In Situ Tests by Seismic Dilatometer (SDMT)

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ABSTRACT: The seismic dilatometer (SDMT) is the combination of the standard flat dilatometer (DMT) with a seismic module for measuring the shear wave velocity $V_S$. This paper summarizes the experience gained from SDMT tests performed at 34 sites. In particular the paper presents an overview of the SDMT equipment, comparisons of $V_S$ measured by SDMT and by other methods, interrelationships $G_0$, $E_D$, $M_{DMT}$ based on 2000 data points and a selection of significant SDMT results and related comments. The paper also illustrates the major issues of present research on use and applications of the SDMT, mostly focused on the development of methods for deriving the in situ $G$-$\gamma$ decay curves and for evaluating the liquefaction resistance of sands based on SDMT results.

KEYWORDS: Seismic Dilatometer SDMT, Flat Dilatometer DMT, Shear Wave Velocity $V_S$, $G$-$\gamma$ Curves, Working Strain Modulus, Liquefaction

INTRODUCTION

The seismic dilatometer (SDMT) is the combination of the traditional "mechanical" Flat Dilatometer (DMT) introduced by Marchetti (1980) with a seismic module placed above the DMT blade. The SDMT module is a probe outfitted with two receivers, spaced 0.5 m, for measuring the shear wave velocity $V_S$. From $V_S$ the maximum shear modulus $G_0$ may be determined using the theory of elasticity.

Motivations of the combined probe:

– $V_S$ (and $G_0$) are at the base of any seismic analysis.
– The $G$-$\gamma$ decay curves are an increasingly requested input in seismic analyses and in general in non linear analyses.
– Increasing demand for liquefiaibility evaluations.
– Seismic site classification using directly $V_S$ rather than $N_{SPT}$ or $c_u$. 
Availability of the usual DMT results (e.g. constrained modulus \( M_{DMT} \)) for current design applications (e.g. conventional settlement predictions).

This paper comments on the most significant SDMT results obtained in the period 2004-2007 at 34 sites.

Information on the mechanical DMT, not described in this paper, can be found in the comprehensive report by the ISSMGE Technical Committee TC16 (2001).

THE SEISMIC DILATOMETER (SDMT)

The seismic dilatometer (SDMT) is the combination of the standard DMT equipment with a seismic module for measuring the shear wave velocity \( V_S \).

The test is conceptually similar to the seismic cone SCPT. First introduced by Hepton (1988), the SDMT was subsequently improved at Georgia Tech, Atlanta, USA (Martin and Mayne 1997, 1998; Mayne et al. 1999). A new SDMT system (Fig. 1) has been recently developed in Italy. The seismic module (Fig. 1a) is a cylindrical element placed above the DMT blade, equipped with two receivers, spaced 0.5 m. The signal is amplified and digitized at depth. 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 and not to different blows in sequence, which are not necessarily identical. Hence the repeatability of \( V_S \) measurements is considerably improved (observed \( V_S \) repeatability \( \approx 1-2 \% \)). \( V_S \) is obtained (Fig. 1b) as the ratio between the difference in distance between the source and the two receivers \( (S_2 - S_1) \) and the delay of the arrival of the impulse from the first to the second receiver \( (\Delta t) \). \( V_S \) measurements are obtained every 0.5 m of depth.

![FIG. 1. Seismic Dilatometer: (a) DMT blade and seismic module. (b) Schematic layout of the seismic dilatometer test. (c) Seismic dilatometer equipment.](image-url)
The shear wave source at the surface (Fig. 2) is a pendulum hammer (≈ 10 kg) which hits horizontally a steel rectangular base pressed vertically against the soil (by the weight of the truck) and oriented with its long axis parallel to the axis of the receivers, so that they can offer the highest sensitivity to the generated shear wave.

The determination of the delay from SDMT seismograms, normally carried out using the cross-correlation algorithm, is generally well conditioned being based on the two seismograms – in particular the initial waves – rather than being based on the first arrival time or specific marker points in the seismogram.

Fig. 3 shows an example of seismograms obtained by SDMT at various test depths at the site of Fucino (it is a good practice to plot side-by-side the seismograms as recorded and re-phased according to the calculated delay).

Fig. 4 (Fiumicino) is an example of the typical graphical format of the SDMT output. Such output displays the profile of $V_s$ as well as the profiles of four basic
**TABLE 1.** Example of repeatability of $V_S$ measurements by SDMT (Zelazny Most Tailing Dam, Poland)

<table>
<thead>
<tr>
<th>$Z$ [m]</th>
<th>$V_S$ [m/s]</th>
<th>$V_S$ values [m/s] corresponding to different hammer blows at each depth $Z$</th>
<th>Coefficient of variation [%]</th>
</tr>
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<tr>
<td>7.00</td>
<td>179</td>
<td>178,178,180,180,180,179,178,180,180</td>
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<tr>
<td>7.50</td>
<td>231</td>
<td>234,232,232,230,229,231,232,229,230</td>
<td>0.68</td>
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<tr>
<td>8.00</td>
<td>225</td>
<td>227,225,232,235,225,226,225,226,224</td>
<td>0.40</td>
</tr>
<tr>
<td>8.50</td>
<td>276</td>
<td>276,276,280,275,275,275,273,287,287</td>
<td>1.68</td>
</tr>
<tr>
<td>9.00</td>
<td>296</td>
<td>291,286,301,292,296,288,290,301,300</td>
<td>0.60</td>
</tr>
<tr>
<td>9.50</td>
<td>248</td>
<td>244,251,250,247,250,249,250,249,242</td>
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<tr>
<td>10.00</td>
<td>292</td>
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<tr>
<td>10.50</td>
<td>320</td>
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<tr>
<td>11.00</td>
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<tr>
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<td>307,309,307,309,309,309,309,309,309</td>
<td>0.29</td>
</tr>
</tbody>
</table>

DMT parameters – the material index $I_D$ (soil type), the constrained modulus $M$, the undrained shear strength $c_u$ and the horizontal stress index $K_D$ (related to OCR) – obtained using current DMT correlations. It may be noted from Fig. 4 that the repeatability of the $V_S$ profile is very high, similar to the repeatability of the other DMT parameters, if not better.

Table 1 shows an example of another kind of repeatability of $V_S$ by SDMT (Zelazny Most Tailing Dam, Poland). Each $V_S$ value at a given test depth corresponds to a different hammer blow. The coefficient of variation of $V_S$ is in the range 1-2 %.

Such repeatability is more than adequate for normal engineering needs. However, especially in earthquake geotechnical engineering, where the design is increasingly based on the acceptability of the permanent displacements, accurate $V_S$ (and $G_0$) estimates are a necessary prerequisite for correctly predicting such displacements.

$V_S$ measurements by SDMT have been validated by comparison with $V_S$ measurements obtained by other in situ seismic tests at various research sites. As an example Fig. 5 shows $V_S$ comparisons at the research site of Fucino, Italy (NC cemented clay), extensively investigated at the end of the '80s. The profile of $V_S$ obtained by SDMT in 2004 (Fig. 5) is in quite good agreement with $V_S$ profiles obtained by SCPT, Cross-Hole and SASW in previous investigations (AGI 1991). Similar favourable comparisons are reported by various Authors, e.g. by Hepton (1988), McGillivray and Mayne (2004) and Młynarek et al. (2006).

**FIG. 5.** Comparison of $V_S$ profiles obtained by SDMT and by SCPT, Cross-Hole and SASW (AGI 1991) at the research site of Fucino (Italy)

**INTERRELATIONSHIPS BETWEEN EXPERIMENTAL $G_0$, $E_D$, $M_{DMT}$**

The experimental diagrams presented in this section have been constructed using same-depth $G_0$, $E_D$, $M_{DMT}$ 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 \(G_0, E_D, M_{DMT}\). Of the over 2000 data points available, only 800 high quality data points have been considered, relative to "uniform" one-m soil intervals where \(\log I_D, K_D, E_D, M_{DMT}, V_S\) 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 as in Marchetti (1980) or Table 1 in TC16 (2001).

Diagrams of the Ratio \(G_0/E_D\)

The ratio \(G_0/E_D\) are plotted versus \(K_D\) (Fig. 6a) and \(I_D\) (Fig. 6b). It can be seen that data points tend to group according to their \(I_D\) and \(K_D\). From Fig. 6, if \(I_D\) and \(K_D\) are available, rough estimates of \(G_0\) can be made from \(E_D\), in absence of direct \(G_0\) measurements.

Recognizable trends in Fig. 6 are: \(G_0/E_D\) is mostly in the range 1.5 to 3 in sand, 2.5 to 13 in silt, 3 to 25 in clay. The widest range and the maximum variability of \(G_0/E_D\) are found in clay. For all soils \(G_0/E_D\) decreases as \(K_D\) (related to OCR) increases.

Diagrams of the Ratio \(G_0/M_{DMT}\)

The ratio \(G_0/M_{DMT}\) are plotted versus \(K_D\) (Fig. 7a) and \(I_D\) (Fig. 7b). The diagrams indicate a wide range of the ratio \(G_0/M_{DMT}\) (≈ 0.5 to 25 for all soils), hence the unfeasibility of estimating the operative modulus \(M\) from \(G_0\) by dividing \(G_0\) for a fixed number. Again the data points tend to group according to their \(I_D\) and \(K_D\). It can be seen that \(G_0/M_{DMT}\) is strongly dependent on (at least) both soil type and stress history. Hence the use of only one parameter (e.g. \(c_u\) in cohesive soils) as an estimate for \(V_S\) (or \(G_0\)) for the seismic soil classification appears problematic.

Recognizable trends in Fig. 7 are: \(G_0/M_{DMT}\) is mostly in the range 0.5 to 3 in sand, 1 to 10 in silt, 1 to 20 in clay. The widest range and the maximum variability of \(G_0/M_{DMT}\) are found in clay. For all soils \(G_0/M_{DMT}\) decreases as \(K_D\) (related to OCR) increases.

If \(I_D\) and \(K_D\) are available, Fig. 7, where the dispersion is slightly less than in Fig. 6, is to be preferred to Fig. 6 to obtain rough estimates of the ratio \(G_0/M\), i.e. \(G_0\) from \(M\) or \(M\) from \(G_0\), when only one of them is available.

Diagrams of the Ratio \(G_{DMT}/G_0\)

Fig. 8 shows the same experimental information as in Figures 6 and 7, but involves the additional modulus \(G_{DMT}\) derived from \(M_{DMT}\) using the formula of linear elasticity:

\[
G = M / \left[ 2(1-\nu) / (1-2\nu) \right] \tag{1}
\]

For \(\nu = 0.15, 0.20\) and \(0.25\), the denominator in Eq. 1 would be 2.43, 2.67 and 3
respectively. For the conversion, the denominator 2.67 has been retained, i.e.:
\[ G_{DMT} = M_{DMT} / 2.67 \]  

(2)

All the \( G_{DMT} \) have been derived from \( M_{DMT} \) using Eq. 2, then the ratios \( G_{DMT}/G_0 \) have been calculated too and plotted versus \( K_D \) (Fig. 8a) and \( I_D \) (Fig. 8b).

The reason of constructing Fig. 8 is the following. The ratio \( G/G_0 \) is the usual ordinate of the normalized \( G-\gamma \) decay curve and has the meaning of a strain decay factor. Since \( M_{DMT} \) is a \textit{working strain modulus} one might hypothesize that \( G_{DMT} \) is a \textit{working strain shear modulus} too, in which case \( G_{DMT}/G_0 \) could be regarded as the shear modulus decay factor at \textit{working strains}.

It is emphasized that, at this stage, the legitimacy of using linear elasticity for deriving \( G_{DMT} \) from \( M_{DMT} \) (Eq. 2) and the assumption that \( G_{DMT} \) is a \textit{working strain shear modulus} are only working hypotheses, likely more difficult to investigate than verifying that \( M_{DMT} \) is a \textit{working strain constrained modulus} (the matter is discussed later in the paper). The very designation \textit{working strain shear modulus} (or operative shear modulus) requires clarification. Anyway, if the above hypotheses were acceptable, Fig. 8 could provide, if \( I_D \) and \( K_D \) are known, rough estimates of the decay factor at \textit{working strains}. If complete SDMT are available, then said rough estimates could be skipped and the decay factor could be obtained directly as the ratio between \( G_{DMT} \) from Eq. 2 and \( G_0 \).

Trends emerging from Fig. 8 are: (a) The \( G \) decay in sands is much less than in silts and clays. (b) The silt and clay decay curves are very similar. (c) For all soils the decay is maximum in the NC or lightly OC region (low \( K_D \)).

Fig. 7a and Fig. 8a are reproduced in a more readable format in Fig. 9 and Fig. 10 respectively, where the data points relative to clay, silt and sand have been plotted separately. Best fit equations are indicated for each of the six diagrams.

**IN SITU \( G-\gamma \) DECAY CURVES BY SDMT**

SDMT provides routinely at each depth, besides a \textit{small strain modulus} \( (G_0 \text{ from } V_S) \), also a \textit{working strain modulus} \( (M_{DMT}) \). These two moduli could possibly be of help when selecting the \( G-\gamma \) curves. Such potentiality is heavily founded on the basic premise that \( M_{DMT} \) is a reasonable estimate of the operative \textit{working strain modulus}. It is therefore considered appropriate to recall here the presently available evidence.

**\( M_{DMT} \) as an Operative or Working Strain Modulus**

The terms Operative Modulus and Working Strain Modulus are considered synonyms in this paper and are used interchangeably. They are defined as those moduli that, introduced into the linear elasticity formulae, provide reasonable estimates of the settlements under a shallow foundation (say for a safety factor \( F_s \approx 2.5 \) to 3.5).
FIG. 6. Ratio $G_0/E_D$ vs. $K_D$ and $I_D$

FIG. 7. Ratio $G_0/M_{DMT}$ vs. $K_D$ and $I_D$

FIG. 8. Decay ratio $G_{DMT}/G_0$ vs. $K_D$ and $I_D$
Comparisons of Surface Settlements

Schmertmann (1986) reported 16 case histories at various locations and for various soil types, with measured settlements ranging from 3 to 2850 mm. In most cases settlements from DMT were calculated using the Ordinary 1-D Method. The average ratio DMT-calculated/observed settlement was 1.18, with the value of the ratio mostly in the range 0.7 to 1.3 and a standard deviation of 0.38.

Monaco et al. (2006) reviewed numerous other real-life well documented comparisons of DMT-predicted versus measured settlements. The average ratio DMT-calculated/observed settlement for all cases reviewed by Monaco et al. (2006) is ≈ 1.3, with an observed settlement within ± 50 % from the DMT-predicted settlement.
The above settlements comparisons appear to support the assumption that $M_{DMT}$ is a reasonable estimate of the constrained working strain modulus.
Comparisons of Moduli

Even more direct, but rarely available, are data comparing $M_{DMT}$ with moduli back-figured from local vertical strain measurements.

In 2002 a major research project, funded by the Italian Ministry of University and Scientific Research and by Consorzio Venezia Nuova, was undertaken by a consortium of three Italian Universities (Padova, Bologna and L’Aquila).

A full-scale cylindrical heavily instrumented test embankment (40 m diameter, 6.7 m height, applied load 104 kPa – Fig. 11a) was constructed at the site of Venezia-Treporti, typical of the highly stratified, predominantly silty deposits of the Venezia lagoon (Fig. 11b). The loading history, the progression of the settlements and the drainage conditions – practically fully drained – are shown in Fig. 11c.

A specific aim of the research was to obtain a profile of the observed 1-D operative modulus $M$ under the center of the embankment. For this purpose a high precision sliding micrometer was used to accurately measure the local vertical strain $\varepsilon_v$ at 1 m depth intervals.

$M$ values were back-calculated from local vertical strains $\varepsilon_v$ in each 1 m soil layer as $M = \Delta \sigma_v / \varepsilon_v$, with vertical stress increments $\Delta \sigma_v$ calculated at the mid-height of each layer by linear elasticity formulae (approximation considered acceptable in view of the very low $\varepsilon_h$).

Fig. 11d, which is believed to be one of the most important results of the Venezia-Treporti research, shows an overall satisfactory agreement between $M_{DMT}$ and moduli back-figured from the test embankment performance, also considering the marked soil heterogeneity. Fig. 11e compares the observed versus DMT-predicted settlements at each depth. Again the agreement is rather satisfactory, considering that the DMT predicted settlements were calculated using the simple linear 1-D conventional approach $s = \Sigma (\Delta \sigma_v / M_{DMT}) \Delta H$, where $\Delta \sigma_v$ is calculated by Boussinesq linear elasticity formulae.

As to the surface settlements, the total settlement measured under the center of the embankment at the end of construction (180 days) was $\approx 36$ cm (Fig. 11c). The settlement predicted by $M_{DMT}$ using the 1-D approach (before knowing the results) was 29 cm. Hence the 29 cm predicted by DMT (which does not include secondary) are in good agreement with the 36 cm observed settlement (which includes some secondary during construction).

(Cunha (2004) wondered if it is right to attribute the 7 cm settlement difference (20 %) to secondary or to other causes. The question is legitimate. But in practical circles settlement predictions within a factor of 1.5-2 are often considered satisfactory for normal design. Mayne (2005) reports an SPT-DMT settlement comparison where the SPT prediction was wrong by a factor of 5 (the DMT prediction "was in line with the observed performance"). Factors of 3 or 5 are not unusual. In general, engineering decisions on the foundation type are based on knowing if the foundation will settle 1 mm or 10 mm or 100 mm. While it is desirable to reduce the error factor below 5 or 3, once it is reduced to 1.5 to 1.2, additional efforts may not be worthwhile or even inherently unfruitful due the many uncertainties involved in the definition of the settlement components and in their precise measurement).
(a) Test embankment. Penetrometer truck for testing after construction.

(b) Superimposed profiles of all SDMT data

(c) Settlement vs. time at the center of the embankment and comparison of measured vs. DMT-predicted settlements at the end of construction

(d) $M_{DMT}$ vs. $M$ back-calculated from local $\varepsilon_v$ measured at 1 m depth intervals under the center at the end of construction

(e) Observed vs. DMT-predicted settlement under the center at the end of construction

FIG. 11. Venezia-Treporti Research Embankment. SDMT profiles. Predicted vs. observed moduli and settlements (Marchetti et al. 2006).
FIG. 12. Tentative method for deriving $G-\gamma$ curves from SDMT

More details on the Venezia-Treporti research can be found in Marchetti et al. (2006), also containing numerous additional bibliographic references.

In conclusion also the Venezia-Treporti case-history supported the assumption that $M_{DMT}$ is a reasonable estimate of the constrained working strain modulus.

A note of caution. In OC clays oedometer moduli, even from good quality samples, are generally too low to be taken as operative moduli in situ. As noted by Ladd (1971), quoting Terzaghi-Peck (1964), the compressibility of even good oedometer samples of OC clay may be 2 to 5 times larger than the in situ compressibility. Indeed many engineers feel that the Skempton-Bjerrum reduction factor for settlements in OC clays was prompted by the fact that oedometer-based settlement predictions in OC London clay were systematically too high. Moduli back-figured from local strain measurements are far more realistic and are preferable for calibration or comparison purposes.

Construction of the $G-\gamma$ Curves

Such curves could tentatively be constructed by fitting "reference typical-shape" laboratory curves (see Fig. 12, where $G$ is normalized to $G_0$) through two points, both obtained by SDMT: (1) the initial modulus $G_0$ from $V_S$, and (2) a working strain modulus $G_{DMT}$ (Eq. 2). To locate the second point it is also necessary to know, at least approximately, the shear strain corresponding to $G_{DMT}$. Indications by Mayne (2001) locate the DMT moduli at an intermediate level of strain ($\gamma \approx 0.05-0.1 \%$) along the $G-\gamma$ curve. Similarly Ishihara (2001) classified the DMT within the group of methods of measurement of soil deformation characteristics involving an intermediate level of strain (0.01-1 %). The above indications, to be supplemented by further investigations, could possibly help develop methods for deriving in situ $G-\gamma$ curves from SDMT.

Lines of research currently under investigation are:

(a) Enter the $G_{DMT}/G_0$ ratios of Fig. 8 in the vertical axis of "reference typical-shape" $G-\gamma$ curves recommended in the literature for the corresponding soil type. The
range of abscissas of the intersection points with the \( G-\gamma \) curves could possibly help to better define the shear strain corresponding to \( G_{DMT} \).

(b) Develop a procedure for selecting the \( G-\gamma \) curve, among the typical curves recommended in the literature, making use of \( I_D \) for choosing the band of curves recommended for the soil type (sand or silt or clay), and \( K_D \) (possibly \( G_0/M_{DMT} \) too) for selecting one curve in the band.

(c) Evaluate for each of the 800 data points in Figures 6-7-8 the settlement under a simple loading scheme using the simple linear analysis with input \( M_{DMT} \) (operation equivalent to converting a DMT investigation into a "virtual" load test). Then calculate the settlement by non linear analyses with \( G-\gamma \) curves having variable rates of decay as input. By trial and error identify the \( G-\gamma \) curve (originating in \( G_0 \)) producing agreement between the two predicted settlements. Consider such \( G-\gamma \) curve reasonably correct and use it in the development of procedures for selecting the \( G-\gamma \) curves from SDMT data.

**DERIVABILITY OF THE OPERATIVE MODULUS \( M \) FROM \( G_0 \)**

This section discusses the possibility of deriving the operative modulus \( M \) by dividing \( G_0 \) by a constant.

Fig. 13 (Barcelona airport site) shows that, while the modulus \( M_{DMT} \) exhibits a drastic drop at \( \approx 12 \) m depth, at the transition from an upper stiff sand layer to a lower very soft clay layer, \( V_S \) shows only a minor decrease. Hence \( G_0 = \rho V_S^2 \), even considering the power 2, is far from being proportional to the working strain modulus \( M \). Similar lack of proportionality, with variations of the ratio \( G_0/M_{DMT} \) often of one order of magnitude, has been observed at many sites (including Venezia, Fig. 11d), suggesting that it is next to impossible (at least without local layer-specific correlations) to derive the working strain modulus by simply reducing the small strain modulus by a fixed percent factor (e.g. 50 %, Simpson 1999).

On the other hand the poor correlability was expected, since at low strains the soil tendency to dilate or contract is not active yet. Such tendency substantially affects the operative modulus \( M \), but does not affect \( G_0 \). Said in a different way, \( M \) includes some stress history information, \( G_0 \) does not (Powell and Butcher 2004).

The high variability of the ratio \( G_0/M \) was already noted earlier in Fig. 7. That figure explains that part of the difference in the amount of decrease in the Barcelona \( M \) and \( V_S \) profiles is due to the transition from sand (where \( G_0/M_{DMT} \) is in the range 0.5-3) to clay (where \( G_0/M_{DMT} \) is in the range 1-20). Fig. 7 (or the equivalent Fig. 9), entered with \( I_D \) and \( K_D \), can provide rough estimates of the ratio, hence \( M \) from \( G_0 \). However the direct measurements of both \( M \) and \( G_0 \) are preferable if accurate estimates of these parameters are required.

**ESTIMATING OCR IN SAND FOR ADVANCED PREDICTIVE MODELS**

Computer programs based on advanced soil models are increasingly used not only by researchers but also by practitioners for everyday design. Hence an important aim of in situ tests is to possibly provide input parameters for such models.
An input parameter required by many models is OCR. In clays reasonable OCR estimates can be obtained by laboratory samples, or in situ sometimes by the DMT OCR-K_D correlations. In sands, however, OCR evaluations are problematic. As today, to the authors’ knowledge, one of the least imprecise methods for evaluating OCR in sand by in situ tests is the one suggested by TC16 (2001). Such method consists in evaluating OCR based on the ratio M_DMT/q_c (q_c from CPT) using as a guide: M_DMT/q_c = 5-10 in NC sands, M_DMT/q_c = 12-24 in OC sands. The basis of such ratios is explained in TC16 (2001). In essence: when imparting stress history to the sand – for instance by compaction – M_DMT increases considerably faster than q_c (see e.g. Schmertmann et al. 1986, Jendeby 1992), hence M_DMT/q_c increases with OCR.

The above guide provides very rough estimates of OCR. The uncertainty however may not be due necessarily to the approximate nature of the correlations. Many sands could simply not have a well defined break in their insitu e-log p curve (Fig. 14) due to the complexity of the OCR sources (cementation, desiccation, water level fluctuations, etc.). Besides, layers of sands are often stratified, as the sand layers in Fig. 11b, with OCR presumably seesawing, so that the break in the e-log p of the composite layer will be rounded, and assigning a unique value to OCR of the layer could be inappropriate.

Uncertainty in the values of OCR represents a problem for many models requiring a precise value of OCR in sand because their predictions are generally critically sensitive to OCR. For instance in the case of Venezia-Treporti mentioned before, using advanced models with OCR = 1.2 or OCR = 1.6 leads to completely different settlement predictions, while the conventional analysis using the tangent modulus M_DMT produced a stable and satisfactory prediction (Fig. 11c).

The cause of the advanced model sensitivity can be understood even with the simple oedometer scheme. If a sand has an in situ e-log p curve of the type in Fig. 14b, and is modeled as in Fig. 14a, the predicted settlements will be highly dependent on the choice of the abscissa of the (in reality non existing) break.
Therefore sands whose in situ $e$-log $p$ curve are of the type in Fig. 14b should probably be treated with models attenuating the stiffness discontinuity across the preconsolidation stress.

In short, the problem could be not so much the determination of the exact OCR in sand, but the possibly incorrect assumption of the model that the sand has a sharp break.

It is generally recommended to run both advanced and traditional analyses to avoid gross errors that are likely if one is not familiar with the details of the program. This recommendation appears appropriate in this case, because, at least in the described Venezia-Treporti case, the simplified analysis using $M$ produced a stable and satisfactory prediction, while the "advanced" analysis was found to be critically dependent on the possibly elusive value of OCR.

**USE OF SDMT FOR LIQUEFACTION**

SDMT routinely provides, among other measurements, pairs of profiles of $K_D$ and $V_S$ – both correlated with the liquefaction resistance of sands. Hence SDMT permits to obtain two parallel independent estimates of liquefaction resistance CRR, one from $K_D$ and one from $V_S$, using CRR-$K_D$ and CRR-$V_S$ correlations – where CRR is the cyclic resistance ratio, a basic input in the commonly used Seed and Idriss (1971) simplified procedure.

The use of $V_S$ for evaluating CRR is well known. The most popular CRR-$V_S$ correlation (Fig. 15) is the one proposed by Andrus and Stokoe (2000), modified by Andrus et al. (2004). CRR is obtained as a function of $V_{SI} = V_S (p_a/\sigma^*_{vo})^{0.25}$, shear wave velocity corrected for the overburden stress $\sigma^*_{vo}$ ($p_a$ = atmospheric pressure). The CRR-$V_{SI}$ curves in Fig. 15 are for magnitude $M_w = 7.5$ earthquakes (magnitude scaling factors should be applied for different magnitudes).

Correlations CRR-$K_D$ have been developed in the last two decades, stimulated by the recognized sensitivity of $K_D$ to a number of factors which are known to increase liquefaction resistance, which are difficult to sense by other tests, such as stress history, prestraining, cementation, structure, and by the relationship of $K_D$ to relative density and state parameter.
A key element of the correlation CRR-$K_D$ (Monaco and Schmertmann 2007, Monaco and Marchetti 2007) is the ability of $K_D$ to reflect aging in sands. Calibration chamber data (Jamiolkowski and Lo Presti 1998) suggest that sensitivity to aging of sand is 3 to 7 times higher for $K_D$ than for penetration resistance (see Fig. 6 in Monaco and Marchetti 2007). Aging in sand is a factor having a first order of magnitude influence on liquefaction behavior, as pointed out e.g. by Leon et al. (2006).

Fig. 16 summarizes the various correlations developed to estimate CRR from $K_D$ (for magnitude $M = 7.5$ and clean sand) – to be used according to "simplified procedure" – including the latest CRR-$K_D$ correlation (Monaco et al. 2005), based on all previous data.

Comparisons based on parallel measurements of $K_D$ and $V_S$ by SDMT at several sandy sites (Maugerri and Monaco 2006) have indicated that methods based on $K_D$ and $V_S$ often provide, at the same site, substantially different estimates of CRR. Generally CRR from $V_S$ was found to be "more optimistic".

This finding opens the question "which CRR should be given greater weight", which is further discussed in the next section.

**SDMT RESULTS AT VARIOUS TEST SITES**

This section presents three examples of SDMT results considered of some interest.

**OCR and $K_D$ Crusts in Sand**

"Crust-like" $K_D$ profiles, very similar to the typical $K_D$ profiles found in OC desiccation crusts in clay, have been found at the top of many sand deposits. Various indications (Maugerri and Monaco 2006) suggest that "$K_D$ crusts" in sands reflect stress history (OCR, cementation, aging and/or other effects), rather than higher relative density. In the case shown in Fig. 17 (Catania), as in many other cases, the
existence of a shallow "stress history crust" (believed by far not liquefiable) is clearly highlighted by the $K_D$ profile, but almost "unfelt" by the $V_S$ profile. This suggests a lesser ability of $V_S$ to profile liquefiability.

**Role of the Interparticle Bonding**

The SDMT profiles in Fig. 18 (Cassino) show relatively high $V_S$ values coexisting with very low values of $K_D$ and moduli $M$. A possible explanation: the shear wave travels fast due to the interparticle bonding (typical of many volcanic sands in this area), preserved at small strains. By contrast $K_D$ is "low" because it reflects a different material, where the interparticle bonding has been at least partly destroyed by the DMT blade penetration. As noted by Andrus and Stokoe (2000), weak interparticle bonding can increase $V_S$ (measured at small strains), while not necessarily increasing resistance to liquefaction, a phenomenon occurring at medium to high strains (range of $K_D$ measurement). Thus, for liquefiability, the $K_D$ predictions could be possibly more fitting in case of strong earthquakes. Very light earthquakes, however, may not destroy bonding, then CRR evaluated by $V_S$ may be appropriate in this case.

**Limiting "No Liquefaction" Values of $V_{SI}$ and $K_D$**

The vertical asymptotes of the curves CRR-$V_{SI}$ (Fig. 15) and CRR-$K_D$ (Fig. 16) identify limiting values of $V_{SI}$ and $K_D$ (roughly, for clean sand, $V_{SI}^* = 215$ m/s and $K_{D}^* = 5.5$) for which liquefaction can be definitely excluded for any earthquake.

At the site of the Zelazny Most dam (Fig. 19) the indications derivable from such vertical asymptotes put in evidence a clear contradiction. While the values of $V_{SI} > 215$ m/s suggest "no liquefaction" even in case of strong earthquakes, the values of $K_D \approx 1.5-2$ indicate that liquefaction may occur above a certain seismic stress level (high cyclic stress ratio CSR). Even in this case, as noted before, CRR from $V_S$ is "more optimistic" – one reason being that it partly relies on bonding or equivalent phenomena.

In the case of the Zelazny Most dam the contradiction has no practical effects, since the region is non seismic and both Fig. 15 and Fig. 16 indicate no liquefaction. But for high seismicity cases the question "which CRR should be given greater weight" remains open.

Figures 17-18-19 are also examples of a commonly noted feature: the much smoother shape of the $V_S$ profiles compared with the $M$ or $K_D$ profiles.

**SDMT INSIDE BACKFILLED BOREHOLES**

In cases where the soil is too hard to penetrate (or even in rock), SDMT can be carried out inside a borehole backfilled with sand (only $V_S$, no DMT measurements).

The good agreement observed between $V_S$ profiles obtained by parallel SDMT soundings carried out, at the same site, in the natural soil and in a backfilled borehole (Fig. 20) supports the reliability of $V_S$ values obtained by this procedure.
FIG. 17. SDMT profiles at the site of Catania – San Giuseppe La Rena (Italy)

FIG. 18. SDMT profiles at the site of Cassino (Italy)

FIG. 19. SDMT profiles at the site of the Zelazny Most Tailing Dam (Poland)
FIG. 20. Comparison of $V_S$ profiles obtained by SDMT in the natural soil and in a backfilled borehole at the site of Montescaglioso – Ginosa (Matera), Italy

CONCLUSIONS

The seismic dilatometer (SDMT) provides accurate and highly reproducible measurements of the shear wave velocity $V_S$ – a basic input parameter for seismic analyses. Besides $V_S$, SDMT provides the usual DMT results (e.g. constrained modulus $M_{DMT}$) for current design applications.

Based on a large number of results by SDMT, diagrams showing experimental interrelationships $G_0$, $E_D$, $M_{DMT}$ have been constructed. In particular Fig. 9 and Fig. 10 illustrate the most significant observed trends.

Recent experience indicates that SDMT investigations can be performed with good results also in unusual conditions, e.g. offshore or in non penetrable soils ($V_S$- only measurements in backfilled boreholes).

Current research investigates the possible use of the SDMT for deriving "in situ" decay curves of soil stiffness with strain level, by fitting "reference G-γ curves" through two points provided by SDMT at different strain levels: the small strain shear modulus $G_0$ (from $V_S$) and a working strain modulus corresponding to $M_{DMT}$.

Deriving the operative modulus $M$ for settlement predictions from $G_0$ appears arduous. Often to drastic variations in the $M$ profile correspond barely visible variations in the $G_0$ profile. The ratio $G_0/M$ varies in the wide range 0.5 to 20 (Fig. 7), hence it is far from being a constant, especially in clays and silts. Its value is strongly dependent on multiple information, e.g. soil type and stress history. Hence the use of only one information (e.g. $c_u$ in cohesive soils) as a proxy of $V_S$ (or $G_0$) for the seismic soil classification appears problematic.

If only mechanical DMT results are available rough estimates of $G_0$ from $M$ can be obtained from Fig. 9.

The SDMT provides two parallel independent evaluations of the liquefaction resistance CRR from $V_S$ and from $K_D$ (horizontal stress index) by means of
correlations CRR-$V_S$ (Fig. 15) and CRR-$K_D$ (Fig. 16), to be used in the framework of the Seed and Idriss (1971) simplified procedure. Preliminary studies indicate that methods based on $K_D$ and $V_S$ often provide substantially different estimates of CRR. In principle, the authors would propose to give greater weight to CRR by $K_D$ for various reasons – above all the higher sensitivity of $K_D$ to stress history and aging, factors which greatly increase liquefaction resistance. Very light earthquakes, however, may not destroy bonding, and in that case CRR evaluated by $V_S$ may be more appropriate. The above obviously deserves additional verification, supported by real-life liquefaction case histories.

REFERENCES


