Experience with Seismic Dilatometer (SDMT) in various soil types

D. Marchetti  
*Studio Prof. Marchetti, Rome, Italy*

S. Marchetti, P. Monaco & G. Totani  
*University of L’Aquila, Italy*

ISC’3  
TAIPEI, 2008

**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 a large number of SDMT tests performed in 2004-2007 at over 30 sites. In particular, the paper presents an overview of the SDMT equipment, comparisons of \( V_S \) measured by SDMT and by other methods and a selection of 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.

1 INTRODUCTION

The seismic dilatometer (SDMT) combines the traditional features of the "mechanical" flat dilatometer (DMT) introduced by Marchetti (1980) with the ability of measuring the shear wave velocity \( V_S \). Initially conceived for research, the SDMT is gradually entering into use in current site investigation practice. Motivations of the combined probe:

- \( V_S \) (and the small strain shear modulus \( G_0 \) obtained from \( V_S \)) are at the base of any seismic analysis.
- The \( G-\gamma \) decay curves of stiffness with strain level are an increasingly requested input in seismic analyses and, in general, in non-linear analyses.
- Increasing demand for liquefiable evaluations.
- Availability of the usual DMT results (e.g. constrained modulus \( M_{DMT} \)) for common design applications (e.g. settlement prediction).

This paper comments on the most significant SDMT results obtained in the period 2004-2007 at over 30 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).

2 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 & 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, outfitted 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. The shear wave source at the surface (Fig. 1d) is a pendulum hammer (\( \approx 10 \) 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.

Figure 2 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).
3 COMPARISONS OF $V_S$ BY SDMT AND $V_S$ BY OTHER TESTS

$V_S$ 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 Figure 4 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. 4) 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 e.g. by Hepton (1988), McGillivray & Mayne (2004) and Młynarek et al. (2006).

4 IN SITU G-$\gamma$ CURVES BY SDMT

SDMT provides routinely at each depth, besides a small strain modulus ($G_0$ from $V_S$), also a working strain modulus. Numerous favourable real-life comparisons of DMT-predicted vs. measured settlements, summarized by Monaco et al. (2006), indicate that the DMT constrained modulus $M_{DMT}$ can be assumed as a reasonable estimate of the constrained working strain modulus (i.e. the modulus that,
introduced into the linear elasticity formulae, predicts with acceptable accuracy the settlements under working loads).

Research in progress investigates the possible use of the SDMT for deriving "in situ" decay curves of soil stiffness with strain level (G-γ curves or similar). Such curves could be tentatively constructed by fitting "reference typical-shape" laboratory curves (Fig. 5) through two points, both obtained by SDMT: (1) the initial modulus \( G_0 \) from \( V_S \), and (2) a working strain modulus corresponding to \( M_{DMT} \).

To locate the second point it is necessary to know, at least approximately, the shear strain corresponding to \( M_{DMT} \). Indications by Mayne (2001) locate the DMT moduli at an intermediate level of strain (\( γ \approx 0.05-0.1 \% \)) along the \( G-γ \) 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 could possibly help develop methods for deriving in situ \( G-γ \) curves from SDMT. Lines of research currently under investigation are illustrated by Lehane & Fahey (2004) and by Marchetti et al. (2008).

5 INTERRELATIONSHIPS \( G_0 / M_{DMT} \)

Marchetti et al. (2008) present experimental diagrams constructed using same-depth values of \( G_0 \), \( E_D \) (dilatometer modulus) and \( M_{DMT} \) determined by SDMT at 34 different sites in a variety of soil types.

Figure 6 shows the diagrams of the ratio \( G_0 / M_{DMT} \) plotted vs. the horizontal stress index \( K_D \) for clay, silt and sand. Recognizable trends in Figure 6 are: (a) \( G_0 / M_{DMT} \) is mostly in the range 0.5 to 3 in sand, 1 to 10 in silt, 1 to 20 in clay. (b) The widest range and the maximum variability of \( G_0 / M_{DMT} \) are found in clay. (c) For all soils \( G_0 / M_{DMT} \) decreases as \( K_D \) (related to OCR) increases.

Figure 7 shows the diagrams of the ratio \( G_{DMT} / G_0 \) vs. \( K_D \) for clay, silt and sand – where \( G_{DMT} \) is the working strain shear modulus derived from \( M_D \). Using the linear elasticity formula \( G_{DMT} = M_{DMT} / 2.67 \) (see Marchetti et al. 2008 for details and comments). The ratio \( G_{DMT} / G_0 \) could be regarded as the shear modulus decay factor at working strains. Trends emerging from Figure 7 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 \( K_D \)).

Best fit equations are indicated for each of the six diagrams in Figures 6-7. If \( I_D \) and \( K_D \) are known, Figure 6 can provide rough estimates of the ratio \( G_0 / M_D \) (i.e. \( G_0 \) from \( M \) or \( M \) from \( G_0 \)) when only one of them is available. However the direct measurement of both \( M \) and \( G_0 \) is preferable, if accurate estimates of these parameters are required. Figure 7 could provide, if \( I_D \) and \( K_D \) are known, rough estimates of the decay factor at working strains. If complete SDMT are available, the decay factor could be obtained directly as the ratio between \( G_{DMT} \) derived from \( M_{DMT} \) and \( G_0 \).

The Marchetti et al. (2008) paper shows also diagrams similar to Figure 6 (of this paper) but having in the ordinates the ratio \( G_0 / E_D \) rather than \( G_0 / M_{DMT} \). The degree of correlation was found to be lower.

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

Figure 6 indicates a wide range of the ratio \( G_0 / M_{DMT} \) (\( \approx 0.5 \) to 20 for all soils), hence the unfeasibility of estimating \( M \) from \( G_0 \) by dividing \( G_0 \) for a fixed number. It can be seen that \( G_0 / M_{DMT} \) is strongly dependent on (at least) both soil type and stress history.

Figure 8 (Barcelona airport) 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 slight 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, 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).
Figure 5. Tentative method for deriving $G-\gamma$ curves from SDMT
7 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 & Idriss (1971) simplified procedure.

The use of $V_S$ for evaluating CRR is well known. The most popular CRR-$V_S$ correlation (Fig. 9) is the one proposed by Andrus & Stokoe (2000) and its subsequent versions. CRR is obtained as a function of $V_S = V_S (p_0 / \sigma'_v)^{0.25}$, shear wave velocity correct-
ed for the overburden stress $\sigma'_{vo}$ ($p_o = \text{atmospheric pressure}$). The CRR-$V_{S1}$ curves in Figure 9 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 (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 & Schmertmann 2007, Monaco & Marchetti 2007) is the ability of $K_D$ to reflect aging in sands, a factor having a first order of magnitude influence on liquefaction behaviour (see e.g. by Leon et al. 2006).

Figure 10 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 (Maugeri & Monaco 2006) indicate that methods based on $K_D$ and $V_S$ often provide 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 discussed by Maugeri & Monaco (2006) and by Monaco & Marchetti (2007).

8 OFFSHORE SDMT

SDMT investigations have also been carried out offshore, operating the shear wave source at the sea bottom, with results of quality similar to onshore investigations (see e.g. Fig. 11, Vado Ligure).

9 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. 12) supports the reliability of $V_S$ values obtained by this procedure.
10 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 common design applications.

Recent experience indicates that SDMT tests 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 $G-\gamma$ 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. 6), 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. If only mechanical DMT results are available, rough estimates of $G_0$ from $M$ can be obtained from Figure 6.

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. 9) and CRR-$K_D$ (Fig. 10), to be used in the framework of the Seed & 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 propend (particularly in case of strong earthquakes, see Monaco & Marchetti 2007) 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. The above obviously deserves additional verification, supported by real-life liquefaction case histories.

REFERENCES


