Geotechnical and Geophysical Site Characterization 4 – Coutinho & Mayne (eds)

Site characterization by Seismic Dilatometer (SDMT) in the area of L'Aquila following the April 6, 2009 earthquake

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ABSTRACT: This paper comments on the results obtained by a large number of Seismic Dilatometer Tests (SDMT) executed in the area of L'Aquila (Italy) following the April 6, 2009 earthquake. SDMT soundings were executed by the normal penetration procedure only in a limited number of sites, mostly in silt. At the majority of the sites, in coarse-grained non-penetrable soils, V_S measurements by SDMT—but not the other DMT parameters—were obtained in backfilled boreholes, using the technique briefly described in the paper. The test results illustrated in the paper include: (a) SDMT results obtained by the normal penetration procedure, (b) V_S-only profiles obtained by the backfilling procedure, (c) comparisons of V_S profiles obtained by SDMT and by other techniques (Down-Hole, Cross-Hole, surface waves tests), and (d) comparisons of profiles of V_S measured by SDMT and estimated from mechanical DMT data.

1 INTRODUCTION

The April 6, 2009 L'Aquila (Italy) earthquake (M_W= 6.3) caused 309 victims, about 1,600 injured, 40,000 homeless and huge economic losses. The earthquake caused heavy damages in the city of L'Aquila (MCS Intensity I = VIII-IX) and in several nearby villages (maximum MCS Intensity I = IX-X at Onna and Castelnuovo).

Subsequently the area of L'Aquila was extensively investigated by a variety of geotechnical and geophysical testing techniques, involving several working groups (see e.g. Monaco et al. 2012).

This paper presents a review of results obtained by seismic dilatometer tests executed in the area of L'Aquila in the period 2009–2011. Some of these tests were carried out in the first months following the April 6, 2009 earthquake, as part of investigations planned for the geotechnical characterization of sites selected for the construction of new temporary houses for the homeless people (C.A.S.E. Project). SDMT results were also used, among other soil data, in the seismic microzonation project of the area of L'Aquila promoted by the Italian Department of Civil Protection (MS–AQ Working Group 2010). In addition, several seismic dilatometer tests were executed, both in the historic city center and in the suburban area of L'Aquila, as part of investigations planned to obtain input data for site seismic response analyses for design of restoration / retrofitting of important public buildings, severely damaged by the earthquake.

2 SEISMIC DILATOMETER TEST (SDMT)

2.1 *SDMT by the standard penetration procedure*

The seismic dilatometer (SDMT) is the combination of the mechanical flat dilatometer (DMT), introduced by Marchetti (1980), with an add-on seismic module for measuring the shear wave velocity V_S. 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 (Marchetti et al. 2008).

The seismic module (Fig. 1a) is a cylindrical element placed above the DMT blade, equipped with two receivers spaced 0.50 m. The shear wave source, located at ground surface, is a pendulum hammer (≈ 10 kg) which hits horizontally a steel rectangular plate 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. When a shear wave is generated at the surface (Fig. 1b) it reaches first the upper receiver, then, after a delay, the lower receiver. The seismograms acquired by the two receivers, amplified and digitized at depth, are transmitted to a PC at the surface, which determines the delay. V_S is obtained 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).

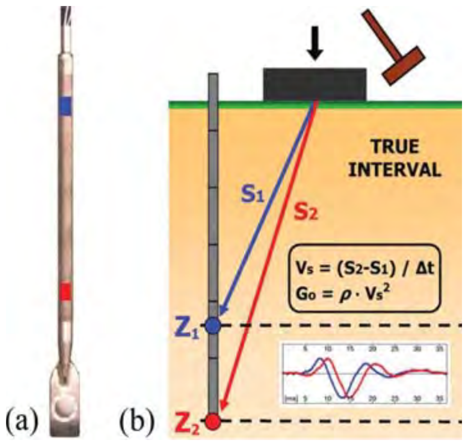

Figure 1. Seismic dilatometer test: (a) DMT blade and seismic module; (b) Schematic test layout.

V_S measurements are typically taken every 0.50 m of depth (while the mechanical DMT readings are taken every 0.20 m).

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%, i.e. a few m/s).

The determination of the delay from SDMT seismograms, normally obtained using a cross-correlation algorithm, is generally well conditioned, being based on the waveform analysis of the two seismograms rather than relying on the first arrival time or specific single points in the seismogram. An example of seismograms obtained by SDMT—as recorded and re-phased according to the calculated delay—is shown in Figure 2.

Validations of V_S measurements by SDMT compared to V_S measured by other in situ techniques at various research sites are reported by Marchetti et al. (2008). Besides V_S, the seismic dilatometer provides the parameters obtained from the usual flat dilatometer interpretation (Marchetti 1980, TC16 2001).

2.2 *SDMT by the backfilling procedure in non-penetrable soils*

The SDMT test procedure proves to be an effective, quick and cost-saving alternative to conventional Down-Hole tests in soft to firm soils (no need of holes with pipes to be grouted, operations requiring a few days pause for the cement to set up before testing). A disadvantage of the SDMT is the impossibility of penetrating very hard soils. However a procedure for obtaining SDMT V_S profiles—but not the other DMT parameters—in non-penetrable soils (e.g. in gravel, or even in rock) has been devised by Totani et al. (2009). The procedure is the following:

1. A borehole is drilled to the required test depth.
2. The borehole is backfilled with sand.
3. The SDMT is inserted and advanced into the backfilled borehole in the usual way (e.g. by use of a penetrometer rig) and V_S measurements are taken every 0.50 m of depth. No DMT measurements—meaningless in the backfill soil—are taken in this case.

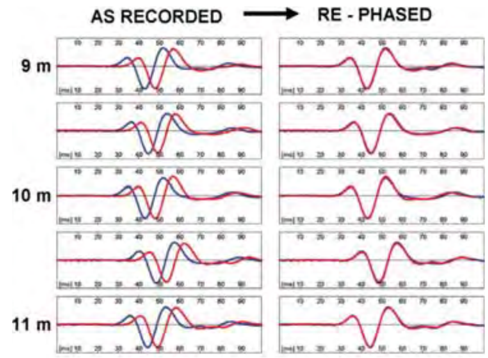

Figure 2. Example of seismograms obtained by SDMT (test site of Fucino, Marchetti et al. 2008).

The possibility of such measurement descends from the fact that the path of the shear wave from the surface to the upper and lower receiver includes a short path in the backfill of very similar length for both receivers. Comparative tests at various sites where both the usual penetration procedure and the backfilling procedure were adoptable, reported by Totani et al. (2009), indicate that the values of V_S obtained in a backfilled borehole are essentially coincident with the V_S obtained by penetrating the "virgin" soil.

3 SDMT RESULTS IN THE AREA OF L'AQUILA

3.1 *SDMT test sites in the area of L'Aquila*

Figure 3 shows the location of the sites investigated by SDMT in the area of L'Aquila after the April 6, 2009 earthquake. A brief description of the basic geological setting of the L'Aquila basin can be found e.g. in Monaco et al. (2012).

Whenever possible, in soils ranging from clay to silty sand (silt in the majority of the cases), the seismic dilatometer tests were executed by the normal penetration procedure. However, due to the

Figure 3. Location of the sites investigated by SDMT in the area of L'Aquila. *On the right*: Detail of location of the test sites in L'Aquila city center.

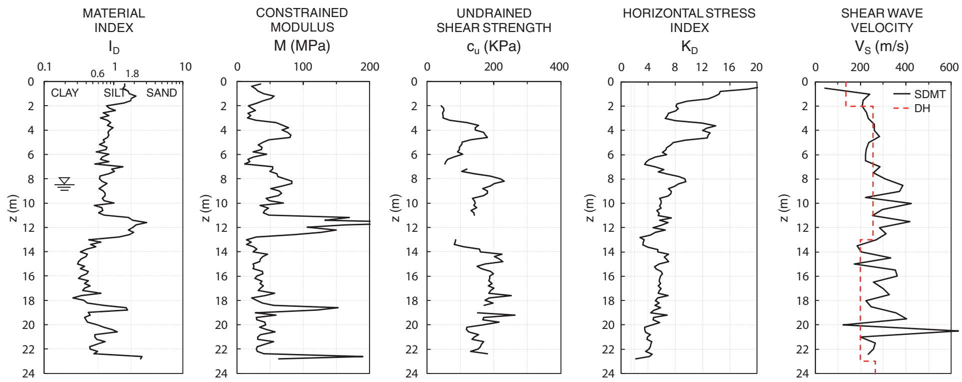

Figure 4. SDMT results at the site of Cese di Preturo (C.A.S.E. Project), L'Aquila. *On the right*: Comparison of profiles of V_S from SDMT and Down-Hole (Polo Geologico, MS–AQ Working Group 2010).

characteristics of the soils commonly encountered in this area (mostly coarse-grained, non-penetrable), SDMT measurements (V_S-only) were generally executed in backfilled boreholes, according to the Totani et al. (2009) procedure previously described.

3.2 *SDMT results by the penetration procedure*

Figures 4, 5 and 6 show the SDMT results obtained at three C.A.S.E. Project sites (Cese di Preturo, Pianola, Roio Piano), in fine- to medium-grained soils, investigated by the standard penetration procedure.

The soils at the above sites, mostly composed of silts or silty sands, belong to the Pleistocene lacustrine deposits which fill the bottom of the L'Aquila basin.

The typical graphical SDMT output in Figures 4 to 6 displays the profile of V_S as well as the profiles of four basic DMT parameters: the material index I_D (indicating soil type), the constrained modulus M, the undrained shear strength c_u (in clay) and the horizontal stress index K_D (related to OCR), calculated with usual DMT interpretation formulae (Marchetti 1980, TC16 2001).

The diagrams on the right in Figures 4, 5 and 6 show the comparison between the V_S profiles obtained by SDMT and the V_S profiles obtained by parallel Down-Hole tests executed by Polo Geologico (Figs. 4, 5, 6) and by surface waves tests (MASW) executed by Politecnico di Torino (Figs. 5, 6). The results of Down-Hole and surface waves tests, entrusted by the Italian Department of Civil Protection, are included in MS–AQ Working Group (2010). It can be noted that the V_S profiles obtained by SDMT are generally in satisfactory agreement with the V_S profiles obtained by Down-Hole and MASW.

Additional SDMT results obtained by the penetration procedure in the area of L'Aquila can be found in Amoroso et al. (2011). A case of liquefaction triggered by the April 6, 2009 main shock at Vittorito (≈45 km far from the epicenter), analyzed by

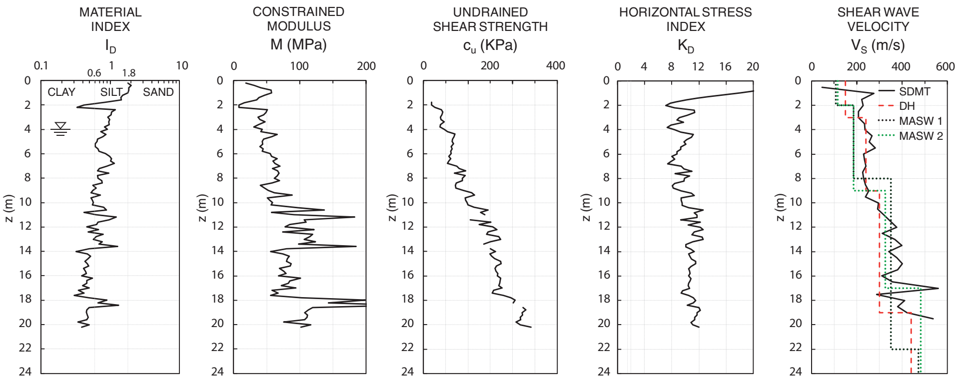

Figure 5. SDMT results at the site of Roio Piano (C.A.S.E. Project), L'Aquila. *On the right*: Comparison of profiles of V_S from SDMT, Down-Hole (Polo Geologico) and MASW (Politecnico di Torino, MS–AQ Working Group 2010).

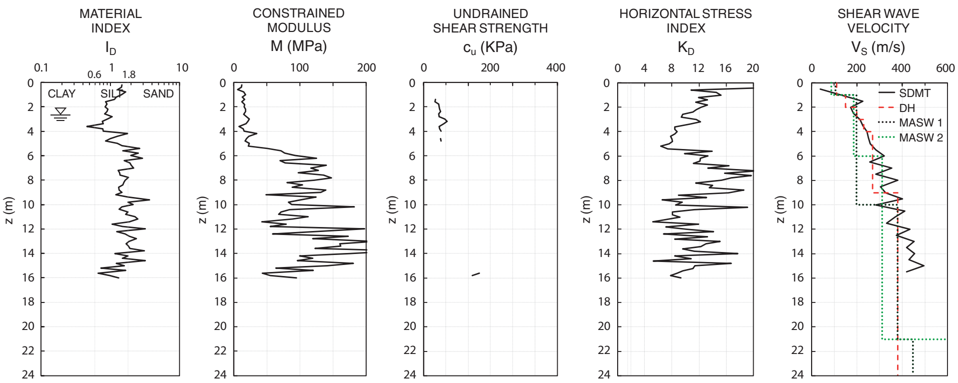

Figure 6. SDMT results at the site of Pianola (C.A.S.E. Project), L'Aquila. *On the right*: Comparison of profiles of V_S from SDMT, Down-Hole (Polo Geologico) and MASW (Politecnico di Torino, MS–AQ Working Group 2010).

use of SDMT results, was presented by Monaco et al. (2011a). In general, at all sites investigated by the penetration procedure in this area, the maximum test depth (limited by the push capacity of the penetrometer rig) was ≈ 17 to 23 m. The measured V_S values seldom trespass 400 m/s within ≈ 20 m depth.

3.3 *SDMT results by the backfilling procedure in non-penetrable soils*

Figures 7 to 14 show the SDMT results (in terms of V_S profile only—no DMT parameters) obtained by the backfilling procedure in non-penetrable soils at various sites in the area of L'Aquila.

In particular, Figures 7 to 11 show the V_S profiles obtained by SDMT in backfilled boreholes and the schematic soil profiles at various sites in the city center of L'Aquila (see detail on the right in Fig. 3), which includes most of the historical heritage and several old masonry buildings, heavily damaged by the April 6, 2009 earthquake. At all the above sites the upper portion of the subsoil, investigated by SDMT, belongs to the deposit known as "Brecce dell'Aquila" (typical of L'Aquila city center), composed of fine to coarse calcareous fragments of variable size (mostly of some centimeters) embedded in sandy or silty matrix. In the city center the breccias, about 80–100 m thick, are superimposed to the fine- to medium-grained, mostly silty lacustrine deposits, which are placed on the calcareous bedrock located below 300 m depth.

It can be noted in Figures 7 to 10 that the values of V_S measured in the breccias (down to 74 m depth at Palazzo Camponeschi, Fig. 7) are mostly ≈ 600–1000 m/s or higher, generally increasing with depth. Lower values (V_S ≈ 200–300 m/s) have been locally measured in shallow fill materials. The observed dispersion of the V_S values measured in the breccias possibly reflects some variability in grain size distribution, cementation and/or mechanical properties typical of this material.

The underlying lacustrine silty deposit was investigated by SDMT at the site of Fontana 99 Cannelle, located at ≈ 100 m lower elevation near the south-western border of the city center (see detail on the right in Fig. 3). Here the thickness of the breccias is reduced to the first 15–20 m or less. At Fontana 99 Cannelle (Fig. 11) the backfilling procedure permitted to obtain V_S measurements by SDMT

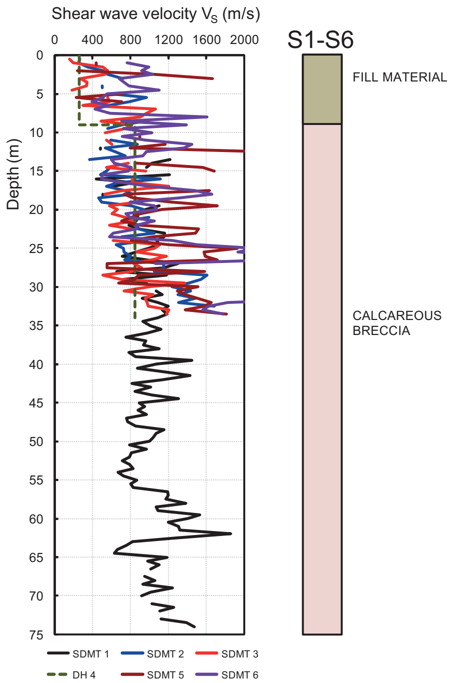

Figure 7. Profiles of V_S measured by SDMT in 5 backfilled boreholes, V_S measured by Down-Hole and schematic soil profile at the site of Palazzo Camponeschi, L'Aquila.

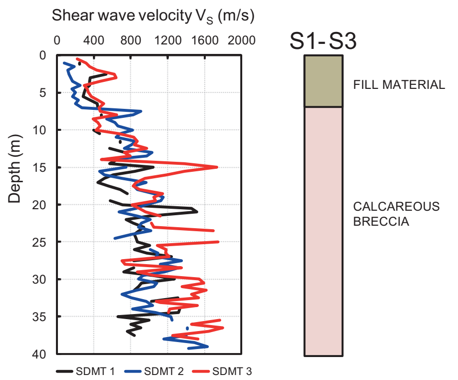

Figure 8. Profiles of V_S measured by SDMT in 3 backfilled boreholes and schematic soil profile at the site of Palazzo Carli, L'Aquila.

down to 133 m. Below ≈ 100 m depth the ratio signal/noise of the SDMT seismograms was found too low to determine V_S by the usual interpretation. In this case V_S was obtained using the "stacking" technique, consisting of summing up the signals recorded by the receivers at the same depth and in the same conditions. (In this way the energy of the signal is summed, while the energy of the noise, having a zero mean value, remains the same).

Also shown in Figure 11, superimposed to the V_S profile obtained by SDMT at Fontana 99 Cannelle, is the profile of V_S obtained by a Cross-Hole test to 78 m depth executed by Cardarelli & Cercato (2010)

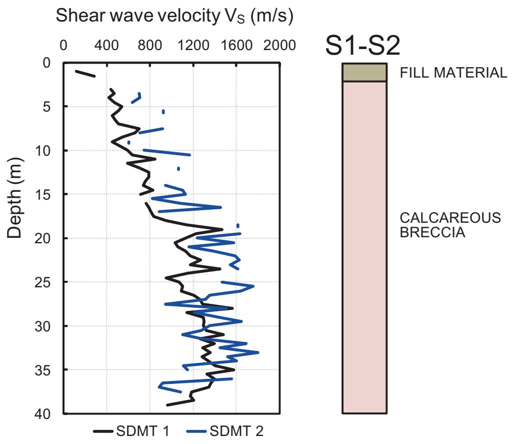

Figure 9. Profile of V_S measured by SDMT in 2 backfilled borehole and schematic soil profile at the site of Palazzo Margherita, L'Aquila.

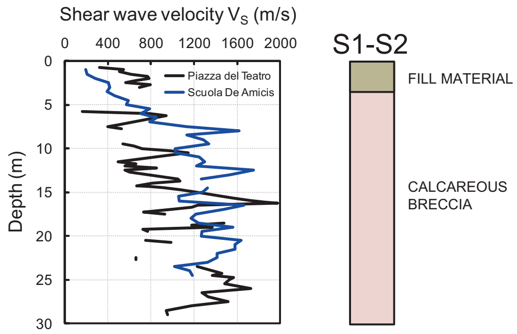

Figure 10. Profile of V_S measured by SDMT in 2 backfilled borehole and schematic soil profile at the site of Piazza del Teatro—Scuola De Amicis, L'Aquila.

at the site of Madonna del Ponte, located at ≈500 m distance and ≈ 15 m lower elevation, in which the same lacustrine deposit is outcropping. Accounting for the different elevation of the ground surface at the two sites, the V_S values measured by SDMT, mostly comprised between 400 m/s to 600–700 m/s, are in reasonable agreement with the trend of V_S obtained by Cross-Hole at Madonna del Ponte.

Figures 12 to 14 show the profiles of V_S obtained by SDMT in backfilled boreholes at various sites located in the western suburban area of L'Aquila (see Fig. 3), in the densely populated districts of Coppito (San Salvatore Hospital, Fig. 12), Cansatessa (Via Solaria, Fig. 13) and Pettino (Via Sila Persichelli, Fig. 14). These recently developed residential districts, generally composed of 3–6 storey reinforced concrete frame buildings, were also considerably damaged by the earthquake. The sites investigated in these area are mostly characterized by the presence of coarse-grained soils (calcareous gravel in sandy-silty matrix or sand). The V_S measured at the above sites are generally ≈ 400–600 m/s to 1000 m/s or higher, increasing with depth.

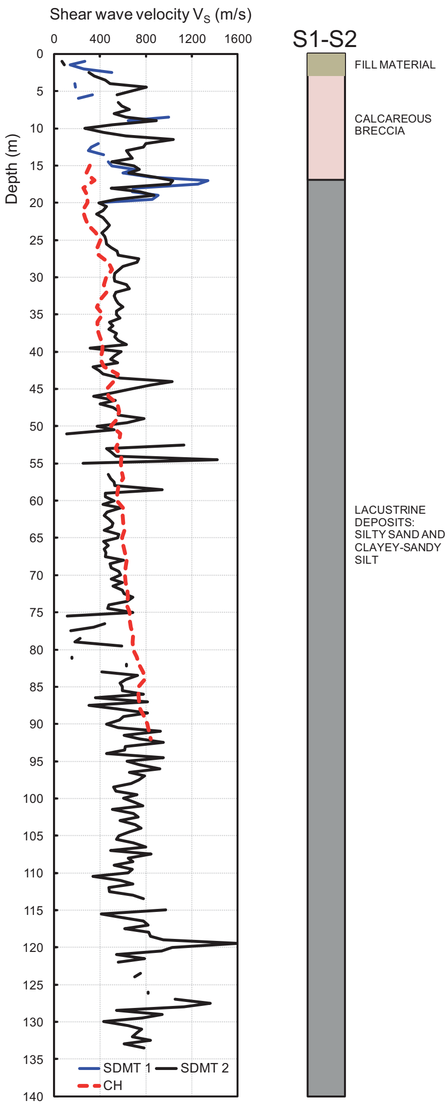

Figure 11. Profiles of V_S measured by SDMT in 2 backfilled boreholes, V_S measured by Cross-Hole in a nearby site (Cardarelli & Cercato 2010) and schematic soil profile at the site of Fontana 99 Cannelle, L'Aquila.

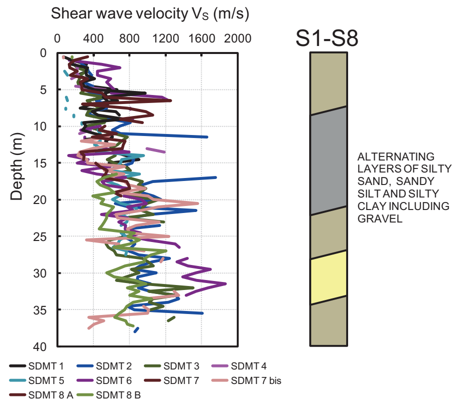

Figure 12. Profiles of V_S measured by SDMT in 8 backfilled boreholes and schematic soil profile at the site of San Salvatore Hospital (Coppito), L'Aquila.

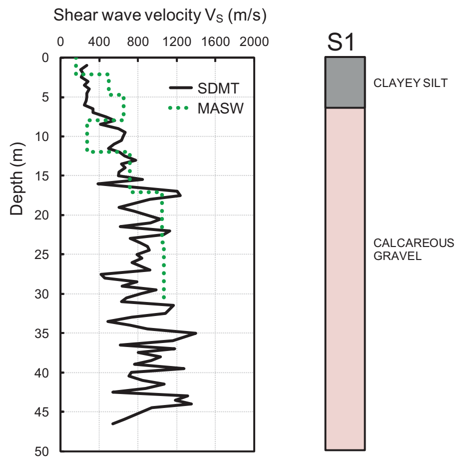

Figure 13. Profile of V_S measured by SDMT in a backfilled borehole, V_S measured by MASW (IAMC-CNR, MS–AQ Working Group 2010) and schematic soil profile at the site of Via Solaria (Cansatessa), L'Aquila.

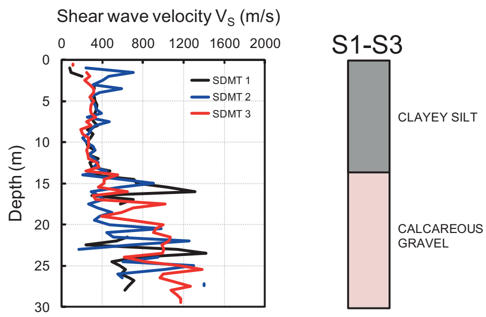

Figure 14. Profile of V_S measured by SDMT in 3 backfilled boreholes and schematic soil profile at the site of Via Sila Persichelli (Pettino), L'Aquila.

In Figure 13 the profile of V_S obtained by SDMT is compared to the V_S profile obtained by surface waves tests (MASW) executed at the same site by IAMC-CNR for the seismic microzonation study (MS–AQ Working Group 2010). At this site the V_S profiles by SDMT and MASW were found in acceptable agreement.

At some sites in the area of Pettino (Via Sila Persichelli, Fig. 14), characterized by the presence of an upper layer of soft silty-clayey sediments of maximum thickness ≈10–15 m overlying stiff gravel, the profiles of V_S obtained by SDMT clearly identified a contrast of shear wave velocity—potential source of local amplification of the ground motion—between the upper soft clay layer ($V_S \approx 300$ m/s) and the lower gravel layer ($V_S \approx 600$–900 m/s).

Additional SDMT results obtained by the backfilling procedure in the area of L'Aquila are presented by Amoroso et al. (2011).

The V_S profiles obtained by SDMT illustrated in this section have been used to define the input data for site seismic response analyses. Monaco et al. (2011b) presented the results of numerical analyses carried out to assess the different seismic response of two sites, one located in L'Aquila city center (Palazzo Camponeschi, Fig. 7) and one in the Pettino district (Via Sila Persichelli, Fig. 14). These two areas—both severely damaged by the April 6, 2009 earthquake—are characterized by substantially different subsoil conditions. Basically, in the city center the subsoil is characterized by an inversion of the shear wave velocity with depth, at the transition from the breccias to the lacustrine silts, and the bedrock (*geological* and *seismic*) is over 300 m deep. In contrast in the area of Pettino the shear wave velocity increases with depth and the *seismic* bedrock (V_S > 800 m/s) is frequently encountered at ≈20 m depth or less, often in combination with significant contrasts of V_S at the shallow contact silty clay/gravel. The results presented by Monaco et al. (2011b) confirm that site effects, related to different subsoil conditions, played an important role in the observed non-uniform damage distribution due to the April 6, 2009 earthquake—in agreement with comparisons of strong motion recordings of the main shock at different stations and with the results of the seismic microzonation study (MS–AQ Working Group 2010).

4 ESTIMATES OF V_S FROM MECHANICAL DMT DATA

The SDMT (by the standard penetration procedure) provides routinely, at each test depth, both the *small strain* shear modulus G_0 (obtained as $G_0 = \rho V_S{}^2$) and the *working strain* constrained modulus M_{DMT} (obtained from the usual DMT interpretation—as supported by the good agreement observed in a large number of well documented comparisons between measured and DMT-predicted settlements or moduli, see Marchetti et al. 2008).

The experimental interrelationship between G_0 and M_{DMT} is illustrated in the diagram in Figure 15—where the ratio G_0/M_{DMT} is plotted vs. the DMT horizontal stress index K_D (related to OCR)—constructed by Monaco et al. (2009) using the SDMT results at 34 different sites, in a variety of soil types.

As a general rule it is obviously advisable to measure V_S directly. However Figure 15 might turn out helpful to obtain rough estimates of V_S (via G_0) at sites where V_S has not been measured and only mechanical DMT results are available. Examples of application of Figure 15 for obtaining rough estimates of V_S at various sites in the area of L'Aquila where V_S was not measured directly, but data files from past mechanical DMT investigations were available, are presented by Monaco et al. (2012).

The comparisons shown in Figure 16 indicate a good agreement between the profiles of V_S measured directly by SDMT (black solid line) and V_S estimated from mechanical DMT data (blue dashed line) obtained in the same SDMT sounding, using the correlations in Figure 15, at six sites in the area of L'Aquila investigated by the penetration procedure.

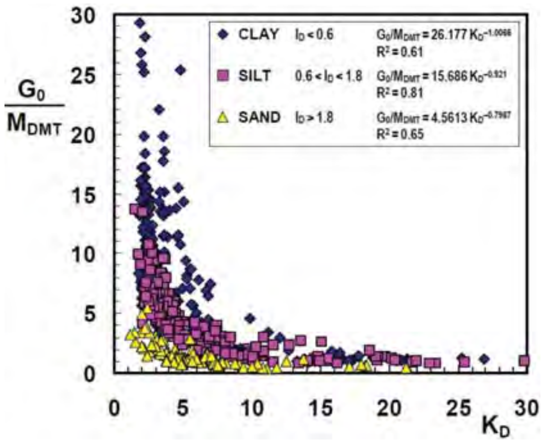

Figure 15. Ratio G_0/M_{DMT} vs. K_D (OCR) for various soil types (Monaco et al. 2009).

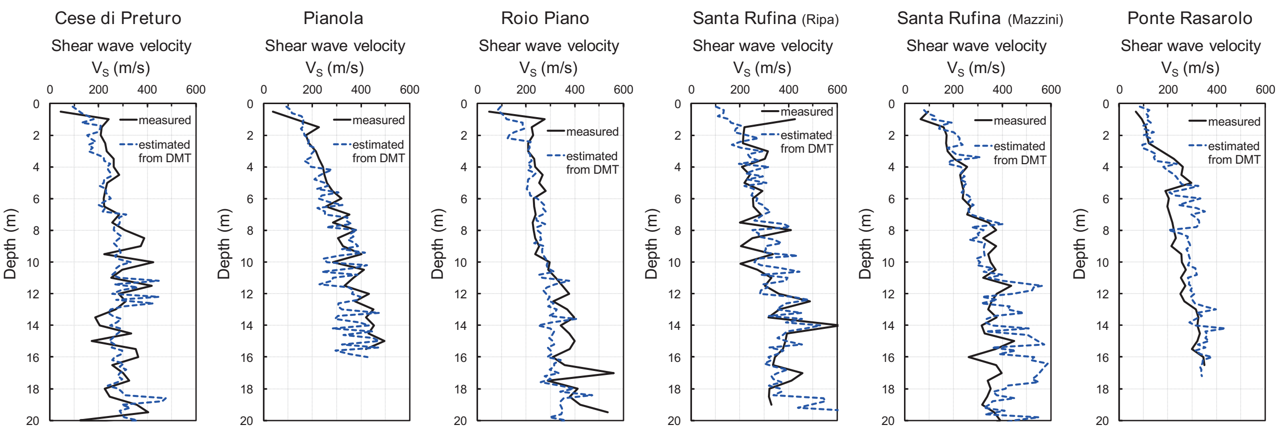

Figure 16. Comparison of profiles of V_S measured by SDMT and estimated from mechanical DMT data, by use of the correlations in Figure 15, at six sites in the area of L'Aquila.

5 CONCLUSIONS

A large number of seismic dilatometer tests were executed in the area of L'Aquila following the April 6, 2009 earthquake. The SDMT results provided useful data for the geotechnical characterization of new temporary residential sites (C.A.S.E. Project), for the seismic microzonation of the area and for site seismic response analyses aimed at design of restoration/retrofitting of important public buildings, particularly in the historic center of L'Aquila.

Due to the characteristics of the soils generally encountered in the area of L'Aquila, mostly coarse-grained, the seismic dilatometer tests were executed by the normal penetration procedure only in a limited number of sites. However the backfilling procedure permitted to obtain V_S profiles by SDMT also in non-penetrable soils at several sites, both in the city center and in the suburban area of L'Aquila. In some cases the backfilling procedure permitted to obtain V_S measurements by SDMT down to very large depths (≈70 to 130 m), by use of the "stacking" technique for interpreting the SDMT seismograms in case of low signal/noise ratio.

If only mechanical DMT results are available, e.g. from past investigations, rough estimates of V_S (from G_0) can be obtained using the correlations in Figure 15 (Monaco et al. 2009). Comparisons of profiles of V_S measured by SDMT and estimated from mechanical DMT data at different sites in the area of L'Aquila, showing a good agreement, are presented in the paper.

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