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-γ 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-γ 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 liquefiability 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 ≈ 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 (Δt). V_S measurements are obtained every 0.5 m of depth. The shear wave source at the surface (Fig. 1d) 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.

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).

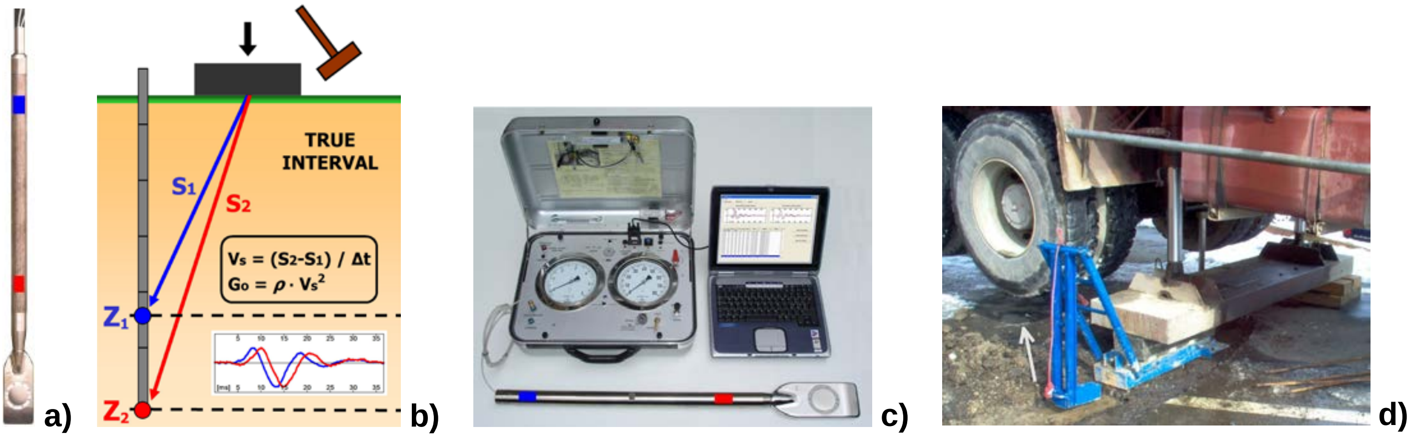

Figure 1. (a) DMT blade and seismic module. (b) Schematic layout of the seismic dilatometer test. (c) Seismic dilatometer equipment. (d) Shear wave source at the surface.

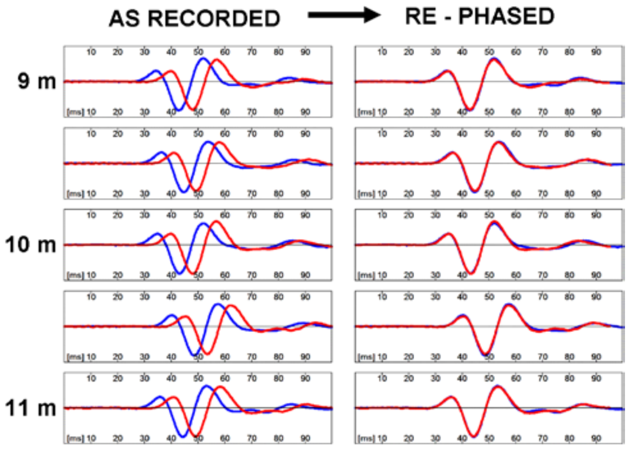

Figure 2. Example of seismograms obtained by SDMT at the research site of Fucino (Italy)

Figure 3 (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 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 in Figure 3 that the repeatability of the V_S profile is very high, similar to the repeatability of the other DMT parameters.

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-γ 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,

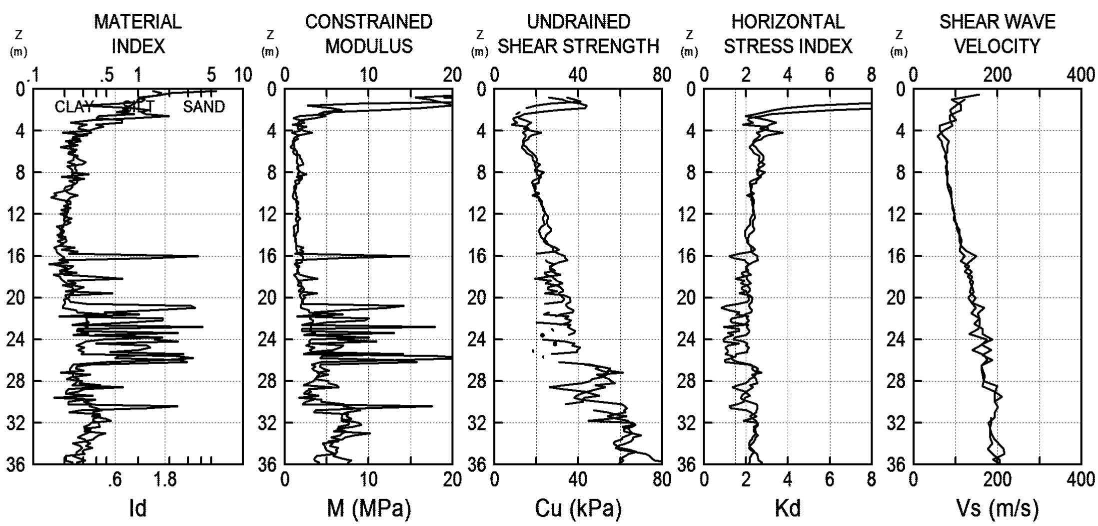

Figure 3. Superimposed SDMT profiles at the site of Fiumicino (Italy)

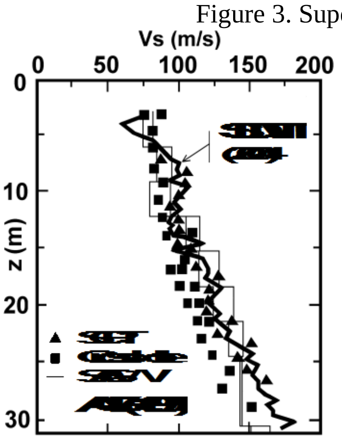

Figure 4. Comparison of V_S profiles obtained by SDMT and by SCPT, Cross-Hole and SASW (AGI 1991) at the research site of Fucino (Italy)

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 ($\gamma \approx$ 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_{DMT} 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 (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).

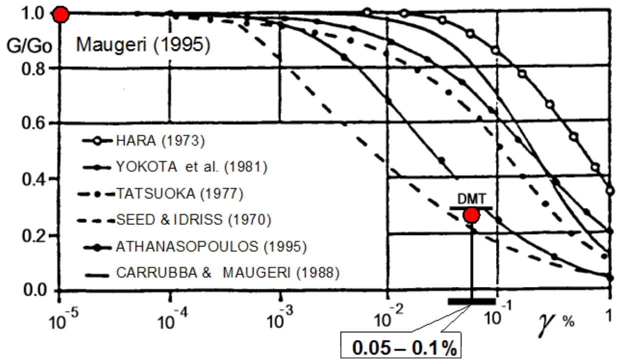

Figure 5. Tentative method for deriving G-γ curves from SDMT

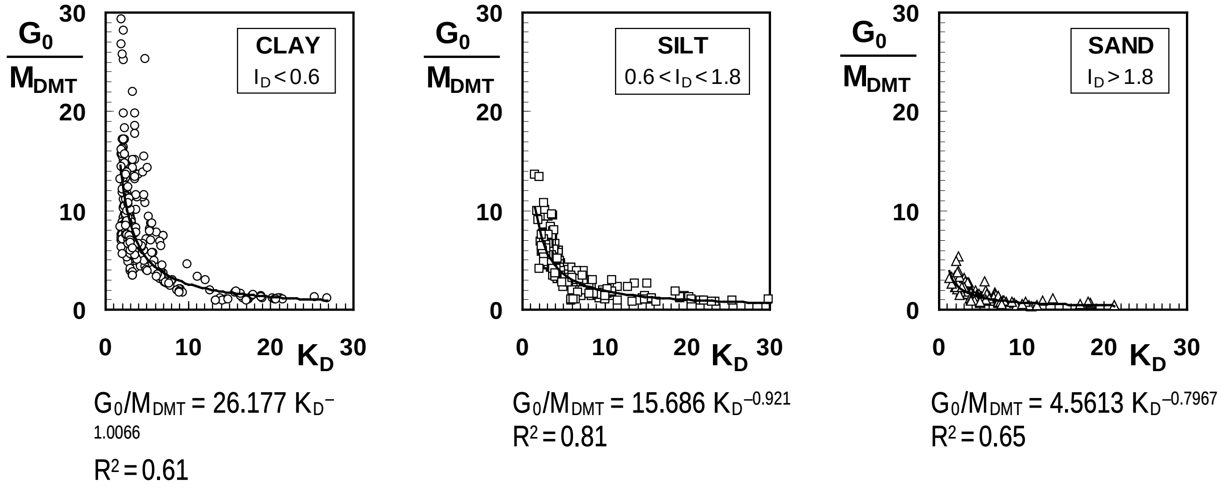

Figure 6. Ratio G_0 /M_{DMT} vs. K_D for clay, silt and sand (Marchetti et al. 2008)

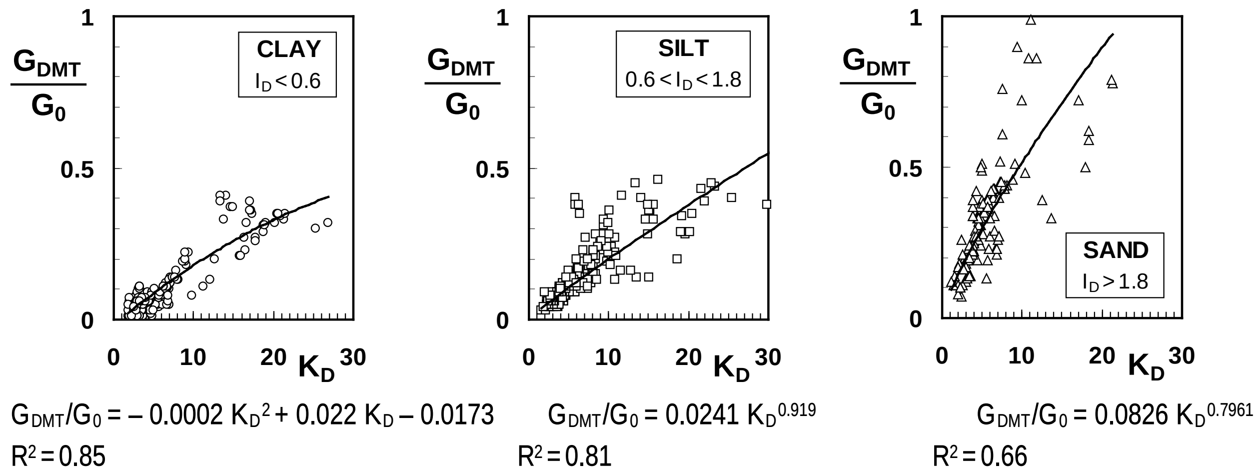

Figure 7. Decay ratio G_{DMT} /G_0 vs. K_D for clay, silt and sand (Marchetti et al. 2008)

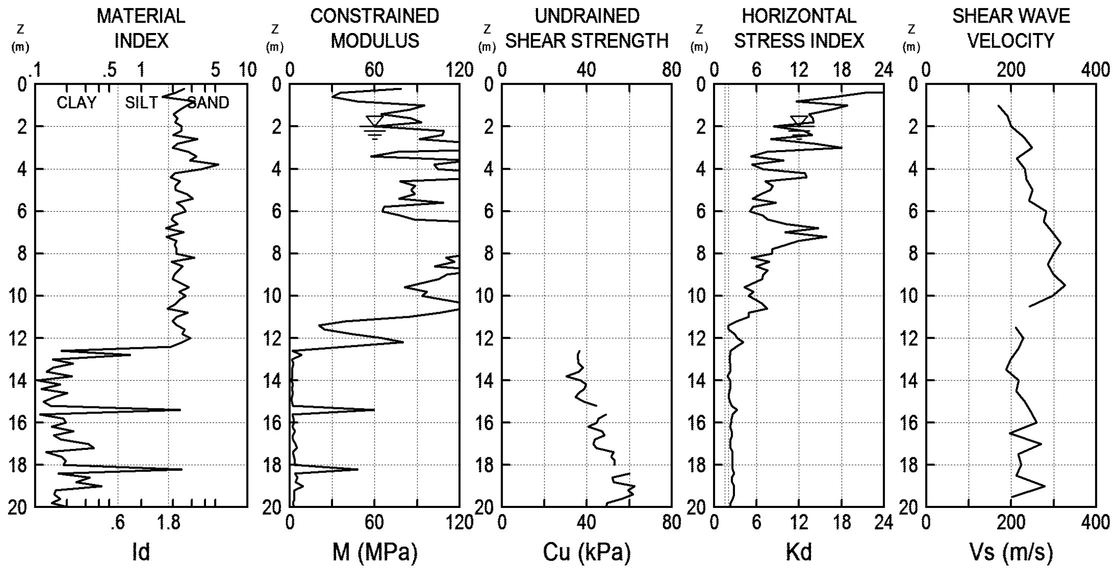

Figure 8. SDMT profiles at the site of Barcelona – El Prat Airport (Spain)

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 $V_{S1} = V_S\,(p_a/\sigma'_{v0})^{0.25}$, shear wave velocity corrected for the overburden stress σ'_{v0} (p_a = atmospheric pressure). The CRR-V_{S1} curves in Figure 9 are for

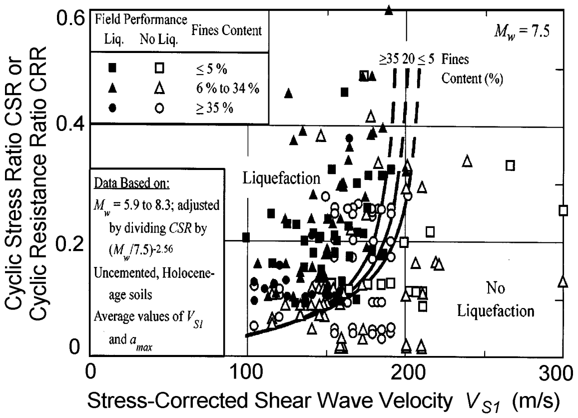

Figure 9. Curves for evaluating CRR from V_S for clean uncemented soils (Andrus & Stokoe 2000)

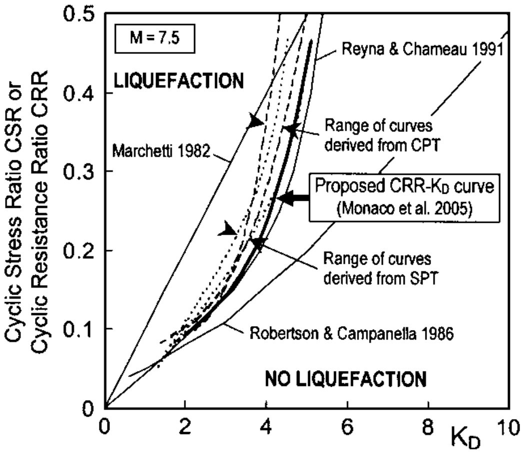

Figure 10. Curves for evaluating CRR from K_D (Monaco et al. 2005)

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

SMDT 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.

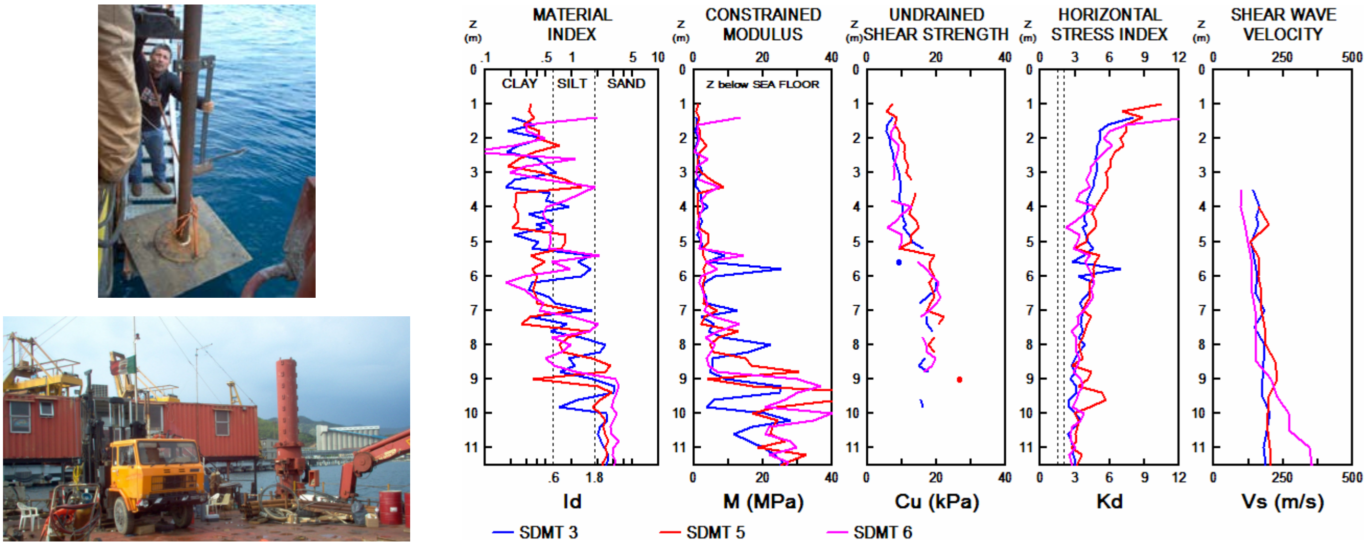

Figure 11. Details of *offshore* SDMT investigations and test profiles at the site of Vado Ligure (Savona), Italy

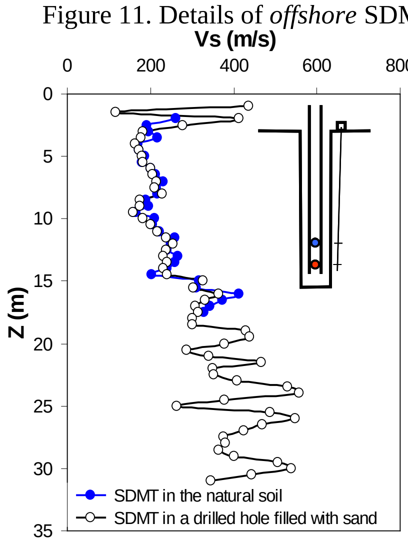

Figure 12. Comparison of V_S profiles obtained by SDMT in the natural soil and in a backfilled borehole at the site of Montescaglioso – Ginosa (Matera), Italy

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-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. 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

AGI 1991. Geotechnical Characterization of Fucino Clay. Proc. X ECSMFE, Firenze, 1: 27-40.

Andrus, R.D. & Stokoe, K.H., II. 2000. Liquefaction resistance of soils from shear-wave velocity. J. Geotech. Geoenv. Engrg., ASCE, 126(11): 1015-1025.

Hepton, P. 1988. Shear wave velocity measurements during penetration testing. Proc. Penetration Testing in the UK, ICE, 275-278.

Ishihara, K. 2001. Estimate of relative density from in-situ penetration tests. Proc. Int. Conf. on In Situ Measurement of Soil Properties and Case Histories, Bali, 17-26.

Lehane, B. & Fahey, M. 2004. Using SCPT and DMT data for settlement prediction in sand. Proc. 2nd Int. Conf. on Site Characterization ISC'2, Porto, 2: 1673-1679.

Leon, E., Gassman, S.L. & Talwani, P. 2006. Accounting for Soil Aging When Assessing Liquefaction Potential. J. Geotech. Geoenv. Engrg., ASCE, 132(3): 363-377.

Marchetti, S. 1980. In Situ Tests by Flat Dilatometer. J. Geotech. Engrg. Div., ASCE, 106(GT3): 299-321.

Marchetti, S., Monaco, P., Totani, G. & Marchetti, D. (2008). In Situ Tests by Seismic Dilatometer (SDMT). In "From Research to Practice in Geotechnical Engineering", ASCE Geotech. Spec. Publ. Honoring John H. Schmertmann.

Martin, G.K. & Mayne, P.W. 1997. Seismic Flat Dilatometer Tests in Connecticut Valley Varved Clay. ASTM Geotech. Testing J., 20(3): 357-361.
Martin, G.K. & Mayne, P.W. 1998. Seismic flat dilatometer in Piedmont residual soils. Proc. 1st Int. Conf. on Site Characterization ISC'98, Atlanta, 2: 837-843.
Maugeri, M. & Monaco, P. 2006. Liquefaction Potential Evaluation by SDMT. Proc. 2nd Int. Conf. on the Flat Dilatometer, Washington D.C., 295-305.
Mayne, P.W. 2001. Stress-strain-strength-flow parameters from enhanced in-situ tests. Proc. Int. Conf. on In Situ Measurement of Soil Properties and Case Histories, Bali, 27-47.
Mayne, P.W., Schneider, J.A. & Martin, G.K. 1999. Small- and large-strain soil properties from seismic flat dilatometer tests. Proc. 2nd Int. Symp. on Pre-Failure Deformation Characteristics of Geomaterials, Torino, 1: 419-427.
McGillivray, A. & Mayne, P.W. 2004. Seismic piezocone and seismic flat dilatometer tests at Treporti. Proc. 2nd Int. Conf. on Site Characterization ISC'2, Porto, 2: 1695-1700.
Młynarek, Z., Gogolik, S. & Marchetti, D. 2006. Suitability of the SDMT method to assess geotechnical parameters of post-flotation sediments. Proc. 2nd Int. Conf. on the Flat Dilatometer, Washington D.C., 148-153.
Monaco, P. & Marchetti, S. 2007. Evaluating liquefaction potential by seismic dilatometer (SDMT) accounting for aging/stress history. Proc. 4th Int. Conf. on Earthquake Geotechnical Engineering ICEGE, Thessaloniki.
Monaco, P., Marchetti, S., Totani, G. & Calabrese, M. 2005. Sand liquefiability assessment by Flat Dilatometer Test (DMT). Proc. XVI ICSMGE, Osaka, 4: 2693-2697.
Monaco, P. & Schmertmann, J.H. 2007. Discussion of "Accounting for Soil Aging When Assessing Liquefaction Potential" by Leon, E. et al. (in J. Geotech. Geoenv. Engrg., ASCE, 2006, 132(3): 363-377). J. Geotech. Geoenv. Engrg., ASCE, 133(9): 1177-1179.
Monaco, P., Totani, G. & Calabrese, M. 2006. DMT-predicted vs observed settlements: a review of the available experience. Proc. 2nd Int. Conf. on the Flat Dilatometer, Washington D.C., 244-252.
Seed, H.B. & Idriss, I.M. 1971. Simplified procedure for evaluating soil liquefaction potential. J. G. Engrg. Div., ASCE, 97(9): 1249-1273.
Simpson, B. 1999. Engineering needs. Proc. 2nd Int. Symp. Pre-Failure Deformation Characteristics of Geomaterials, Torino.
TC16 2001. The Flat Dilatometer Test (DMT) in Soil Investigations - A Report by the ISSMGE Committee TC16. Reprinted in Proc. 2nd Int. Conf. on the Flat Dilatometer, Washington D.C., 7-48.