrostatic level, at times describes a slightly dilative response of sediments but more often corresponds to a contractive behavior, though with moderate excess pore pressure values. Accordingly, the pore pressure parameter B_q, as defined in Eq. (1), is generally positive but rarely exceeds 0.5. Furthermore, significant oscillations and spikes can be observed in both the u and B_q profiles, most likely due to the chaotic assortment of different grain-sized sediments.

As regards the pseudo-interval V_s profile depicted in column (e), apart from the upper Holocene-age sandy layer, which is characterized by an approximately constant value of the shear wave velocity (≈200 m/s), a general increase with depth can be observed. However, it must be noted that no marked differences in the seismic response of the different soil classes can be generally detected, while the significant decreases in V_s at approximately 27 m and 34 m in depth can be reasonably associated with the presence of thin layers of peat. For completeness, representative points of the stress-normalized shear wave velocity V_{s1} (Robertson et al., 1992), given by:

$$V_{s1} = V_s\left(\frac{p_a}{\sigma'_{v0}}\right)^{0.25} (\mathrm{m/s}) \tag{7}$$

have been plotted in Fig. 3(e).

In order to provide a better insight into the above-mentioned subsoil stratigraphic complexity, the rather sophisticated piezocone-based classification chart developed by Schneider et al. (2008) has been applied to SCPTU14 data (Fig. 4). The approach, based on the normalized cone tip resistance ($Q = q_{t,net}/\sigma'_{v0}$) and the normalized excess pore pressure ($\Delta u/\sigma'_{v0}$), was primarily derived to aid in separating whether cone penetration is drained, undrained or partially drained, hence the method is recognized as superior to other well-known classification charts when evaluating CPTU measurements in nontextbook geomaterials, such as silts and mixed soil types. As evident from Figs. 4 and 5(b), most of the experimental points from 8 to 20 m in depth fall in the domains of silts (1a) and 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. Very rare layers of clays (1b) and sands (2) can be occasionally detected. By contrast, soil layers below 22 m are characterized by a complex assortment of fine to coarse sediments without any evident specific trend. As a consequence of the general intermediate nature of such sediments, cone penetration may occur under conditions of partial consolidation (Tonni and Gottardi, 2009, 2010), hence the application of standard design correlations, intended for deriving drained or undrained mechanical parameters, generally results in lower levels of reliability (Schnaid et al., 2004). Fig. 5 also presents the profile of the *SBTn* index I_c deduced from SCPTU14 data, together with the I_c-boundaries for the identification of the soil type zone, according to the well-known CPT-based classification framework developed by Prof. Robertson (Robertson, 1990; Robertson and Wride, 1998; Robertson, 2009). For useful comparison, the grading characteristics of Treporti sediments, as obtained from laboratory tests performed on samples from a borehole located within the bank area, have been provided in column (a). Similar results have been also observed in SCPTU15 and SCPTU19.

Finally, the complete set of V_s data from SDMTs and SCPTUs of the first testing phase is presented in Fig. 6, together with the corrected cone resistance q_t profiles. Measurements collected using both pseudo-interval and true-interval methods are generally in good agreement, irrespective of the test type. False highs and false lows can sometimes be detected in the pseudo-interval profiles, due to slight errors caused by trigger timing, source repeatability issues and small inaccuracies in the depth measurement (McGillivray and Mayne, 2004).

Fig. 7 shows the true-interval V_s measurements from the seismic dilatometer tests of the third phase, in conjunction with the q_t and u profiles obtained from the adjacent piezocone tests. Representative points of the *OCR* values after the bank removal, as back-calculated from the stress history applied with the loading bank, have been superimposed onto the V_s plots in Fig. 7. The influence of overconsolidation on the third phase CPTU measurements has been discussed in detail elsewhere (Tonni and Gottardi, 2011; Tonni et

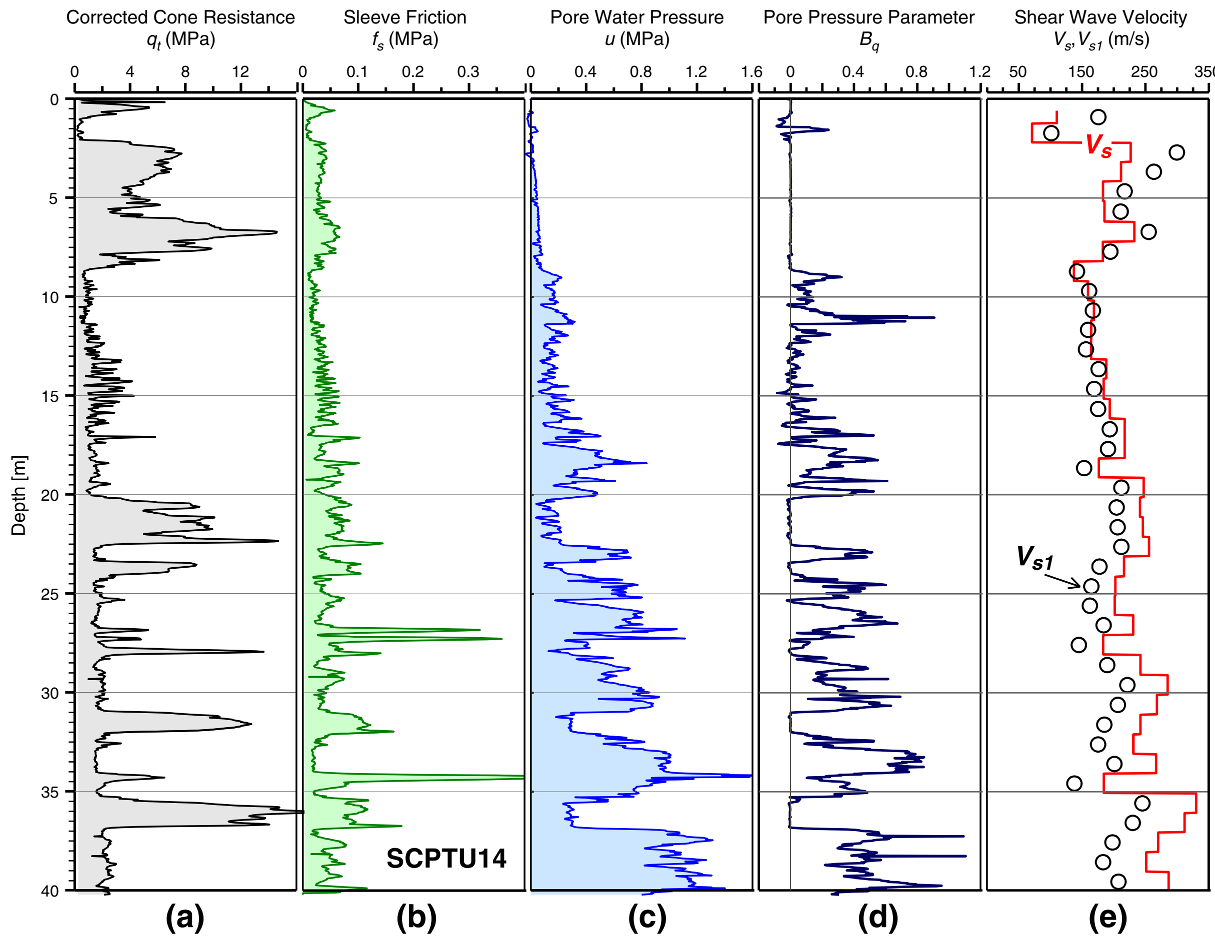

Fig. 3. SCPTU14 log profiles.

al., 2011). It is worth remarking here that, compared to the V_s profiles depicted in Fig. 6, a slight increase in the shear wave velocity values can be generally observed.

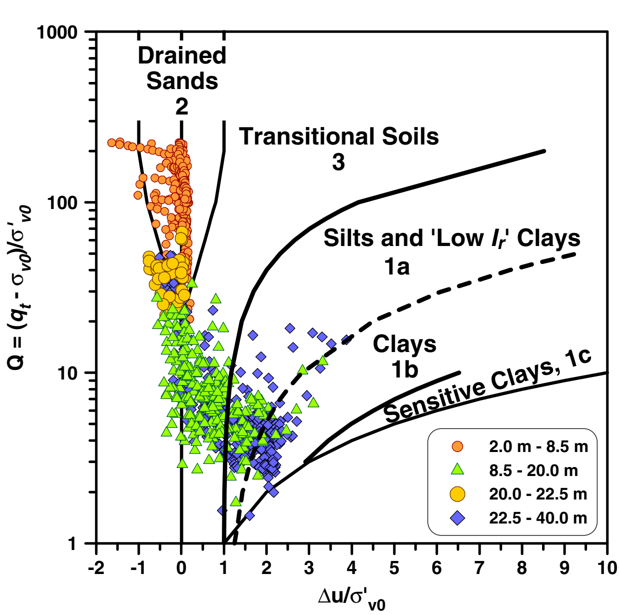

Fig. 4. Soil classification from SCPTU14 using the Schneider et al.'s (2008) chart.

5. Correlations between q_t and V_s

In this section, possible statistical trends between shear wave velocity and piezocone measurements are investigated, in an effort of describing the observed seismic response within a unified approach, valid for the different soil classes of the Venetian lagoon subsoil, with special reference to silts.

Data from the first phase SCPTU tests, plotted simply in terms of q_t and V_s, are shown in Fig. 8(a). Among alternative procedures proposed by various authors on how to pair multiple cone resistance data with a single shear wave velocity measurement, the simple approach of taking the average of the q_t profile over the V_s interval has been finally adopted in order to define the data points plotted in Fig. 8. However, to ensure that each selected value of q_t is a representative value of the corresponding interval, variation of cone penetration measurements within the selected segment has been carefully examined and marked irregularities, associated with very thin interbedded layers of different soils, have been neglected.

Despite the common mineralogical origin and the similar frictional-based mechanical response, Fig. 8(a) clearly shows that predominantly sandy sediments follow a different trend behavior compared to silts–silt mixtures and transitional soils, thus confirming the influence of particle size on the V_s–q_t relationship. Furthermore, a certain scatter can be appreciated in sands. A purely statistical analysis of the data associated with silts and silt mixtures has led to the following relationship:

$$V_s = 104.1 \cdot q_t \left[R^2 = 0.92\right] \quad (8)$$

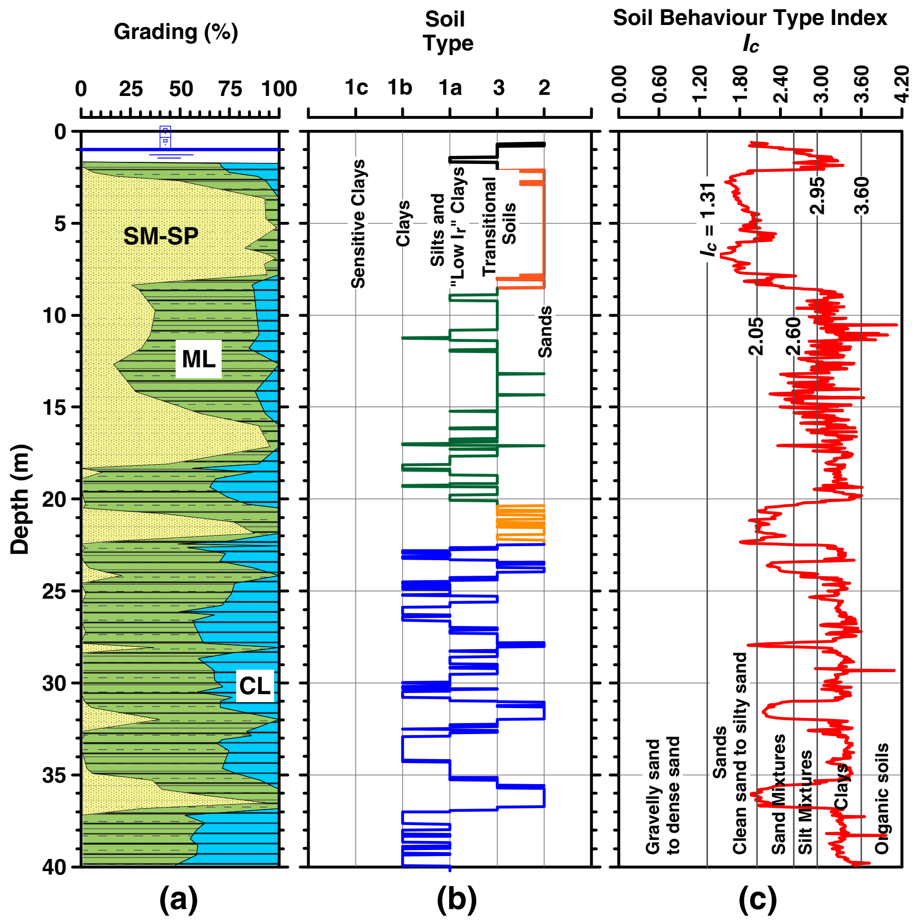

Fig. 5. (a) Grading characteristics of the Treporti subsoil; (b) Profile of the soil classes using the Schneider et al.'s chart; (c) Soil behaviour type index I_c from SCPTU14.

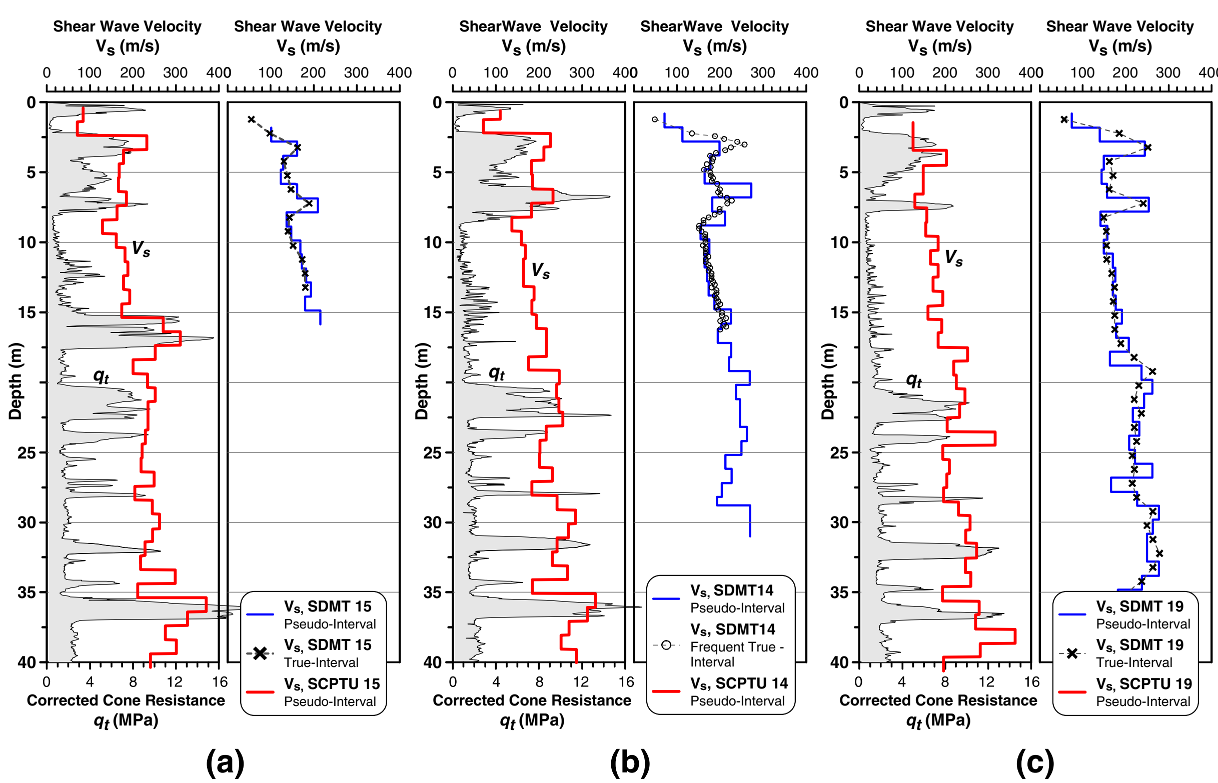

Fig. 6. Results from side-by-side seismic piezocone and seismic dilatometer tests performed prior to the loading bank construction.

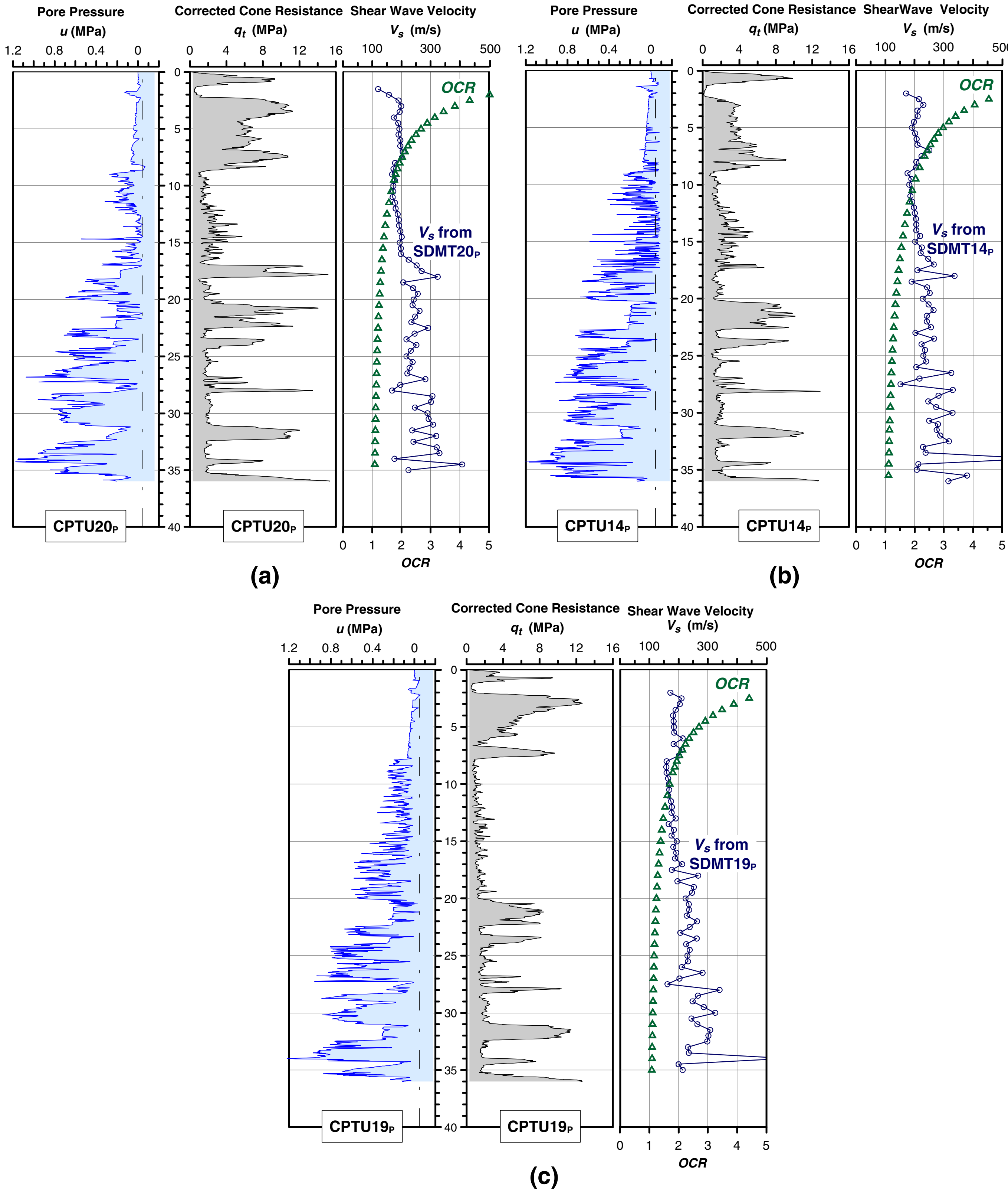

Fig. 7. Results from side-by-side piezocone tests and seismic dilatometer tests performed after the loading bank removal.

while in predominantly sandy sediments the following correlation has been obtained:

$$V_s = 84.3 \cdot q_t^{0.53} \quad \left[R^2 = 0.50\right]. \tag{9}$$

R^2 being the coefficient of determination. In both equations q_t is in MPa and V_s in m/s. A similar response can be observed by plotting both the true-interval and pseudo-interval V_s measurements from the first phase SDMT tests versus the adjacent q_t measurements, as shown in Fig. 8(b). In this case, a slightly greater scatter of data can

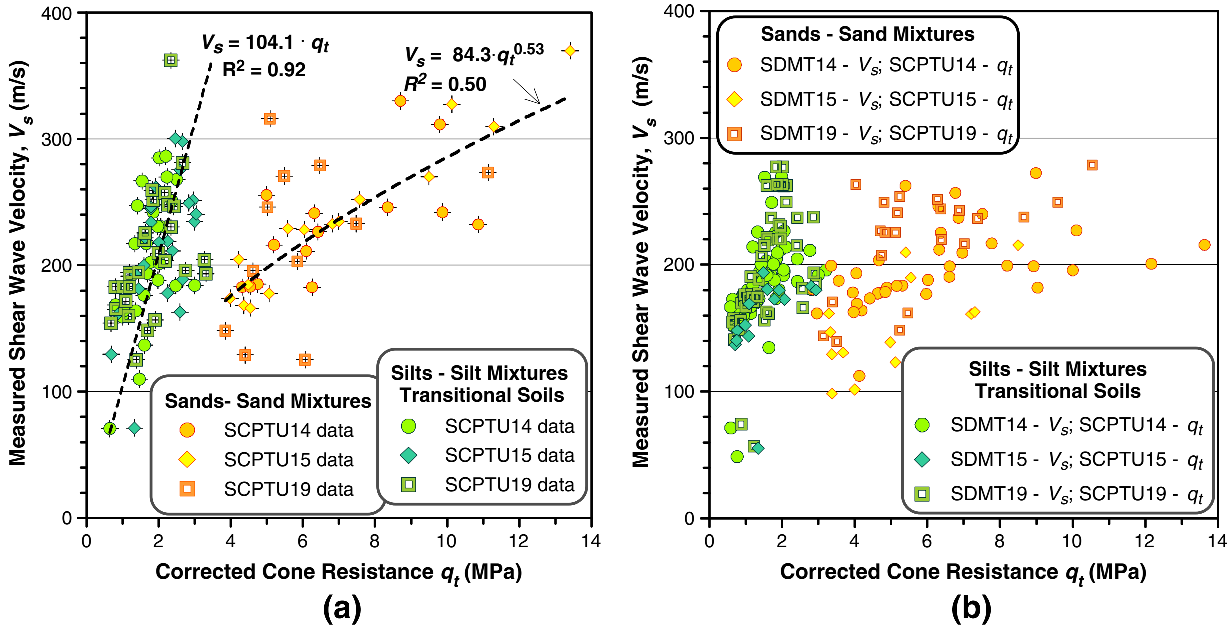

Fig. 8. V_s versus q_t for Venetian sediments. (a) Shear wave velocity measurements from SCPTU; (b) Shear wave velocity measurements from SDMT.

be generally noticed, maybe due to the fact that each point is associated with pairs of measurements from two different, though nearby, soundings.

A series of preliminary analyses have shown the general difficulty of interpreting the seismic response of these heterogeneous sediments within the available and widely-used CPT-based approaches, proposed for either sands or clayey soils. Besides, it must be observed that correlations which rely on both cone resistance and in situ void ratio e_0 as input data cannot be easily applied, because in these soils undisturbed sampling is rather difficult to achieve and a continuous and reliable profile of e_0 is not routinely available. On the other hand, a major issue with the relationships involving a combined dependence on q_t and B_q (e.g. Long and Donohue, 2010) is that in such sediments the pore pressure profiles generally show large oscillations, thus causing significant uncertainties in the selection of a representative value of the pore pressure parameter at each depth of calculation.

In order to explore the possibility of developing a global relationship, applicable to all soil classes irrespective of the sediment grain-size, attention has been first focused on the seismic piezocone database solely. In this way, the resulting V_s–q_t correlation is derived from data of the same soundings and additional uncertainties induced by spatial variability are thus eliminated. A first exercise to statistically derive a power function expression in terms of q_t and B_q has confirmed the drawback of such approach, resulting in a moderate $R^2 = 0.56$.

Afterwards, attempts have been made to interpret data of Fig. 8(a) in terms of the SBTn index I_c, as defined in Eq. (2). Indeed, in last years the use of I_c into cone penetration-based empirical correlations has been investigated by various authors and its effectiveness in reflecting the different mechanical behaviors of soils, together with the ability of allowing a unified description of soil response, is now widely recognized (e.g. Robertson, 2009; Ku et al., 2010). Furthermore, despite the chaotic interbedding of the Venetian subsoil, moderate variations can be generally observed in the I_c profiles derived from CPTU tests, hence representative values of each selected soil layer can be more easily determined.

Different functional forms for the term including I_c have been examined and a formulation similar to that recently proposed by Robertson (2009) has been finally adopted. Starting from the general expression, based on a variable exponent n:

$$V_s = \beta_{vs}\left(\frac{q_t-\sigma_v}{p_a}\right)^n = 10^{(a\cdot I_c+b)}\left(\frac{q_t-\sigma_v}{p_a}\right)^n \tag{10}$$

the multiple regression for the whole amount of SCPTU data has given:

$$V_s = 10^{(0.26\cdot I_c+1.02)}\left(\frac{q_t-\sigma_v}{p_a}\right)^{0.41} \quad \left[R^2 = 0.55\right]. \tag{10a}$$

On the other hand, a much better R^2 can be achieved by assuming the exponent $n = 0.5$, as suggested by Robertson. The resulting correlation is:

$$V_s = 10^{(0.31\cdot I_c+0.77)}\left(\frac{q_t-\sigma_v}{p_a}\right)^{0.5} \quad \left[R^2 = 0.76\right] \tag{11}$$

where constants a and b turn out to be 0.31 and 0.77 respectively, and thus relatively close to the values proposed by Robertson ($a = 0.27$, $b = 0.84$). Results from the application of Eq. (11) are provided in Fig. 9(a).

Similar statistical analyses, performed on the whole set of SDMT-based true-interval and pseudo-interval V_s measurements in conjunction with the adjacent piezocone data, have generally confirmed the trends derived as SCPTU intra-correlations. Slightly lower values of R^2 have been obtained only for the V_s–q_t–B_q relationship, probably due to the horizontal spatial variability between piezocone and dilatometer soundings, which may play some role when a very sensitive indicator of local variations in the soil profile, such as B_q, is included in correlations. Measured V_s values from SDMTs and predictions using Eq. (11) are plotted in Fig. 9(b).

Additional intra-sounding analyses have shown that a significant improvement is attained if correlations of the type described by Eq. (10) are expressed in terms of stress-normalized variables, using overburden correction factors. Indeed, it is well-known that both shear wave velocity and penetration resistance depend on the effective stress level, although they normalize differently with σ'_v. Therefore,

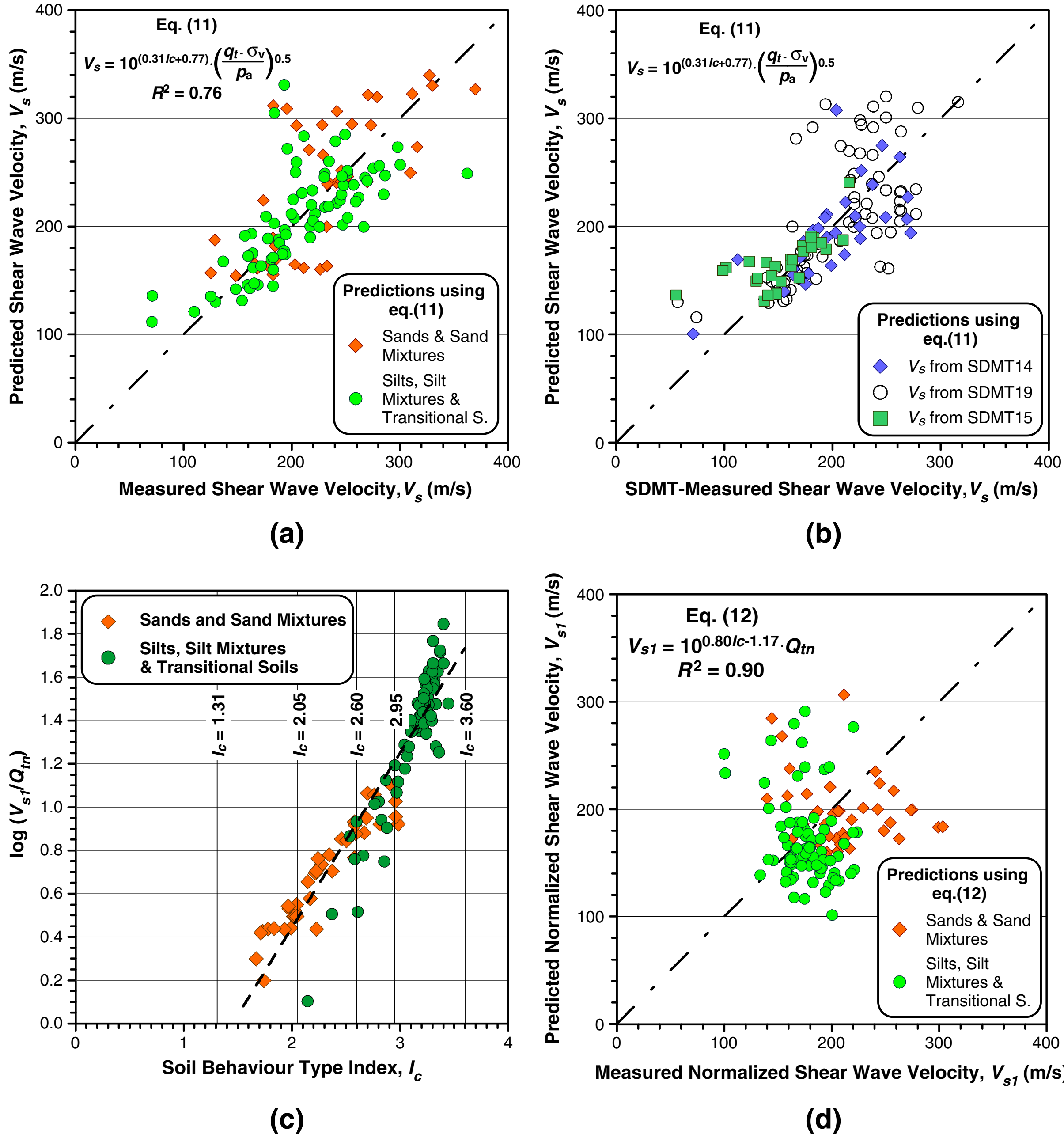

Fig. 9. (a)–(b) Measured versus predicted shear wave velocities, using Eq. (11); (c) V_{s1}/Q_{tn} as a function of the Soil Behaviour Type Index I_c; (d) Measured versus predicted V_{s1} values, using Eq. (12).

correlations based on stress-normalized values turn out to be superior. Regarding V_s, the common overburden correction proposed in Eq. (7) has been adopted in order to obtain V_{s1}. The formulation is based on a constant, empirical stress exponent $m = 0.25$, although such value could in principle vary with soil type, cementation and plasticity index. As regards cone resistance, among different and widely accepted stress normalization procedures, the iterative method described in Eqs. (3) and (5) has been selected, consistently with the approach assumed throughout the study.

From the large number of regression analyses, aimed at exploring various combinations of the stress-corrected variables, the following correlation has provided the best fit of the available data:

$$V_{s1} = 10^{(0.80 \cdot I_c - 1.17)} \cdot Q_{tn} (\mathrm{m/s}) \quad \left[R^2 = 0.90\right]. \tag{12}$$

A stress-normalized relationship, similar to the formulation proposed by Robertson and based on an assumed exponent for Q_{tn} equal to 0.5, has been also evaluated. The resulting correlation, shown in the following equation

$$V_{s1} = 10^{(a \cdot I_c + b)} \cdot (Q_{tn})^{0.5} = 10^{(0.37 \cdot I_c + 0.63)} \cdot (Q_{tn})^{0.5} (\mathrm{m/s}) \quad \left[R^2 = 0.79\right] \tag{13}$$

turns out to be poorer in comparison to Eq. (12). In this case, the least squares analysis has given $a = 0.37$ and $b = 0.63$, which result significantly different from the values proposed by Robertson. Results from the application of Eq. (12) are depicted in Fig. 9(c)–(d). It is worth remarking that simple regression analyses performed in terms of the sole normalized variables V_{s1} and Q_{tn} have provided extremely moderate values of R^2, thus confirming the crucial role of the *SBTn* index in order to get a unified description of the seismic response of such heterogeneous soils.

In light of the aforementioned trends, further analyses have been carried out using a reduced database, only including piezocone measurements in silts and silt mixtures generally present from 8 to 20 m depth. Taking the functional forms of Eqs. (12) and (13) as a base, multiple regressions for such restricted database have provided the following relations:

$$V_{s1} = 10^{(0.86 \cdot I_c - 1.36)} Q_{tn} \quad \left[R^2 = 0.93\right] \tag{14}$$

$$V_{s1} = 10^{(0.41 \cdot I_c + 0.50)} (Q_{tn})^{0.5} \quad \left[R^2 = 0.82\right] \tag{15}$$

with only a marginal improvement of the coefficient of determination in comparison with the original multiple regressions derived from the whole database.

Finally, data from side-by-side piezocone and seismic dilatometer tests, performed after the complete removal of the loading bank, have been compiled and correlations between SDMT-based V_s measurements and adjacent CPTU measurements in overconsolidated soils have been sought. Again, the best coefficient of correlation ($R^2 = 0.90$) has been achieved using a stress-normalized relationship of the type described by Eqs. (12) and (14), with a constant exponent n equal to 1. The resulting expression is:

$$V_{s1} = 10^{(0.77 \cdot I_c - 0.99)} Q_{tn} \quad \left[R^2 = 0.90\right] \tag{16}$$

with V_{s1} in m/s. A very slight improvement is attained if stress history, in terms of *OCR*, is included as an independent variable in the multiple regression analysis. Indeed, the higher level multiple regression performed on the post-bank removal data has given:

$$V_{s1} = 10^{(0.83 \cdot I_c - 1.22)} Q_{tn} \cdot OCR^{0.3} \quad \left[R^2 = 0.91\right]. \tag{17}$$

This result is consistent with the fact that cone resistance also reflects the effect of *OCR*, hence the influence of overconsolidation on V_s can be reasonably taken into account through the only piezocone measurements. Predicted versus measured values are shown in Fig. 10.

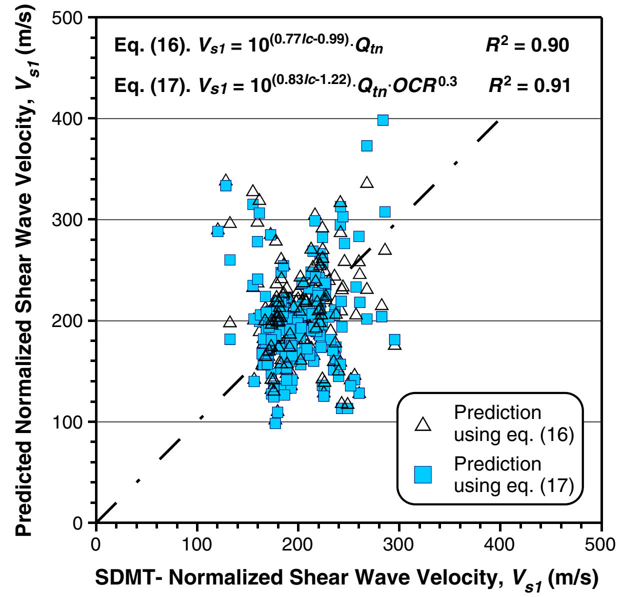

Fig. 10. Measured versus predicted shear wave velocities after the bank removal, using Eq. (16) and Eq. (17).

Assuming the 1*D* conditions as valid along the centerline, the 1-D modulus *M*, referred to a specific stress range, can be derived from plots of the type depicted in Fig. 12, using the formula:

$$M = \frac{\Delta\sigma_z'}{\Delta\varepsilon_z}. \tag{18}$$

On unloading (*U*), soil deformation can be reasonably assumed recoverable, therefore the resulting stiffness obtained from the slope of

6. Small strain stiffness of venetian sediments

Finally, measurements of shear wave velocity have been used for deriving the maximum shear stiffness G_0, assuming a reliable value of the soil mass density. The so-computed small-strain stiffness has been then compared with the in situ stiffness derived from back-analysis of the monitored test bank, based on the subsoil vertical strain measurements beneath the center of the loaded area. Fig. 11 provides curves of local vertical strains and integral displacements recorded by the central sliding deformeter at different times of the loading history, i.e. at the end of bank construction, immediately before its gradual removal, after the first stage of removal and at the end of the unloading process. The vertical strain profile obtained at the end of the bank removal is almost coincident with that referred to the start of unloading, thus confirming that soil swelling was extremely small. A useful way of presenting such deformation data is given by the curves of field differential displacements Δ*H*, provided by the sliding deformeter at every reference distance H_0 (=1 m) for a period of approximately 6 years, in terms of the effective vertical stress σ'_z. A selection of the local vertical strains (ε_z) curves, referred to different depths beneath the center of the bank, is provided in Fig. 12.

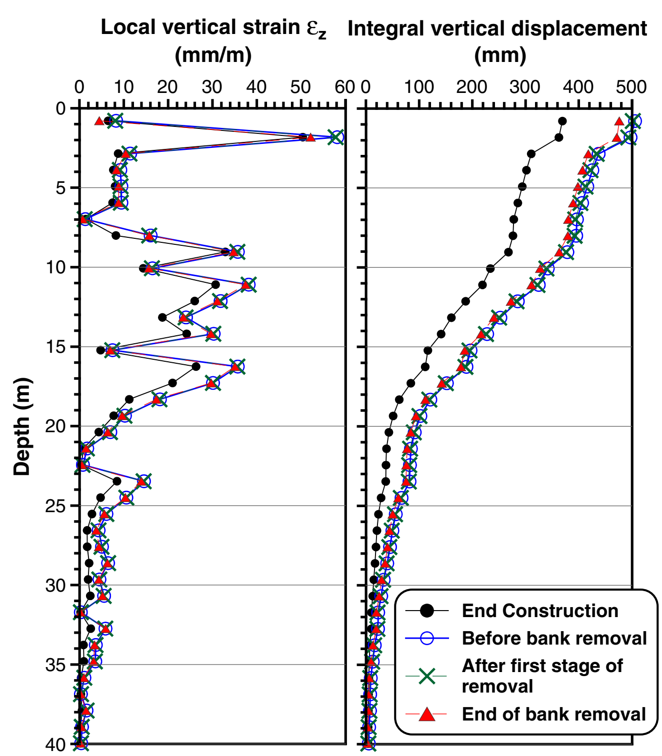

Fig. 11. Local vertical strains and integral displacements recorded at different times by the sliding deformeter beneath the center of the test bank.

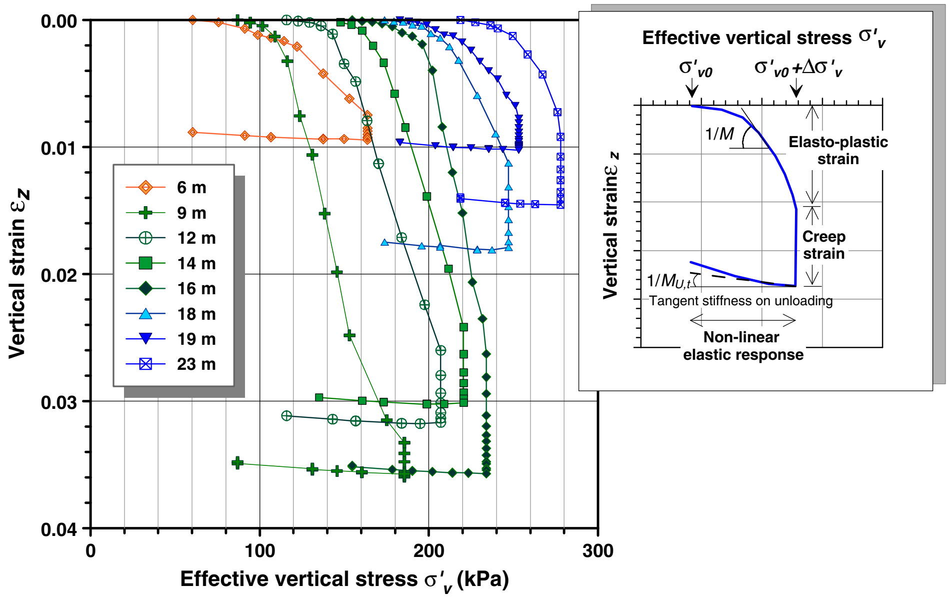

Fig. 12. Field axial strains versus stress, provided by the sliding deformeter beneath the center of the test bank.

the non-linear swelling curve may be interpreted as a fully elastic parameter, irrespective of the stress interval amplitude. In particular, a tangent modulus $M_{U,t}$ can be computed at 1 m intervals with reference to the stress decrements $|\Delta\sigma'_z|$ induced by the first stage of the bank removal and their respective vertical strains. In this case, the derived stiffness values correspond to a strain level ε_z never exceeding 10^{-4}, whereas deformations occurred over the whole unloading process turned out to be slightly higher, typically in the range $10^{-4} \div 10^{-3}$. The resulting profile of $M_{U,t}$ is provided in Fig. 13(a).

Using the elastic theory and assuming a reliable value for the Poisson's ratio ν (=0.2), the equivalent elastic shear modulus G has been then obtained from $M_{U,t}$:

$$G = \frac{M_{U,t}(1-2\nu)}{2(1-\nu)}. \tag{19}$$

The calculated values of G, reflecting the deformation characteristics at a strain level close to the so-called "small strains domain"

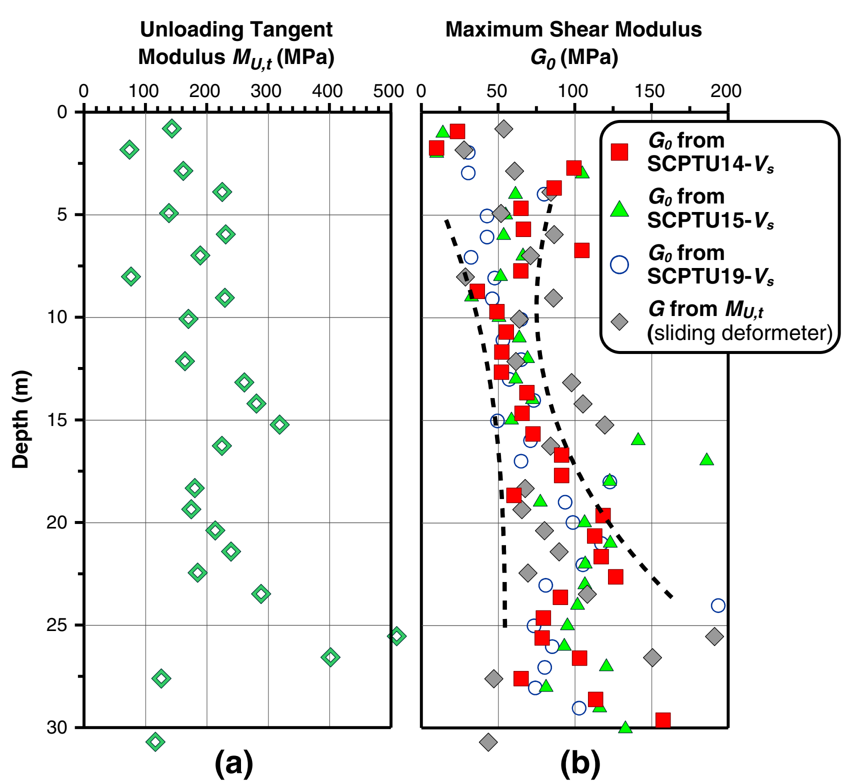

Fig. 13. (a) Values of the tangent 1D modulus on unloading, $M_{U,t}$, derived from the sliding deformeter beneath the center of the test bank; (a) Comparison between values of the small-strain shear modulus G_0 computed from V_s measurements and the tangent shear modulus G, back-calculated from the central sliding deformeter data.

($\gamma_s < 10^{-5}$), have been plotted in Fig. 13(b) together with the G_0 values derived from shear wave velocities V_s measurements. The figure clearly shows that in the shallow 25 m the maximum shear stiffness G_0 generally falls within a rather narrow interval, while a certain dispersion can be observed deeper below, maybe due to the presence of an intense and chaotic alternation of different soil classes but also to some stratigraphic spatial variability. In any case, it is worth remarking that such values of G_0, as well as the observed trend with depth, are similar to other existing data (Cola et al., 1998) collected from investigations in different sites of the Venetian lagoon area.

Comparing the back-calculated values of G with the shear wave velocity-based stiffness G_0, a general good agreement between the two different sets of moduli can be observed from ground level to approximately 25 m in depth, whereas a significant scatter has been generally found below 25 m. On the other hand, it must be observed that the data points representing G from 25 to 40 m show a significant variation with depth, most probably due to the negligible contribution of these soil layers to the overall deformation process and the consequent lack of accuracy of the sliding deformeter measurements.

7. Conclusions

A database of research-quality piezocone test results and shear wave velocity V_s measurements in normally consolidated or slightly overconsolidated silts and silt mixtures has been interpreted in order to study the seismic response of intermediate soils, for which little information can be generally found in the geotechnical literature. Starting from experimental data collected in the silty deposits of the Venetian lagoon area, which are largely recognized as the most well studied silt materials in the world, correlations between the in situ shear wave velocity and piezocone measurements have been investigated for such non-standard, neither clearly coarse-grained nor fine-grained sediments, with a view to providing some guidance for geotechnical engineers working with this soils or other similar natural silts.

According to the experience gained on the Venetian soil classes, it turns out that global correlations, applicable to different soil mixtures, must necessarily rely on a parameter acting as a material index and that the well-known Soil Behaviour Type Index I_c, as defined by Robertson (2009), generally leads to the best fit of the experimental data. Furthermore, the study confirms that statistically significant errors arise from neglecting the influence of overburden stress σ'_v on the relation between cone resistance and shear wave velocity.

Finally, the small-strain stiffness calculated from V_s measurements has been compared with the field stiffness derived from the observed performance of a full-scale test embankment, during the first stage of the bank removal process. Despite field data cannot be strictly associated to "true very small strain" conditions, a significant agreement between the seismic velocity-based stiffness and the back-calculated soil stiffness can be observed.

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References

Akin, M.K., Kramer, S.L., Topal, T., 2011. Empirical correlations of shear wave velocity (Vs) and penetration resistance (SPT-N) for different soils in an earthquake prone area (Erbaa-Turkey). Engineering Geology 119, 1–17.

Andrus, R.D., Stokoe II, K.H., 2000. Liquefaction resistance of soils from shear-wave velocity. Journal of Geotechnical and Geoenviromental Engineering 126 (11), 1015–1025.

Andrus, R.D., Piratheepan, P., Ellis, B.S., Zhang, J., Juang, C.H., 2004. Comparing liquefaction evaluation methods using penetration–V_s relationships. Soil Dynamics and Earthquake Engineering 24, 713–721.

Baldi, G., Bellotti, R., Ghionna, V., Jamiolkowski, M., Lo Presti, D.C.F., 1989. Modulus of sands from CPTs and DMTs. Proc. 12th International Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro (Brazil), vol. 1. Balkema, Rotterdam, pp. 165–170.

Bouckovalas, G., Kalteziotis, N., Sabatakakis, N., Zervogiannis, C., 1989. Shear wave velocity in very soft clay. Proc. of the 12th International Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro (Brazil), vol. 1. Balkema, Rotterdam, pp. 191–194.

Cai, G., Liu, S., Tong, L., 2010. Field evaluation of deformation characteristics of a lacustrine clay deposit using seismic piezocone tests. Engineering Geology 116, 251–260.

Chang, W.-J., Ni, S.-H., Huang, A.-B., Huang, Y.-H., Yang, Y.-Z., 2011. Geotechnical reconnaissance and liquefaction analyses of a liquefaction site with silty fine sand in Southern Taiwan. Engineering Geology 123 (3), 235–245.

Cola, S., Simonini, P., 2002. Mechanical behaviour of silty soils of the Venice lagoon as a function of their grading properties. Canadian Geotechnical Journal 39, 879–893.

Cola, S., Ricceri, G., Simonini, P., 1998. Small strain stiffness of Venetian soils from field and laboratory tests. Geotechnical Hazards, Proc. 11th Danube–European Conference on Soil Mechanics and Geotechnical Engineering. Balkema, Rotterdam, pp. 679–686.

Fear, C.E., Robertson, P.K., 1995. Estimation of the undrained shear strength of sand: a theoretical framework. Canadian Geotechnical Journal 32 (5), 859–870.

Hegazy, Y.A., Mayne, P.W., 1995. Statistical correlations between V_s and cone penetration test data for different soil types. Proc. Int. Symposium on Cone Penetration Testing, CPT'95, Linköping (Sweden). , vol. 2, pp. 173–178.

Jamiolkowski, M., Ghionna, V.N., Lancellotta, R., Pasqualini, E., 1988. New correlations of penetration tests for design practice. Proc. 1st Int. Symposium on Penetration Testing, ISOPT-1, Orlando (USA). , vol. 1. Balkema, Rotterdam, pp. 263–296.

Karray, M., Lefebvre, G., Ethier, Y., Bigras, A., 2011. Influence of particle size on the correlation between shear wave velocity and cone tip resistance. Canadian Geotechnical Journal 48, 599–615.

Kim, J.H., Yoon, H.-K., Lee, J.-S., 2011. Void ratio estimation of soft soils using electrical resistivity cone probe. Journal of Geotechnical and Geoenviromental Engineering 137 (1), 86–93.

Ku, C.S., Juang, C.H., Ou, C.Y., 2010. Reliability of CPT I_c as an index for mechanical behaviour classification of soils. Geotechnique 60 (11), 861–875.

Lee, J.-S., Lee, C., Yoon, H.-K., Lee, W., 2010. Penetration type field velocity probe for soft soils. Journal of Geotechnical and Geoenviromental Engineering 136 (1), 199–206.

Long, M., Donohue, S., 2010. Characterization of Norwegian marine clays with combined shear wave velocity and piezocone cone penetration test (CPTU) data. Canadian Geotechnical Journal 47, 709–718.

Long, M., Gudjonsson, G., Donohue, S., Hagberg, K., 2010. Engineering characterisation of Norwegian glaciomarine silt. Engineering Geology 110, 51–65.

Lunne, T., Robertson, P.K., Powell, J.J.M., 1997. Cone Penetration Testing in Geotechnical Practice. Chapman & Hall, London.

Marchetti, S., Monaco, P., Calabrese, M., Totani, G., 2004. DMT-predicted vs measured settlements under a full-scale instrumented embankment at Treporti (Venice, Italy). Proc. ISC-2 on Geotech. and Geophys. Site Characterization, Porto. , vol. 2. Millpress, Rotterdam, pp. 1511–1518.

Marchetti, S., Monaco, P., Totani, G., 2008. Final report on the seismic dilatometer testing campaign performed after the bank removal in Treporti. 2008University of L'Aquila, Italy (85 pages).

Mayne, P.W., 2000. Enhanced geotechnical site characterization by seismic piezocone penetration tests. Invited lecture, 4th Int. Geotechnical Conference.Cairo University 95–120.

Mayne, P.W., 2007. In-situ test calibration for evaluating soil parameters. Characterization & Engineering Properties of Natural Soils, vol. 3. Taylor & Francis Group, London, pp. 1601–1652.

Mayne, P.W., Rix, G.J., 1993. G_{max}–q_c relationships for clays. Geotechnical Testing Journal 16 (1), 54–60.

Mayne, P.W., Rix, G.J., 1995. Correlations between shear wave velocity and cone tip resistance in natural clays. Soils and Foundations 35 (2), 107–110.

McGillivray, A., Mayne, P.W., 2004. Seismic piezocone and seismic flat dilatometer tests at Treporti. Proc. ISC-2 on Geotech. and Geophys. Site Characterization, Porto, vol. 2. Millpress, Rotterdam, pp. 1695–1700.

Omar, M.N., Abbis, C.P., Taha, M.R., Nayan, K.A.M., 2011. Prediction of long-term settlement on soft clay using shear wave velocity and damping characteristics. Engineering Geology 123 (4), 259–270.

Piratheepan, P., Andrus, R.D., 2002. Estimating shear wave velocity from SPT and CPT data. Final report to U.S. Geological Survey, Award number 01HQR0007.Clemson University, Clemson, S.C.

Roberston, P.K., 2009. Interpretation of cone penetration tests—a unified approach. Canadian Geotechnical Journal 46, 1337–1355.

Robertson, P.K., 1990. Soil classification using the cone penetration test. Canadian Geotechnical Journal 27 (1), 151–158.

Robertson, P.K., Wride, C.E., 1998. Evaluating cyclic liquefaction potential using the cone penetration test. Canadian Geotechnical Journal 35 (3), 442–459.

Robertson, P.K., Woeller, D.J., Finn, W.D.L., 1992. Seismic cone penetration test for evaluating liquefaction potential. Canadian Geotechnical Journal 29 (4), 686–695.

Santamarina, J.C., Aloufi, M., 1999. Micro-scale interpretation of wave propagation in soils–fabric and fabric changes. Proc. 2nd International Symposium on Pre-Failure Deformation Characteristics of Geomaterials—IS TORINO 99, vol. 2. Balkema, Rotterdam, pp. 451–458.

Schnaid, F., Lehane, B.M., Fahey, M., 2004. Characterisation of unusual geomaterials. Proc. ISC-2 on Geotechnical and Geophysical Site Characterization, Porto, vol. 2. Millpress, Rotterdam, pp. 49–73.
Schneider, J.A., Mayne, P.W., Rix, G.J., 2001. Geotechnical site characterization in the greater Memphis area using cone penetration tests. Engineering Geology 62, 169–184.
Schneider, J.A., McGillivray, A.V., Mayne, P.W., 2004. Evaluation of SCPTU intra-correlations at sand sites in the Lower Mississipi River Valley, USA. Proc. ISC-2 on Geotech. and Geophys. Site Characterization, Porto, vol. 2. Millpress, Rotterdam, pp. 1003–1010.
Schneider, J.A., Randolph, M.F., Mayne, P.W., Ramsey, N.R., 2008. Analysis of factors influencing soil classification using normalized piezocone tip resistance and pore pressure parameters. Journal of Geotechnical and Geoenvironmental Engineering 134 (11), 1569–1586.
Simonini, P., 2004. Characterization of the Venice lagoon silts from in-situ tests and the performance of a test embankment. Proc. ISC-2 on Geotech. and Geophys. Site Characterization, Porto, vol. 1. Millpress, Rotterdam, pp. 187–207.
Simonini, P., Cola, S., 2000. Use of piezocone to predict maximum stiffness of Venetian soils. Journal of Geotechnical and Geoenvironmental Engineering 126 (4), 378–382.
Simonini, P., Ricceri, G., Cola, S., 2007. Geotechnical characterization and properties of Venice lagoon heterogeneous silts. Proc. of the 2nd International Workshop on Characterization and Engineering Properties of Natural Soils, Singapore, pp. 2289–2327.
Stokoe II, K.H., Santamarina, J.C., 2000. Seismic-wave-based testing in geotechnical engineering. Proc. Int. Conf. on Geotech. and Geol. Engineering, GeoEng 2000, Melbourne, pp. 1490–1536.
Tonni, L., Gottardi, G., 2009. Partial drainage effects in the interpretation of piezocone tests in Venetian silty soils. Proc. 17th ICSMGE, Alexandria, Egypt, vol. 2, pp. 1004–1007.
Tonni, L., Gottardi, G., 2010. Interpretation of piezocone tests in Venetian silty soils and the issue of partial drainage. Proc. of the 2010 GeoShanghai International Conference, Deep Foundations and Geotechnical In Situ Testing, ASCE Geotechnical Special Publication (205 GSP), pp. 367–374.
Tonni, L., Gottardi, G., 2011. Analysis and interpretation of piezocone data on the silty soils of the Venetian lagoon (Treporti test site). Canadian Geotechnical Journal 48 (4), 616–633.
Tonni, L., Simonini, P., 2012. Evaluation of secondary compression of sands and silts from CPTU. Geomechanics and Geoengineering: An International Journal. http://dx.doi.org/10.1080/17486025.2012.726748.
Tonni, L., Gottardi, G., Berengo, V., Simonini, P., 2010. Classification, overconsolidation and stiffness of Venice lagoon soils from CPTU. Proc. CPT'10, pp. 567–574.
Tonni, L., Gottardi, G., Simonini, P., 2011. Piezocone Data and State Parameter Interpretation for Venetian Silty Soils. IOS Press, pp. 1260–1267.
Tonni, L., Garcia Martinez, M.F., Simonini, P., 2013. Predicting long-term behaviour of coastal defences for safeguarding the Venetian Lagoon. Proc. 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013 (In print).
Wride, C.E., Robertson, P.K., Biggar, K.W., Campanella, R.G., Hofmann, B.A., Hughes, J.M.O., Küpper, A., Woeller, D.J., 2000. Interpretation of in situ test results from the CANLEX sites. Canadian Geotechnical Journal 37 (3), 505–529.
Yoon, H.-K., Lee, J.-S., 2010. Field velocity resistivity probe for estimating stiffness and void ratio. Soil Dynamics and Earthquake Engineering 30 (12), 1540–1549.