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 $K_D$. The CPT correlations are controlled by various parameters: geological age (Pleistocene, Holocene, etc.), cementation, soil type, effective stress state.

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; Bouchovas 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).

\[
\frac{G_0}{M_{DMT}} = 26.177 \cdot K_D^{-1.0066} \cdot I_D < 0.6 \quad (1)
\]

\[
\frac{G_0}{M_{DMT}} = 15.686 \cdot K_D^{-0.921} \cdot 0.6 < I_D < 1.8 \quad (2)
\]

\[
\frac{G_0}{M_{DMT}} = 4.5613 \cdot K_D^{-0.7967} \cdot I_D > 1.8 \quad (3)
\]

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 \( M_{\text{DMT}} \) 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 \( I_D \), \( K_0 \), \( M_{\text{DMT}} \);

- Figure 1 highlights the dominant influence of \( K_0 \) on the ratio \( G_0 / M_{\text{DMT}} \). In case of non availability of \( K_0 \) – which reflects the stress history - the selection of the ratio \( G_0 / M_{\text{DMT}} \) would be hopelessly uncertain. Hence as many as three information, i.e. \( I_D \), \( K_0 \), \( M_{\text{DMT}} \) (though only two independent), are needed to formulate rough estimates of \( G_0 \) and \( V_S \). On the other hand the poor direct correlability \( M_{\text{DMT}} \) to \( G_0 \) in absence of additional information, was expectable. \( M_{\text{DMT}} \) 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 \( M_{\text{DMT}} \), but does not affect \( G_0 \). Said in a different way, \( M_{\text{DMT}} \) includes some stress history information, \( G_0 \) does not (Powell & Butcher 2004);

- based on the latest consideration, the use of \( N_{\text{SPT}} \) 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 (\( I_D \), \( K_0 \), \( M_{\text{DMT}} \)) 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 \( q_0 \) corrected cone tip resistance):

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

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

(4)

\[
\alpha_{V_S} = 10^{(0.55I_c + 1.68)}
\]

(5)

Where \( \sigma_v \) 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:

\[
V_S = \left[ 10.1 \log(q_t) - 11.4 \right]^{0.67} \left[ \frac{l_f}{q_t} \right]^{0.10}
\]

(6)

Where \( l_f \) is the sleeve friction;

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

\[
G_0 = 49.2 \cdot q_c^{0.51}
\]

(7)

- Andrus et al. (2007) equations are valid for Holocene soils (8) and for Pleistocene soils (9):

\[
V_S = 2.27 \cdot q_t^{0.412} \cdot I_c^{0.989} \cdot D^{0.033} \cdot ASF
\]

(8)

\[
V_S = 2.62 \cdot q_t^{0.395} \cdot I_c^{0.912} \cdot D^{0.124} \cdot SF
\]

(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):

\[
V_S = 140 \cdot q_c^{0.30} \cdot f_s^{-0.13}
\]

(10)

\[
V_S = 268 \cdot q_c^{0.21} \cdot f_s^{-0.02}
\]

(11)

\[
V_S = 182 \cdot q_c^{0.33} \cdot f_s^{-0.02}
\]

(12)
\( V_s = 172 \cdot q_c^{0.35} \cdot f_s^{0.05} \)  

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

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

(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).

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 2](image1.png)

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

![Figure 3](image2.png)

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](image3.png)

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 \( K_0 \) 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).](image)

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 \( K_0 \).

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


