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RESEARCH ARTICLE

Prediction of the shear wave velocity V_S from CPT and DMT at research sites

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ABSTRACT The paper examines the correlations to obtain rough estimates of the shear wave velocity V_S from non-seismic dilatometer tests (DMT) and cone penetration tests (CPT). While the direct measurement of V_S is obviously preferable, these correlations may turn out useful in various circumstances. The experimental results at six international research sites suggest that the DMT predictions of V_S from the parameters I_D (material index), K_D (horizontal stress index), M_{DMT} (constrained modulus) are more reliable and consistent than the CPT predictions from q_c (cone resistance), presumably because of the availability, by DMT, of the stress history index K_D.

KEYWORDS horizontal stress index, shear wave velocity, flat dilatometer test, cone penetration test

1 Introduction

The paper examines the correlations to obtain rough estimates of the shear wave velocity V_S from non-seismic dilatometer tests (DMT) and cone penetration tests (CPT). While the direct measurement of V_S is obviously preferable, these correlations may turn out useful in various circumstances.

As to DMT, using the seismic dilatometer (SDMT) results obtained at 34 different sites, Marchetti et al. [1] were able to draw a diagram (Fig. 1) — and interpolate a correlation- providing estimates of the small strain shear modulus G_0 (hence V_S) from the parameters I_D (material index), K_D (horizontal stress index), M_{DMT} (constrained modulus) available from DMT.

As to CPT, using the seismic cone (SCPT) data several Authors [2–7] developed relationships between the cone resistance q_c and V_S. These CPT correlations are controlled by various parameters: Geologic age (Pleistocene, Holocene, etc.), cementation, soil type, effective stress state.

2 Flat dilatometer (DMT)

The Flat Dilatometer (DMT) is an in situ testing tool developed some 30 years ago [8]. The DMT is currently used in practically all industrialized countries. It is standardized in the ASTM [9] and the Eurocode [10]. The DMT has been object of a detailed monograph by the ISSMGE Technical Committee TC16 [11].

The flat dilatometer consists of a steel blade having a thin, expandable, circular steel membrane mounted on one face. When at rest, the membrane is flush with the surrounding flat surface of the blade. The blade is connected, by an electro-pneumatic tube running through the insertion rods, to a control unit on the surface (Fig. 1).

The control unit is equipped with pressure gauges, an audio-visual signal, a valve for regulating gas pressure (provided by a tank) and vent valves. The blade is advanced into the ground using common field equipment, i.e., penetrometers normally used for the cone penetration test (CPT) or drill rigs. The DMT can also be driven, e.g., using the SPT hammer and rods, but statical push is by far preferable. Pushing the blade with a 20 ton penetrometer truck is most effective (up to 80 m of profile per day). The test starts by inserting the dilatometer into the ground. When the blade has advanced to the desired test depth, the penetration is stopped. The operator inflates the membrane and takes, in about 30 s, two readings: the *A* pressure, required to just begin to move the membrane (“lift-off” pressure), and the *B* pressure, required to expand the membrane center of 1.1 mm against the soil. A third

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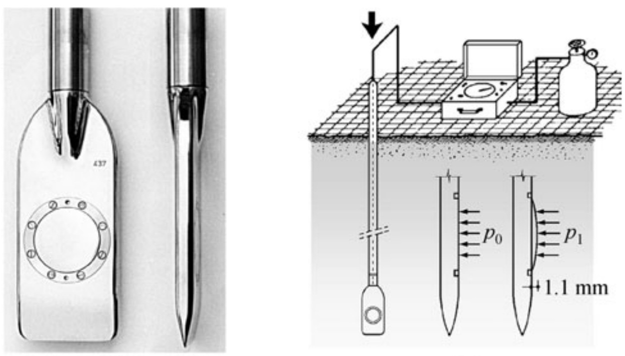
reading C ("closing pressure") can also optionally be taken by slowly deflating the membrane soon after B is reached. The blade is then advanced to the next test depth, with a depth increment of typically 20 cm.

The interpretation proceeds as follows. First the field readings A, B are corrected into the pressures p_0, p_1 that are converted into the DMT intermediate parameters I_D, K_D, E_D (material index, horizontal stress index, dilatometer modulus). Then I_D, K_D, E_D are converted, by means of commonly used correlations, to: constrained modulus M (or M_{DMT}), undrained shear strength s_u, coefficient of earth pressure in situ K_0 (clays), overconsolidation ratio OCR (clays), friction angle φ' (sands), unit weight γ. Consolidation and permeability coefficients may be estimated by performing dissipation tests [11]. The C-reading, in sand, approximately equals the equilibrium pore pressure.

More detailed information on the DMT equipment, test procedure and all the interpretation formulae may be found in the comprehensive report by the ISSMGE Technical Committee TC16 [11].



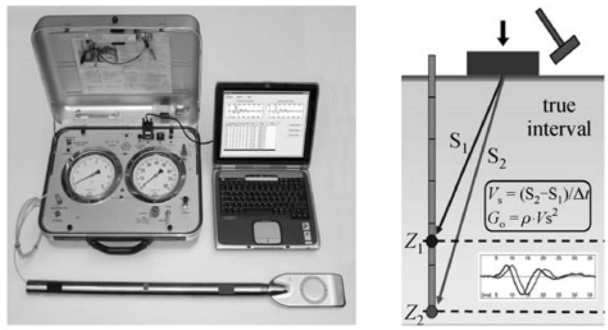
(a) (b)

Fig. 1 Flat Dilatometer [11]. (a) Dilatometer blade; (b) schematic layout of the flat dilatometer test

3 Seismic dilatometer (SDMT)

The SDMT is the combination of the flat dilatometer with an add-on seismic module for the measurement of the shear wave velocity [12–15].

The seismic module (Fig. 2(a)) is a cylindrical element placed above the DMT blade, equipped with two receivers located at 0.5 m distance. When a shear wave is generated at surface, it reaches first the upper receiver, then, after a delay, the lower receiver. The seismograms acquired by the two receivers, amplified and digitized at depth, are transmitted to a PC at the surface, that determines the delay. V_s is obtained (Fig. 2(b)) as the ratio between the difference in distance between the source and the two receivers (S2, S1) and the delay from the first to the second receiver (Δt). The true-interval test configuration with two receivers avoids possible inaccuracy in the determination of the "zero time" at the hammer impact, sometimes observed in the pseudo-interval one-receiver configuration. Moreover, the couple of seismograms recorded by the two receivers at a given test depth corresponds to the same hammer blow. The repeatability of the V_s measurements is remarkable (observed Vs repeatability $\approx$ 1%, i.e., a few m/s).



(a) (b)

Fig. 2 Seismic Dilatometer [1]. (a) Seismic dilatometer equipment; (b) schematic layout of the seismic dilatometer test

4 V_S from DMT

The experimental diagrams presented in Fig. 3 and Eqs. (1) to (3) [1] have been constructed using same-depth G_0, M_{DMT}, I_D and K_D, values determined by SDMT at 34 different sites, in a wide array of soil types. The majority of the sites are in Italy, others are in Spain, Poland, Belgium and USA.

SDMT generates plentiful data points because each sounding routinely provides profiles of G_0 and M_{DMT}. Of the over 2000 data points available, only 800 high quality data points have been considered, relative to uniform" one-meter soil intervals where log I_D, K_D, E_D (dilatometer modulus), M_{DMT}, V_S all differ less than 30% from their average- used then to plot the data points — to insure a proper match of the data. The DMT parameters have been calculated with the usual DMT interpretation formulae [11].

$$G_0/M_{DMT} = 26.177 \cdot K_D^{-1.0066},\ I_D<0.6, \qquad (1)$$

$$G_0/M_{DMT} = 15.686 \cdot K_D^{-0.921},\ 0.6<I_D<1.8, \qquad (2)$$

$$G_0/M_{DMT} = 4.5613 \cdot K_D^{-0.7967},\ I_D > 1.8. \qquad (3)$$

Considerations emerging from the diagram [15]:

— the ratio G_0/M_{DMT} varies in a wide range ($\approx$ 0.5 to 20 for all soils), hence it is far from being a constant. Its value is strongly dependent on multiple information, e.g., (at least) soil type and stress history. Therefore it appears next to impossible to estimate the operative modulus M_{DMT} by dividing G_0 by a constant, as suggested by various Authors;

— if only mechanical DMT data are available, Fig. 3 permits to obtain rough estimates of G_0 (and V_S) by use of the three DMT parameters I_D, K_D, M_{DMT};

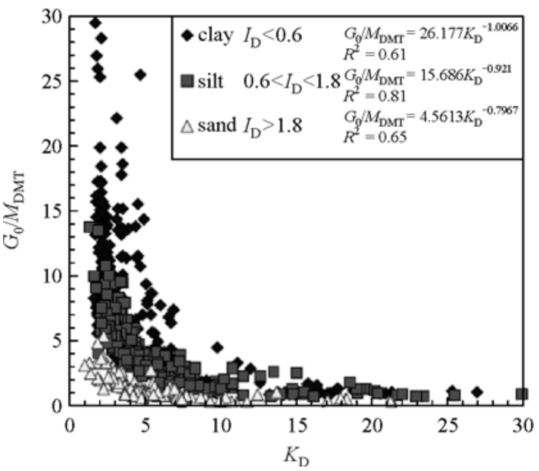


Fig. 3 Ratio G_0/M_{DMT} *vs.* K_D for various soil types [1]

— Fig. 3 highlights the dominant influence of K_D on the ratio G_0/M_{DMT}. In case of non availability of K_D, all the experimental data points would cluster on the vertical axis. In absence of K_D — which reflects the stress history — the selection of the ratio G_0/M_{DMT} would be hopelessly uncertain. Hence as many as three information, i.e., I_D, K_D, M_{DMT} (though only two independent), are needed to formulate rough estimates of G_0 and V_S. On the other hand the poor direct correlability M_{DMT} to G_0, in absence of additional information, was expectable. M_{DMT} to G_0 are inherently different parameters, since at small strains the soil tendency to dilate or contract is not active yet. Such tendency substantially affects the operative modulus M_{DMT}, but does not affect G_0. Said in a different way, M_{DMT} includes some stress history information, G_0 does not [16];

— based on the latest consideration, the use of N_{SPT} or s_u alone as a substitute of V_S (when not measured) for the seismic classification of a site, as proposed e.g., by the Eurocode 8 and by various national codes, does not appear to be founded on a firm basis. In fact, if V_S is assumed to be the primary parameter for the classification of the site, then the possible substitute of V_S must be reasonably correlated to V_S. If three parameters (I_D, K_D, M_{DMT}) are barely sufficient to obtain rough estimates of V_S, then the possibility to estimate V_S from only one parameter appears remote.

Reference [17] shows some comparisons (Fig. 4) between the profiles of V_S measured directly by SDMT (solid line) and V_S estimated from mechanical DMT data (dashed line) obtained in the same SDMT test, using the correlations (1)–(3), at six sites in the area of L'Aquila where SDMTs were performed. The two V_S profiles (measured and estimated) are in good agreement at each site.

Many other researchers have proposed correlations relating DMT results to G_0 before [1]. A well documented method was proposed by [18]. Other methods are summarized by Ref. [19] and in Ref. [20]. Then Ref. [21] found in four NC clay sites (where $K_D \approx 2$) $G_0/E_D \approx 7.5$. They also investigated three sand sites, where they observed that G_0/E_D decreases as K_D increases. In particular they found G_0/E_D decreasing from ≈ 7.5 at small K_D (1.5–2) to ≈ 2 for $K_D > 5$. Similar trends in sands had been observed e.g., by Refs. [22] and [23].

5 V_S from CPT

A concern when estimating V_S from q_c is that the first is a small strain measurement, while the latter is a large strain measurement. The factors controlling behavior at small and large strains may not be exactly the same [5]. Reference [24] demonstrated that V_S in sands is controlled by the number and area of grain-to-grain contacts, which in turn depend on relative density, effective stress state, rearrangement of particles with age and cementation. Penetration resistance in sands is also controlled by relative density, effective stress state and to a lesser degree by age and cementation. Thus, although strong relationships between V_S and penetration resistance exist, some variability should be expected due to age and cementation.

Relationships between q_c and V_S (or G_0) have been investigated since the early 1980s. These investigations have shown that cone tip resistance, cone sleeve friction, confining stress, depth, soil type, and geologic age are factors influencing the relationship. One limitation of the previous relationships is that most of them were developed for either sands or clays, with no intermediate range of soil types. Also, most of the previous relationships are for relatively young deposits [5]. In this respect, the paper refers to different equations that estimate V_S (or G_0) from q_c (or q_t, corrected cone tip resistance).

Reference [2] considers all deposits ranging predominantly from Holocene to Pleistocene age and mostly uncemented:

$$V_S = [\alpha_{VS}(q_t - \sigma_v)/P_a]^{0.5}, \tag{4}$$

$$\alpha_{VS} = 10^{(0.55 I_c + 1.68)}, \tag{5}$$

where σ_v is the total vertical stress, P_a is the atmospheric pressure, I_c is the soil behavior type index.

Reference [3] accommodates all types of soils:

$$V_S = [10.1 \log(q_t) - 11.4]^{1.67} \cdot \left[\frac{f_s}{q_t} \cdot 100\right], \tag{6}$$

where f_s is the sleeve friction;

Reference [4] refers to sand, silt and silty clay of Venice Lagoon:

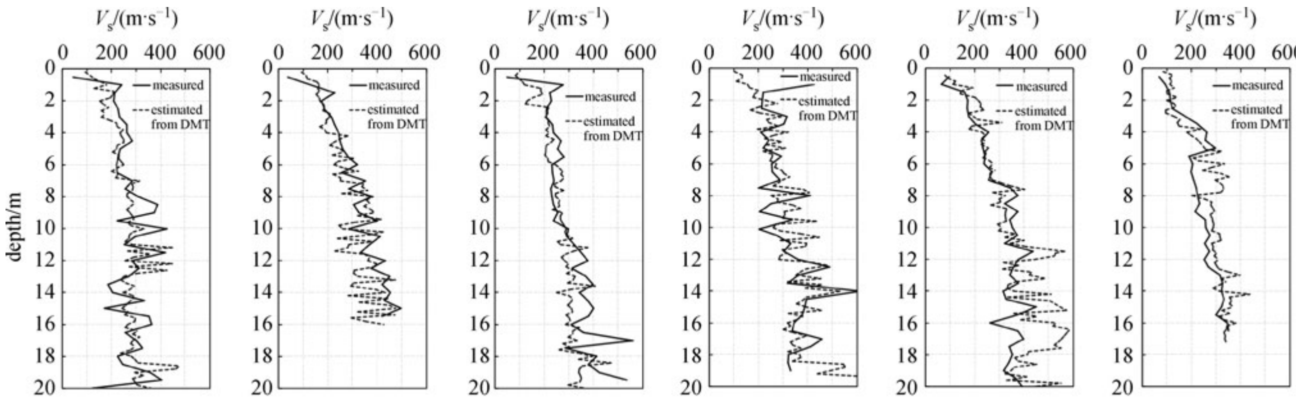


Fig. 4 Comparison of profiles of V_S measured by SDMT and estimated from DMT data at six sites in the area of L'Aquila [17]

$$G_0 = 49.2 \cdot q_c^{0.51}. \quad (7)$$

Reference [5] introduces two equations, one for Holocene soils (8) and one for Pleistocene soils (9):

$$V_s = 2.27 \cdot q_t^{0.412} \cdot I_c^{0.989} \cdot D^{0.033} \cdot ASF, \quad (8)$$

$$V_s = 2.62 \cdot q_t^{0.395} \cdot I_c^{0.912} \cdot D^{0.124} \cdot SF, \quad (9)$$

where D is depth below the ground surface, ASF is an age scaling factor equal to 1.00, SF is a scaling factor equal to 1.12;

Reference [6] relates equations to Holocene cohesive soils (10), Holocene incoherent soils (11), Pleistocene cohesive soils (12), Pleistocene incoherent soils (13):

$$V_S = 140 \cdot q_c^{0.30} \cdot f_s^{-0.13}, \quad (10)$$

$$V_s = 268 \cdot q_c^{0.21} \cdot f_s^{0.02}, \quad (11)$$

$$V_S = 182 \cdot q_c^{0.33} \cdot f_s^{-0.02}, \quad (12)$$

$$V_s = 172 \cdot q_c^{0.35} \cdot f_s^{-0.05}. \quad (13)$$

Reference [7] concerns only very soft clay:

$$G_0 = 28.0 \cdot q_c^{1.40}. \quad (14)$$

(See original references for measurement units in Eqs. (4) to (14)).

6 Sensitivity of DMT and CPT to stress history

Numerous researchers have found that DMT is considerably more sensitive than CPT to stress history, including aging. In particular the horizontal stress index K_D by DMT, is increasingly recognized as a sensitive stress history indicator, for possibly enhancing accuracy and reducing overconservatism of the predictions, as recalled by Ref. [25] in a compilation of cases in the literature.

As noted by by Ref. [26,27], the CPT cone appears to destroy a large part of the modification of soil structure caused by the overconsolidation and it therefore measures very little of the related increase in modulus. In contrast the lower strain penetration of the DMT wedge preserves more of the effect of overconsolidation.

Using the large calibration chamber Ref. [28], showed that K_D is much more sensitive to cyclic prestraining than the penetration resistance q_D of the DMT blade, and presumably of the cone penetration resistance.

Reference [29] recently performed an extensive series of comparative CPT and DMT in the calibration chamber that proved the overconsolidation (OCR = 2–8) increased the normalized q_c by a factor 1.10 to 1.15, while K_D by a factor 1.30 to 2.50.

Reference [30] also confirmed K_D is considerably more sensitive than q_t to stress history. At Treporti (Venice, Italy) SDMT and CPTU soundings performed before embankment application and postremoval highlighted that the overconsolidation effect is reflected to a maximum degree by M_{DMT}, that essentially increased thanks to K_D, and to a medium degree by q_t.

As stated by Ref. [25], some of the reasons of the higher sensitivity of K_D to stress history are related to the effects of one-dimensional overconsolidation (more stable grain structure and increment of the horizontal effective stress σ'_h).

7 Comparisons of V_S measured/estimated from DMT and CPT

The following paragraphs compare the profiles of V_S measured- by seismic dilatometer test (SDMT) or seismic cone penetration test (SCPT) — and V_S estimated from mechanical DMT and CPT data at six research test sites (Treporti, Moss Landing, Perth CBD, East Perth, Shenton

Park, Margaret River). Some of these results are shown in Ref. [31].

7.1 Treporti, Venice (Italy)

At the site of Treporti, Venice (Italy) a full-scale vertically-walled cylindrical test embankment (40 m diameter, 6.7 m height, applied load 106 kPa) was constructed and continuously monitored, from the beginning of its construction until complete removal (four years later) toward pore water pressures, surface settlements, horizontal and vertical displacements with depth [32]. The Treporti test site was extensively investigated by means of piezocone tests [33], flat dilatometer tests [34], seismic piezocone tests and seismic dilatometer tests [35], continuous coring boreholes and high quality laboratory tests [36]. The deposits are of Pleistocene age in the upper 10-15 m and of Holocene age at lower depth and consist of alternate layers of silty sand, sandy silt, clayey silt and silty clay. Significant results of the research program at Treporti have already been published by various research groups [30].

DMT/SDMT and CPTU/SCPTU profiles (material index I_D, constrained modulus M_{DMT}, horizontal stress index K_D, corrected cone resistance q_t, sleeve friction f_s, shear wave velocity V_S) obtained at different locations of the embankment before construction and after removal, as shown in Fig. 5, have been combined using DMT correlations (1), (2), (3) and CPT Eqs. (4), (6)–(13). Figure 6 compare the profiles of V_S measured — by flat dilatometer test (DMT) or cone penetration test (SCPTU) — and V_S estimated from mechanical DMT and CPT data at Treporti test site.

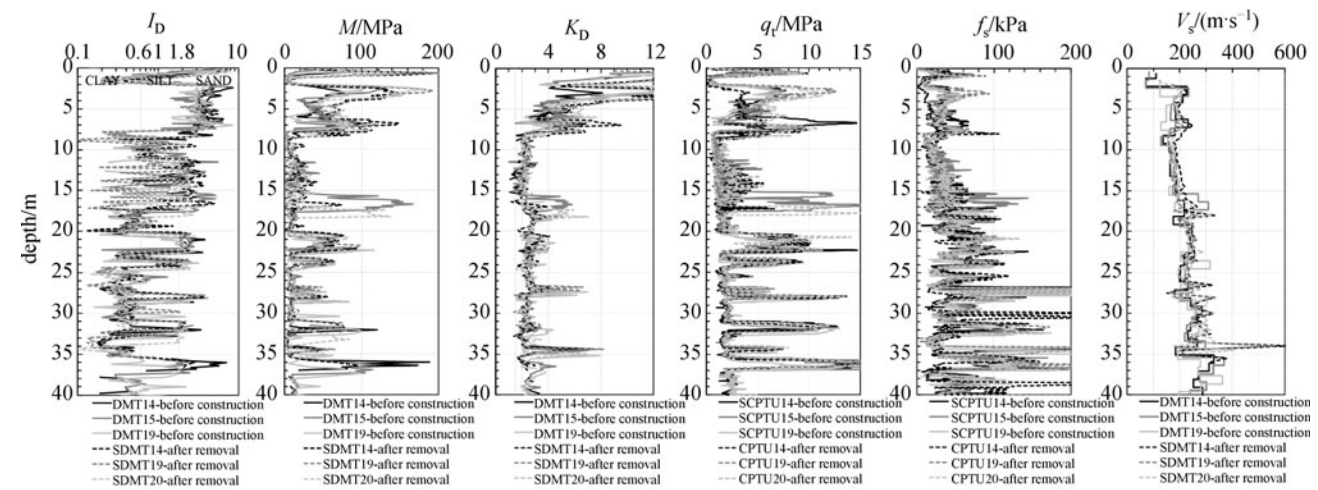


Fig. 5 DMT/SDMT and CPTU/SCPTU profiles at Treporti–Venice Lagoon (Italy) — Before construction and after removal

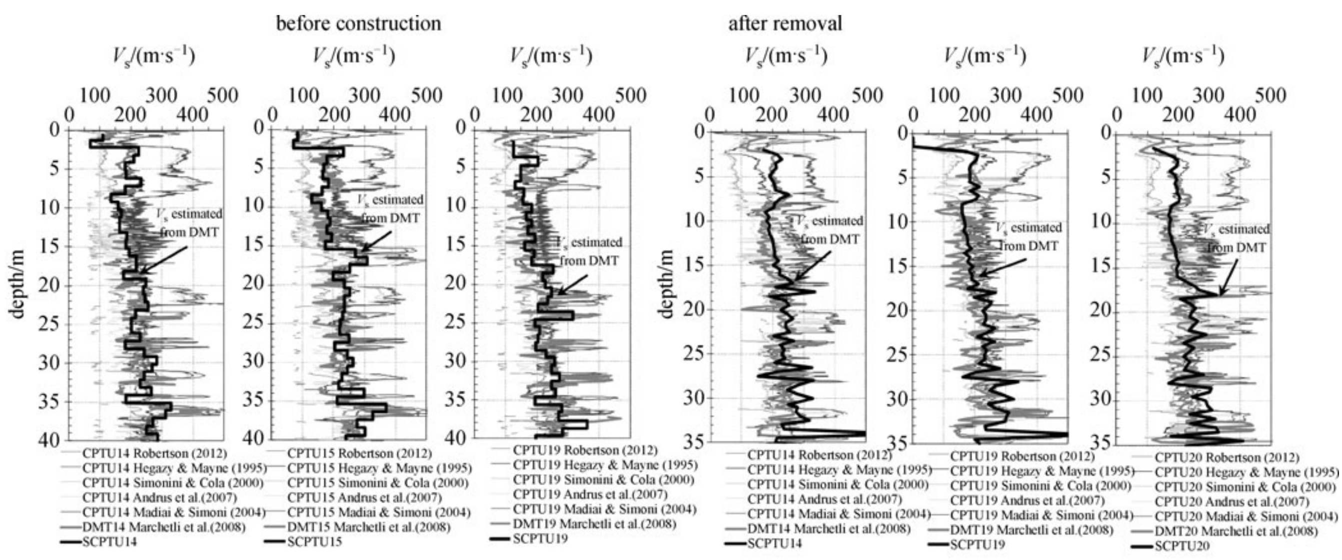


Fig. 6 Comparison of V_S measured by SCPT and estimated from CPT and DMT data at Treporti–Venice Lagoon (Italy) — Before construction and after removal

7.2 Moss Landing, California (USA)

Moss Landing (California, USA) is a Holocene site composed of alluvial sand over stiff clay [37].

SDMT and SCPTU profiles (I_D, M_{DMT}, K_D, q_t, f_s, V_S) obtained at two different locations, as shown in Fig. 7, have been combined using DMT correlations (1), (2), (3) and CPT Eqs. (4), (6), (8)–(13). Figure 8 compare the profiles of V_S measured — by DMT or CPT — and V_S estimated from mechanical DMT and CPT data at Moss Landing test site.

7.3 East Perth (Western Australia)

East Perth is a research site, studied by the University of Western Australia since 1989 [38]. It is a Holocene soft clayey site, located along the banks of the Swan River close to the center of Perth (Western Australia).

During 2010 a pair SDMT-CPT was performed [39] and the geotechnical profiles (I_D, M_{DMT}, K_D, q_t, f_s, V_S), as shown in Fig. 9, have been combined using DMT correlations (1)–(3) and CPT Eqs. (8)–(14). Figure 10 compare the profiles of V_S measured — by DMT or CPT — and V_S estimated from mechanical DMT and CPT data at East Perth test site.

7.4 Shenton Park (Western Australia)

Shenton Park, as well as East Perth, is a research site, studied by the University of Western Australia since 2006 [39–42]. It is a Holocene Pleistocene calcareous sandy site, located about 3–4 km from the west coast and close to the center of Perth (Western Australia).

Many DMT/SDMT and CPT/SCPTU tests were carried out [39–41] and the representative geotechnical profiles of these siliceous dune sands (I_D, M_{DMT}, K_D, q_t, f_s, V_S), as shown in Fig. 11, have been combined using DMT correlations (1), (2), (3) and CPT Eqs. (4), (8)–(13). Figure 10 compare the profiles of V_S measured — by DMT or CPT — and V_S estimated from mechanical DMT and CPT data at Shenton Park test site.

7.5 Margaret River (Western Australia)

Margaret River is a Pleistocene silty and clayey site, located about 300 km South of Perth (Western Australia).

During 2010 several in situ and laboratory tests were performed [39] and a SDMT–CPTU pair, as example, has been plotted in Fig. 12. DMT correlations (1), (2), (3) and CPT Eqs. (4), (6), (8)–(13) have been introduced to compare the profiles of V_S measured — by DMT or CPT — and V_S estimated from mechanical DMT and CPT data at Margaret River test site (Fig. 13).

7.6 Perth CBD (Western Australia)

Perth CBD is a Pleistocene sandy and clayey site, located in the center of Perth (Western Australia).

DMT and CPT/SCPTU tests were carried out [43,44] and the representative geotechnical profiles of the top dune sands and bottom alluvial deposits (I_D, M_{DMT}, K_D, q_t, f_s, V_S), as shown in Fig. 14, have been combined using DMT correlations (1), (2), (3) and CPT Eqs. (4), (8)–(13). Figure 13 compare the profiles of V_S measured — by DMT or CPT — and V_S estimated from mechanical DMT and CPT data at Perth CBD test site.

8 Conclusions

The comparisons predicted *vs.* measured V_S profiles, at the six investigated research sites, suggest that the DMT predictions of V_S are more reliable and consistent than the CPT predictions.

This is probably due to the fact that the evaluation of V_S from DMT includes the horizontal stress index K_D that is

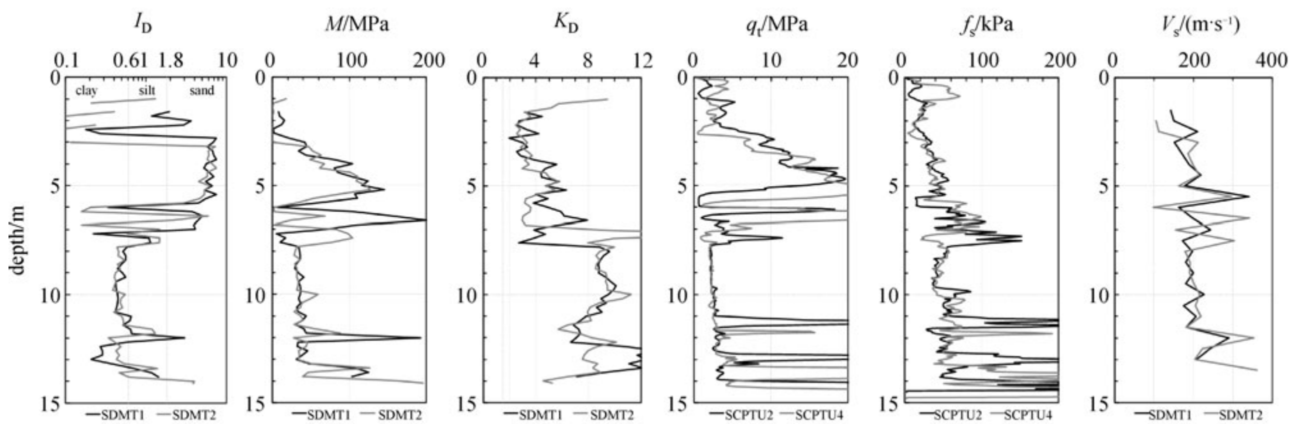


Fig. 7 SDMT and SCPTU profiles at Moss Landing — California (USA)

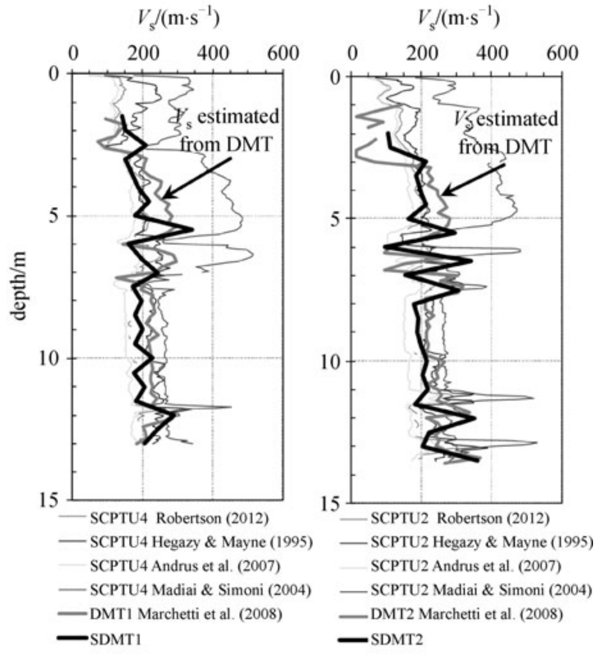


Fig. 8 Comparison of V_S measured by SDMT or SCPT and estimated from CPT and DMT data at Moss Landing — California (USA)

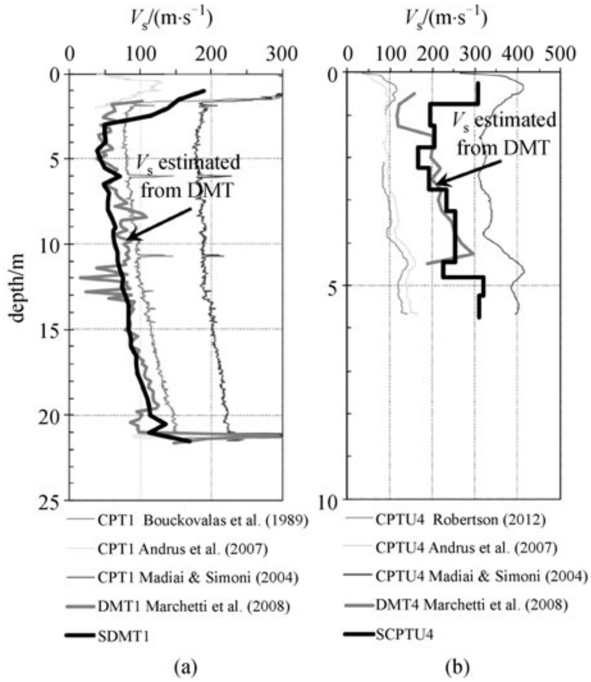


Fig. 10 Comparison of V_S measured by SDMT or SCPT and estimated from CPT and DMT data at East Perth (a) and Shenton Park (Western Australia) (b)

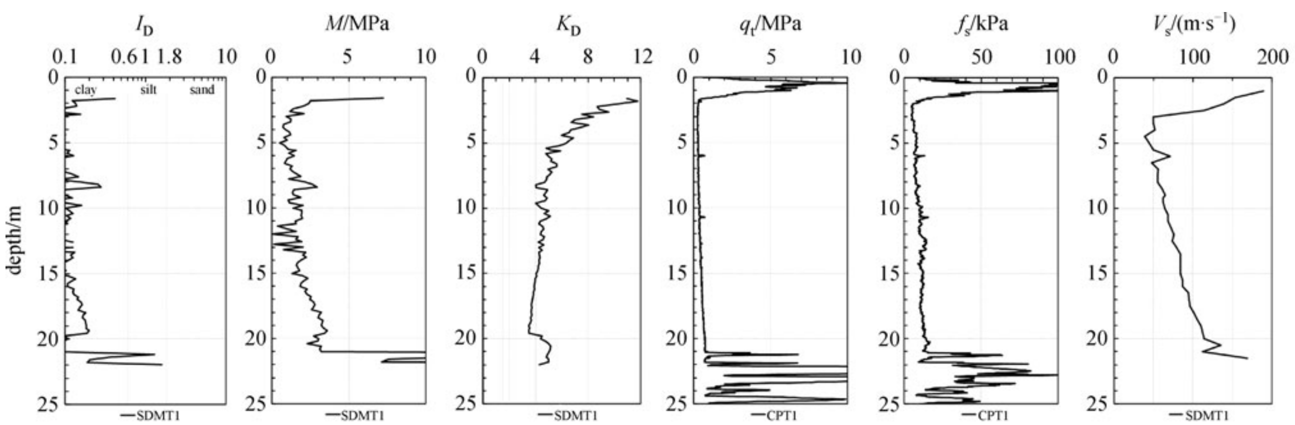


Fig. 9 SDMT and CPT profiles at East Perth (Western Australia)

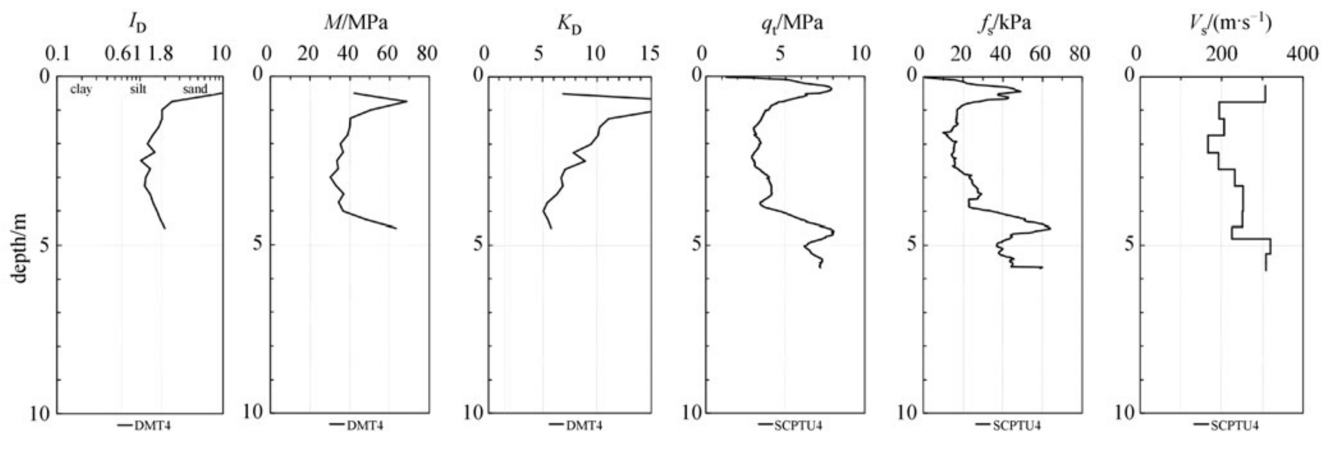


Fig. 11 DMT and SCPTU profiles at Shenton Park (Western Australia)

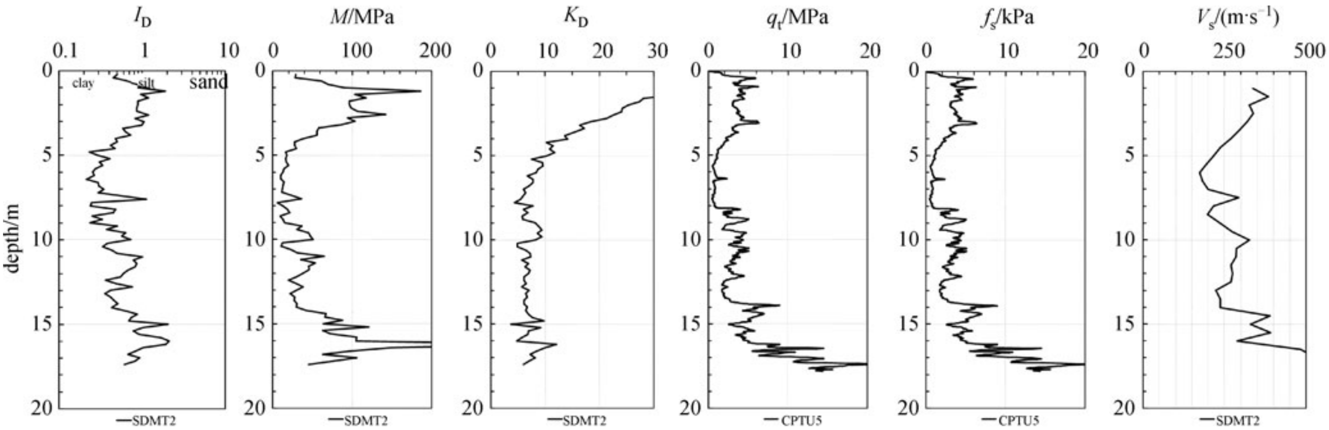


Fig. 12 SDMT and CPTU profiles at Margaret River (Western Australia)

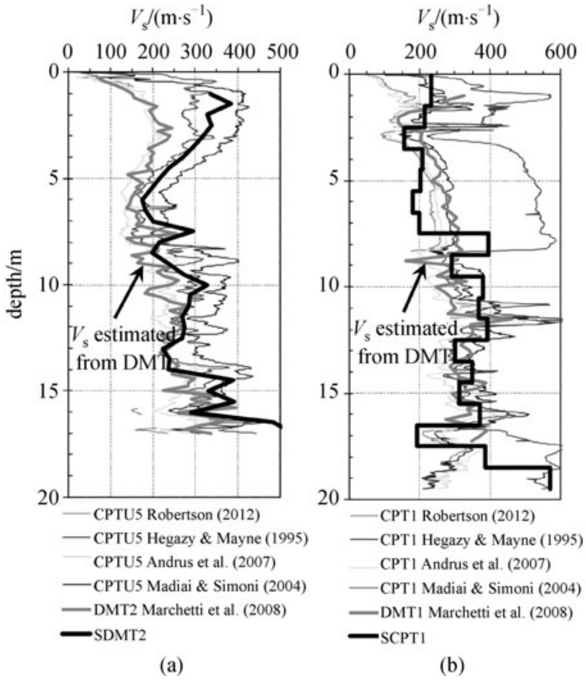


Fig. 13 Comparison of V_S measured by SDMT or SCPT and estimated from CPT and DMT data at Margaret River (a) and Perth CBD (Western Australia) (b)

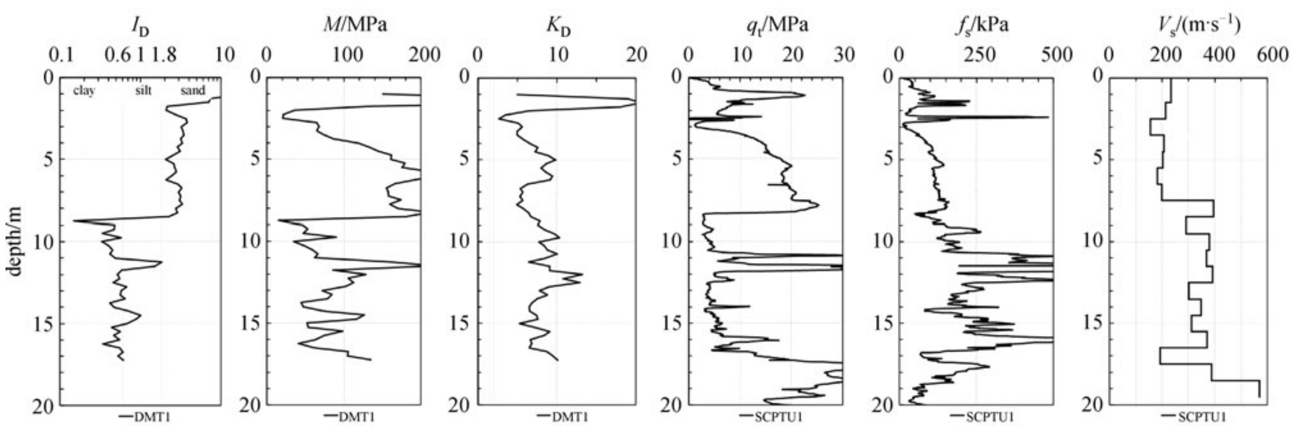


Fig. 14 DMT and SCPTU profiles at Perth CBD (Western Australia)

noticeably reactive to stress history, prestraining/aging and structure, scarcely detected by q_c from CPT [25]. As it clearly appears from Fig. 3, the ratio G_0/M_{DMT} is strongly dependent on (at least) both soil type and stress history. Hence using only one parameter to estimate V_S (or G_0) may be the reason of the higher uncertainty of the CPT predictions.

In addition, the CPT predicted V_S are subjected to the additional uncertainty arising from the selection of which one of the numerous existing correlations is adopted, the choice of the correlation depending on geological age, cementation, soil type, effective stress state.

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