PREDICTION OF THE SHEAR WAVE VELOCITY V_S FROM CPT AND DMT

PREVISION DE LA VITESSE DE ONDES DE CISAILLEMENT V_S PAR CPT ET DMT

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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.

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. (2008) constructed a diagram (Figure 1) - and interpolated 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 (Robertson, 2012; Hegazy & Mayne, 1995; Simonini & Cola, 2000; Andrus et al., 2007; Madiai & Simoni, 2004; Bouchovalas et al., 1989; etc.) developed relationships (Equations 4 to 14) between the cone resistance q_c and V_S. These CPT correlations are controlled by various parameters: geological age (Pleistocene, Holocene, etc.), cementation, soil type, effective stress state.

2. V_S from DMT

The experimental diagrams presented in Figure 1 and Equations (1) to (3) (Marchetti et al., 2008) 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 variety 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 (TC16, 2001).

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

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

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

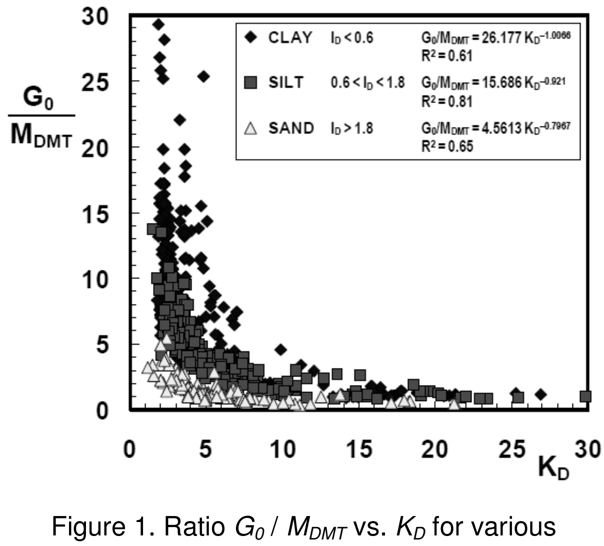

Figure 1. Ratio G_0 / M_{DMT} vs. K_D for various soil types (Marchetti et al., 2008).

Considerations emerging from the diagram (Monaco et al., 2009):

- the ratio G_0 / M_{DMT} varies in a wide range (≈ 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, Figure 1 permits to obtain rough estimates of G_0 (and V_S) by use of the three DMT parameters I_D, K_D, M_{DMT};
- Figure 1 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 (Powell & Butcher 2004);
- 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.

3. V_S from CPT

A concern when estimating V_S from q_c is that the former is a small strain measurement, whereas the latter is a large strain measurement. The factors controlling behavior at small and large strains may not be exactly the same (Andrus et al., 2007). Schneider et al. (2004) 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 (Andrus et al., 2007). 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):

- Robertson (2012) equation considers all deposits ranging predominantly from Holocene to Pleistocene age and mostly uncemented:

$$V_S = \left[\alpha_{VS}(q_t - \sigma_v)/p_a\right]^{0.5} \quad (4)$$

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

Where σ_v is the total vertical stress, p_a is the atmospheric pressure, I_c is the soil behaviour type index;

- Hegazy and Mayne (1995) equation accommodates all types of soils:

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

Where f_s is the sleeve friction;

- Simonini and Cola (2000) equation refers to sand, silt and silty clay of Venice Lagoon:

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

- Andrus et al. (2007) equations are valid for Holocene soils (8) and 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;

- Madiai and Simoni (2004) equations are related to Holocene cohesive soils (10), Holocene incoherent soils (11), Pleistocene cohesive soils (12), Pleistocene incoherent soils (13):

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

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

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

$$V_S = 172 \cdot q_c^{0.35} \cdot f_s^{-0.05} \qquad (13)$$

– Bouchovalas et al. (1989) equation concerns only very soft clay:

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

(see original references for measurement units in Equations 4 to 14).

4. Comparisons of V_S measured/estimated from DMT and CPT

Figures 2, 3, 4, 5 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).

The Treporti 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 (Monaco et al., 2012).

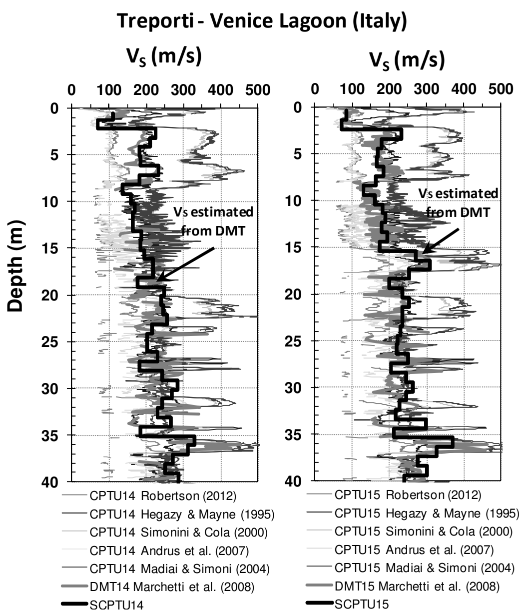

Figure 2. Comparison of V_S measured by SCPT and estimated from CPT and DMT data at Treporti-Venice Lagoon (Italy) - Before construction.

Moss Landing (California, USA) is a Holocene site composed of alluvial sand over stiff clay (Figure 3) (Robertson, 2009).

Finally, Figure 4 and 5 illustrate the profiles obtained in four sites in Western Australia (Amoroso, 2011). Perth CBD is a Pleistocene sandy and clayey site, East Perth is a Holocene soft clayey site, Shenton Park is a Pleistocene calcareous sandy site and Margaret River is a Pleistocene silty and clayey site.

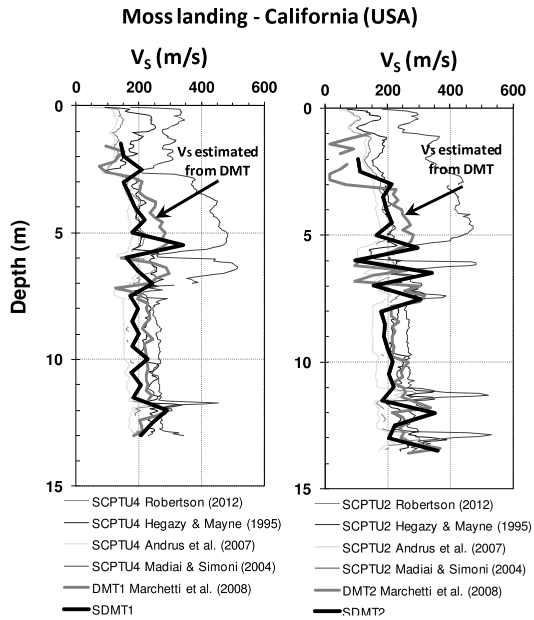

Figure 3. Comparison of V_S measured by SDMT or SCPT and estimated from CPT and DMT data at Moss Landing - California (USA).

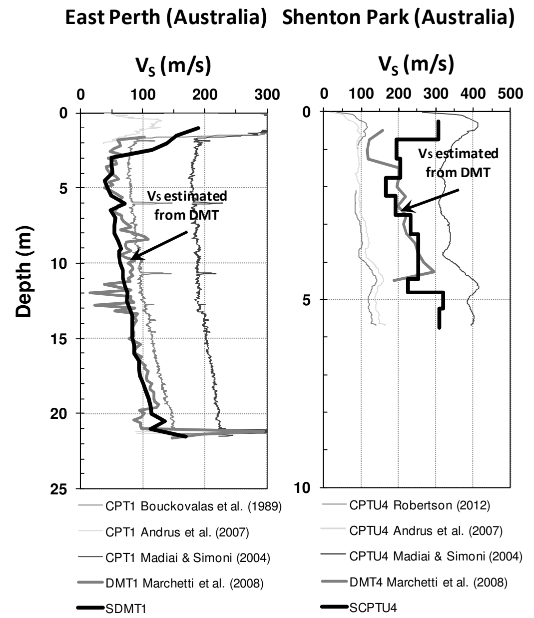

Figure 4. Comparison of V_S measured by SDMT or SCPT and estimated from CPT and DMT data at East Perth and Shenton Park (Western Australia).

The profiles at these sites indicate a reasonable agreement between the measured V_S and the V_S predicted by DMT data (the occasional discrepancies may be related to the presence of cementation), while a certain dispersion is found between the V_S predicted by CPT results and the measured V_S. This is probably due to the fact that the evaluation of V_S from DMT includes the horizontal stress index K_D that is noticeably reactive to stress history, prestraining/aging and structure

(TC16, 2001), scarcely felt by q_c from CPT. As it clearly appears from Figure 1, 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.

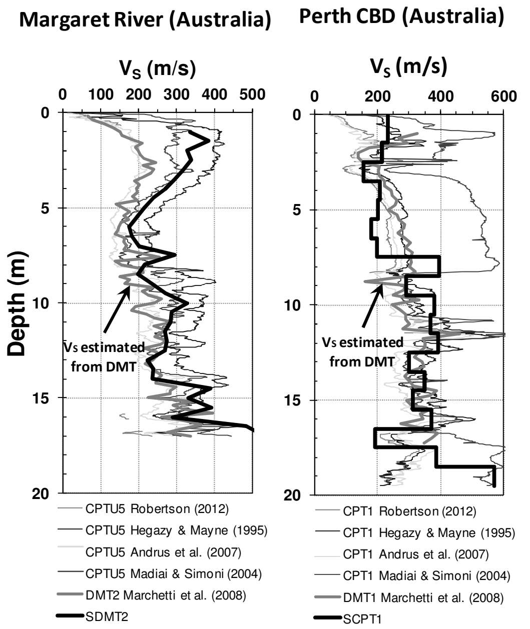

Figure 5. Comparison of V_S measured by SDMT or SCPT and estimated from CPT and DMT data at Margaret River and Perth CBD (Western Australia).

4. 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, presumably because of the availability, by DMT, of the stress history index K_D.

Moreover, while the V_S profiles predicted by DMT using Figure 1 are univocal (the correlations only differ for soil type), the CPT predicted V_S are subjected to the additional uncertainty 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.

5. References

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