Site characterization by seismic dilatometer (SDMT) in the city of L'Aquila

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Sommario

This paper presents a review of results obtained by a large number of seismic dilatometer tests (SDMT) carried out in the area of L'Aquila (central Italy), after the April 6, 2009 earthquake. Due to the characteristics of the soils (mostly coarse-grained, non-penetrable materials), SDMT measurements were generally performed in backfilled boreholes, using the technique briefly described; in these conditions only the shear wave velocity VS, without the other DMT parameters, was measured. The test results illustrated in the paper include: (a) SDMT typical results obtained by the normal penetration procedure (in a limited number of sites, mostly silts); (b) VS-only profiles obtained by the backfilled borehole procedure; (c) comparisons of VS profiles obtained by SDMT and by other techniques (Down-Hole, Cross-Hole, surface waves tests); (d) comparisons of VS measured by SDMT and those estimated from mechanical DMT data. The VS profiles provided by SDMT, combined with the information obtained from geological data and from other investigations, including boreholes down to a maximum depth of 300 m in the city centre, have been used for the soil characterization in numerical seismic response analyses. An example is illustrated in the paper.

1. Introduction

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

Subsequently the area of L'Aquila has been extensively investigated by several different geotechnical and geophysical testing techniques, involving numerous working groups [see e.g. Monaco *et al.*, 2012; Santucci de Magistris *et al.*, this journal].

This paper presents a review of results of site investigations carried out by the geotechnical research group of the University of L'Aquila in the period 2009-2012, including a large number of seismic dilatometer tests (SDMT). Some of these tests were carried out in the aftermath of the earthquake, as part of first-emergency field activities promoted by the Italian Department of Civil Protection, aimed at the geotechnical characterization of new temporary housing sites for the homeless people (C.A.S.E.) and at the seismic microzonation of the area of L'Aquila [MS–AQ Working Group, 2010]. In the following months, several seismic dilatometer tests were executed, both in the historic city centre and in 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.

Additional investigations, promoted by the University of L'Aquila – CERFIS (Centre for Research and Education in Earthquake Engineering), include deep investigations in the city centre, in particular a 300 m deep borehole in Piazza Duomo and a 195 m deep borehole at the site of Madonna del Ponte [Amoroso *et al.*, 2010], aimed at investigating the soil profile down to the bedrock, on the basis of the known geology of the area.

The SDMT results presented in this paper, combined with geological information and data from other investigations, could possibly help in defining the soil characterization for numerical seismic response analyses in different areas of the city of L'Aquila.

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2. Seismic dilatometer test (SDMT)

2.1 SDMT: 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 AND 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 the 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. The shear wave generated at the surface reaches first the upper receiver, then, after a certain delay, the lower receiver (Fig. 1b). The seismograms acquired by the two receivers, amplified and digitized at depth, are visualized on a PC in real time, and the time delay between the signals is determined immediately. 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 time delay between the arrivals of the impulse at the two receivers (Δt). 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 the two receivers, avoids possible inaccuracy in the determination of the "zero time" at the hammer impact, which is necessary if the one-receiver configuration is utilized. Moreover, the couple of seismograms recorded by the two receivers at a given test depth corresponds to the same hammer blow (i.e. same generated waves) 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 time 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 Fig. 1c.

V_S measurements by SDMT have been validated by several comparisons with V_S measured by other in situ techniques at various research sites, as reported by MARCHETTI *et al.* (2008). Besides V_S, the seismic dilatometer provides the parameters obtained by the classical flat dilatometer interpretation [MARCHETTI, 1980; MARCHETTI *et al.*, 2001].

2.2 SDMT: backfilling procedure in non-penetrable soils

The SDMT 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 before testing). A disadvantage of the SDMT is the impossibility of penetrating very hard soils. However a procedure for obtaining V_S profiles – but not the other DMT parameters – in non-penetrable soils (e.g. in gravel, or even in rock)

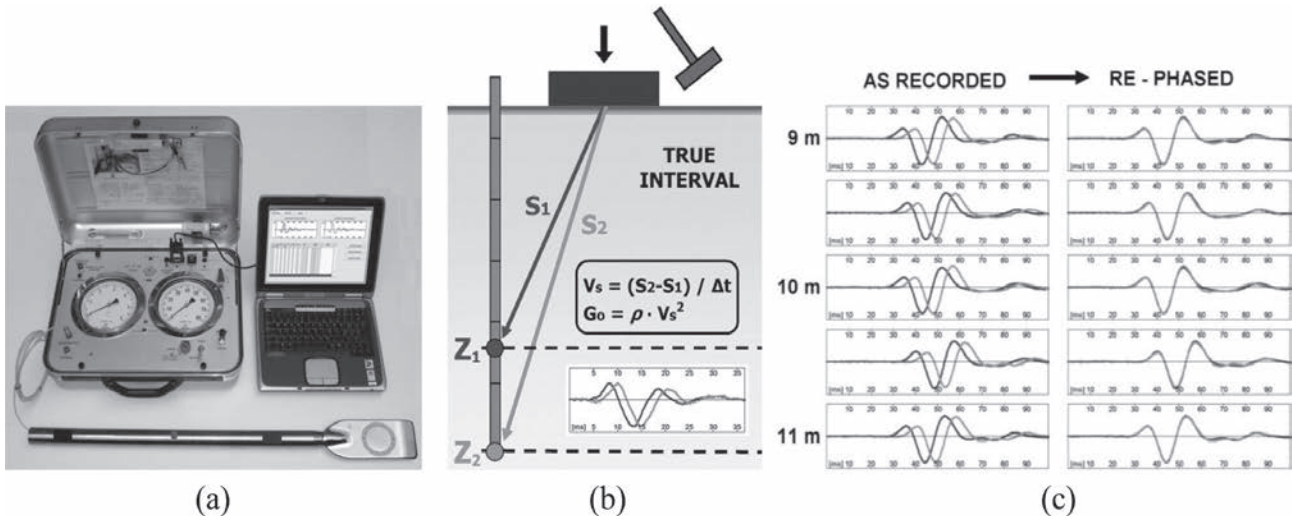

Fig. 1 – Seismic dilatometer test. (a) DMT blade and seismic module. (b) Schematic test layout. (c) Example of seismograms obtained by SDMT.

Fig. 1 – Prova con dilatometro sismico. (a) Lama DMT e modulo sismico. (b) Schema della prova. (c) Esempio di sismogrammi ottenuti da SDMT.

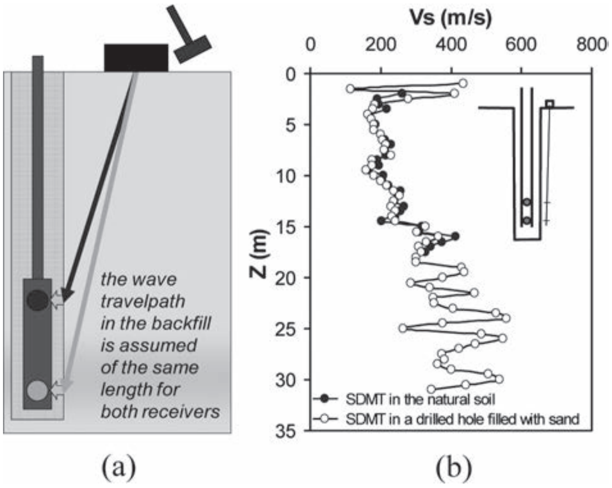

Fig. 2 – V_S measurements by SDMT in backfilled boreholes in non-penetrable soils. (a) Schematic test layout and basis of the method. (b) Validation of the method: comparison of V_S profiles obtained by SDMT in a backfilled borehole and by penetrating the natural soil [after TOTANI *et al.*, 2009].

Fig. 2 – Misure di V_S con SDMT in fori riempiti di sabbia in terreni non penetrabili. (a) Schema della prova e base del metodo. (b) Validazione del metodo: confronto tra profili di V_S ottenuti da SDMT in un foro riempito di sabbia e mediante penetrazione nel terreno naturale [da TOTANI et al., 2009].

has been devised by TOTANI *et al.* (2009). The procedure is the following (Fig. 2):

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.

In this procedure the dilatometer acts only as a vehicle for inserting the seismic module. The method for measuring V_S is similar to a two-receiver Down-Hole test, except for the technique used to fix the receivers to the soil around the borehole (backfilling instead of casing) and for the insertion equipment.

The possibility of such V_S measurement descends from the fact that the wave travelpath from the surface to the upper and lower receiver includes a short path in the backfill which is assumed, in first approximation, to be of the same length (Fig. 2a), i.e. the time delay Δt does not change. Comparative tests at various sites where both the usual penetration procedure and the backfilling procedure were adoptable [TOTANI *et al.*, 2009] indicate that V_S values obtained in the backfilled borehole are essentially coincident with the V_S obtained by penetrating the soil (Fig. 2b).

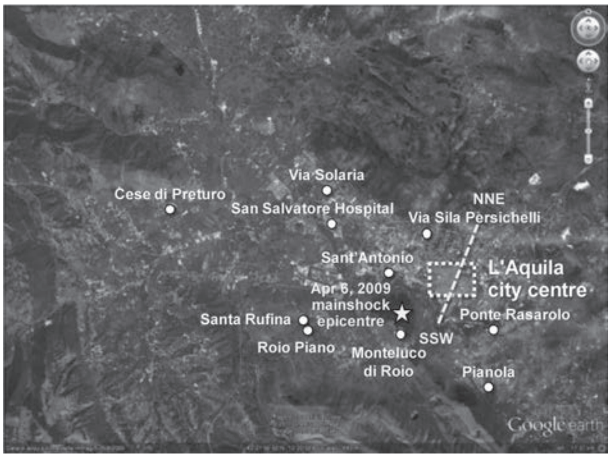

Fig. 3 – (a) Location of the sites investigated by SDMT in the area of L'Aquila. (b) Detail of location of the SDMT test sites in L'Aquila city centre.

Fig. 3 – (a) Ubicazione dei siti indagati con SDMT nell'area dell'Aquila. (b) Particolare dell'ubicazione dei siti di prova SDMT nel centro storico dell'Aquila.

3. SDMT results in the area of L'Aquila

3.1 SDMT test sites

Fig. 3a shows the location of the sites investigated by SDMT in the area of L'Aquila after the April 6, 2009 earthquake. The detail in Fig. 3b shows the location of the SDMT test sites in the city centre, which includes most of the historical heritage and several old masonry buildings, heavily damaged by the earthquake.

The complex geological setting of the L'Aquila basin is extensively described in MS–AQ WORKING GROUP (2010). A basic description can also be found in SANTUCCI DE MAGISTRIS *et al.* (this journal).

In the city centre (see the schematic geological section in Fig. 4) the upper portion of the subsoil is constituted by the deposit known as "Brecce dell'Aquila", composed of fine to coarse calcareous fragments of variable size (mostly of some centime-

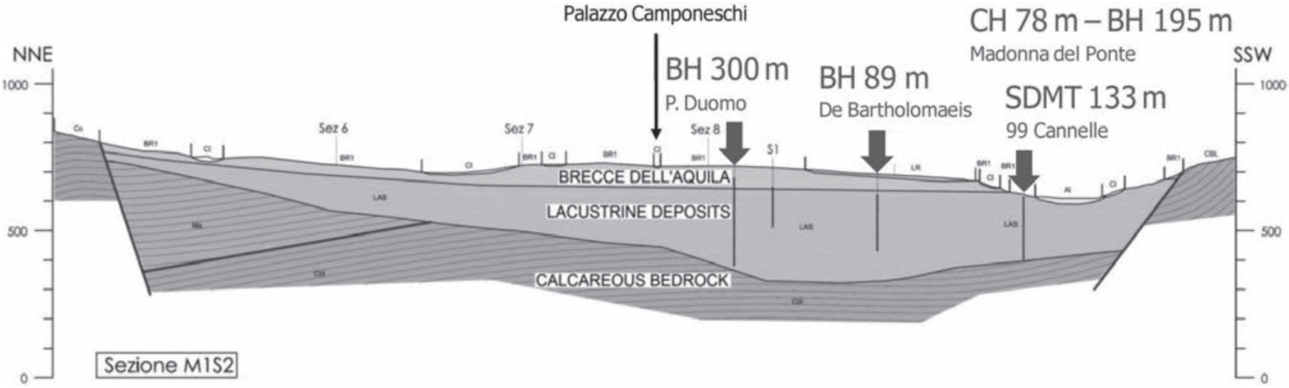

Fig. 4 – Schematic geological section across L'Aquila city centre [modified after MS–AQ WORKING GROUP, 2010], showing the position of deep investigations promoted by University of L'Aquila – CERFIS.
Fig. 4 – Sezione geologica schematica attraverso il centro storico dell'Aquila [modificata a partire da MS–AQ WORKING GROUP, 2010], con indicazione della posizione delle indagini profonde eseguite per conto di Università dell'Aquila – CERFIS.

tres) embedded in sandy or silty matrix (Fig. 5), characterized by highly variable cementation and mechanical properties. The breccias, about 80-100 m thick, lay on fine- to medium-grained, mostly silty lacustrine deposits of average thickness ≈ 250-270 m, placed on the limestone bedrock. Gravimetric investigations [MS–AQ WORKING GROUP, 2010] have indicated that in the city centre the bedrock is located below 300 m depth. This indication has been confirmed directly by deep core-destructive boreholes executed to a maximum depth of 300 m in Piazza Duomo and to 195 m at the site of Madonna del Ponte [AMOROSO *et al.*, 2010; Fig. 6]. Only in the latter site, located at an elevation 100 m lower than Piazza Duomo, the bedrock was encountered at a local depth of 192 m, i.e. at an absolute elevation of 425 m a.s.l..

Whenever possible, in soils ranging from clay to silty sand (silt in the majority of the cases), the seismic

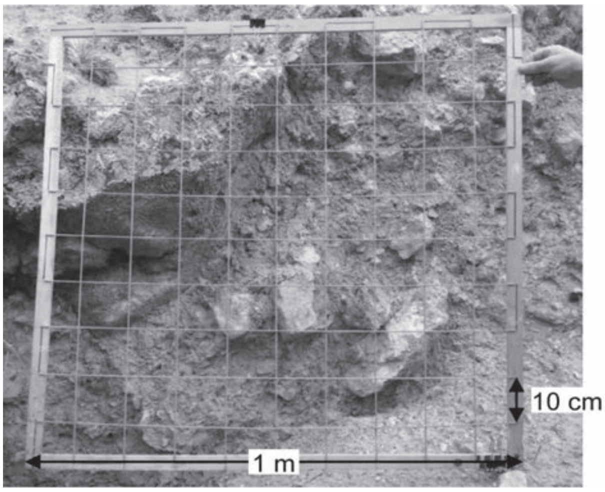

Fig. 5 – Typical composition and grain size distribution of the breccias.
Fig. 5 – Composizione e distribuzione granulometrica tipiche delle brecce.

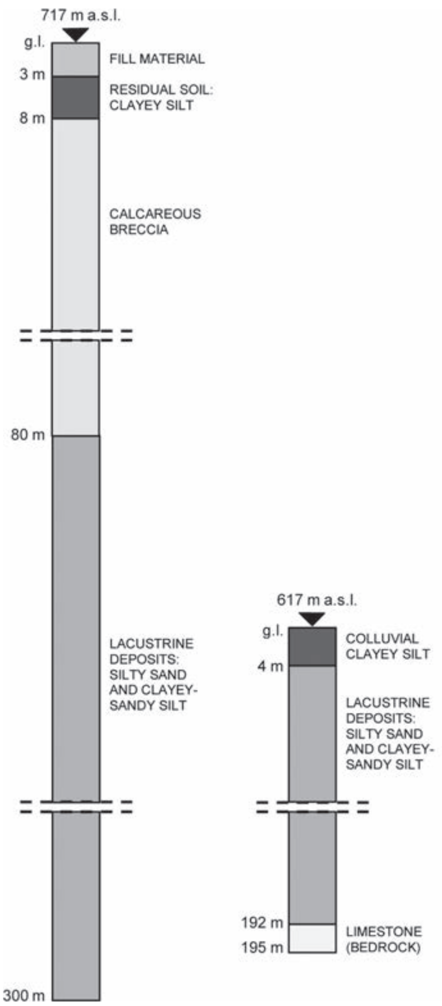

Fig. 6 – Schematic stratigraphic profiles reconstructed from two deep boreholes at the sites of Piazza Duomo (300 m) and Madonna del Ponte (195 m), L'Aquila [after AMOROSO *et al.*, 2010].
Fig. 6 – Profili stratigrafici schematici ricostruiti attraverso due sondaggi profondi a Piazza Duomo (300 m) e Madonna del Ponte (195 m) [da AMOROSO et al., 2010].

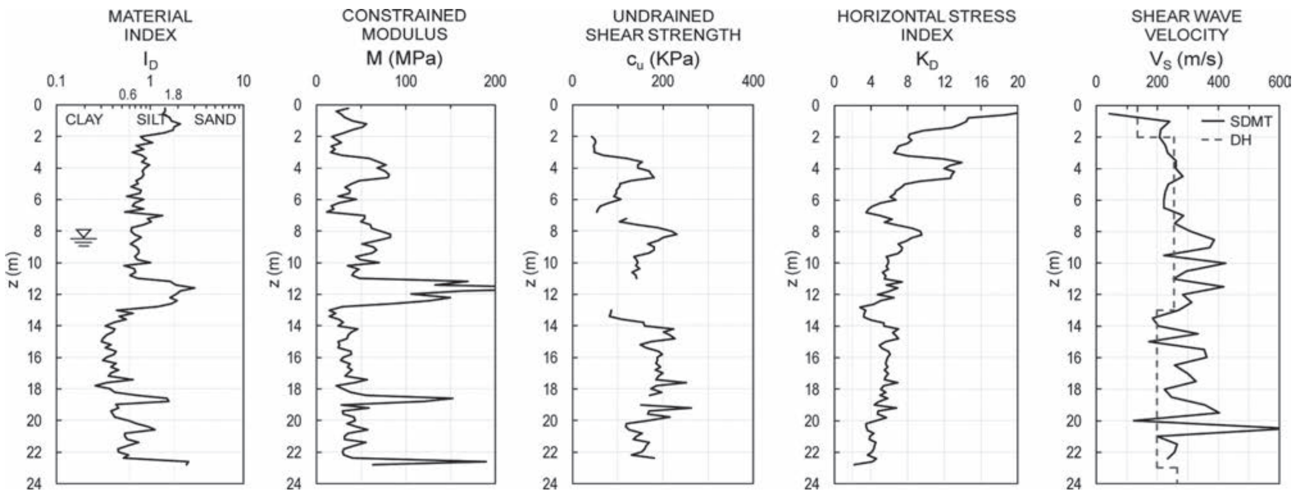

Fig. 7 – SDMT results at the site of Cese di Preturo (C.A.S.E.), L'Aquila. *On the right:* Comparison of profiles of V_S from SDMT and Down-Hole [Polo Geologico, MS–AQ WORKING GROUP, 2010].
Fig. 7 – Risultati SDMT nel sito di Cese di Preturo (C.A.S.E.), L'Aquila. A destra: Confronto tra profili di V_S ottenuti da SDMT e Down-Hole [Polo Geologico, MS–AQ WORKING GROUP, 2010].

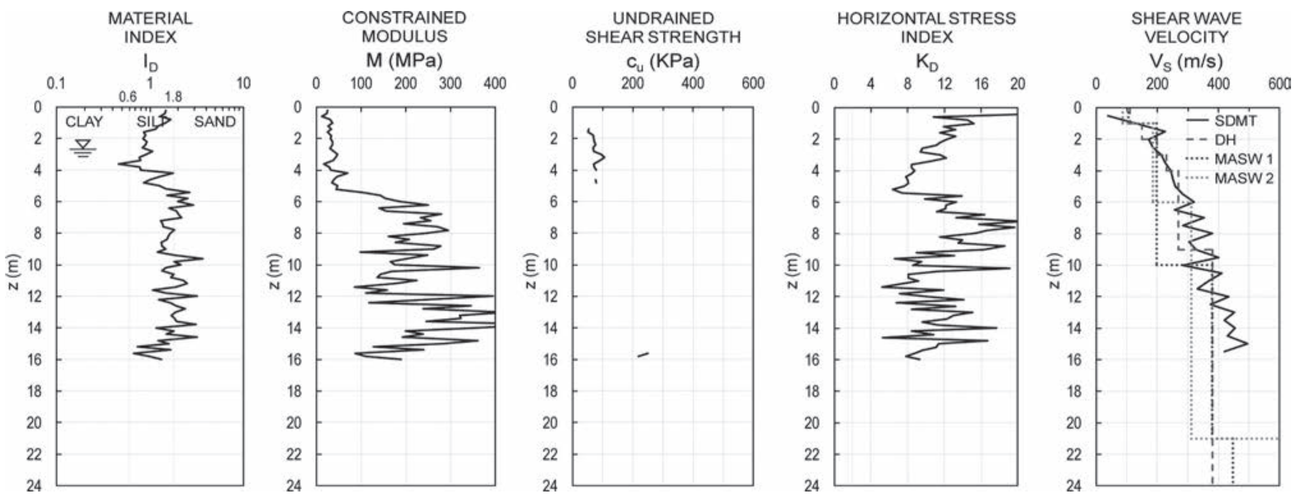

Fig. 8 – SDMT results at the site of Pianola (C.A.S.E.), L'Aquila. *On the right:* Comparison of profiles of V_S from SDMT, Down-Hole (Polo Geologico) and MASW (Politecnico di Torino). DH and MASW data from MS–AQ WORKING GROUP (2010).
Fig. 8 – Risultati SDMT nel sito di Pianola (C.A.S.E.), L'Aquila. A destra: Confronto tra profili di V_S ottenuti da SDMT, Down-Hole (Polo Geologico) e MASW (Politecnico di Torino). Dati DH e MASW da MS–AQ WORKING GROUP (2010).

dilatometer tests were carried out by the classical penetration procedure. However, due to the characteristics of the soils commonly encountered in the area of L'Aquila (mostly coarse-grained, non-penetrable soils), particularly in the city centre, generally V_S-only measurements were performed by use of the SDMT seismic module in backfilled boreholes, according to the TOTANI *et al.* (2009) procedure previously described.

3.2. SDMT results by the penetration procedure

Figs 7 to 11 show SDMT results obtained at various sites investigated by the standard penetration procedure, in fine- to medium-grained soils. The soils, 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 Figs 7 to 11 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; MARCHETTI *et al.*, 2001].

The SDMT results shown in Figs 7, 8 and 9 were obtained at three C.A.S.E. sites (Cese di Preturo, Pi-

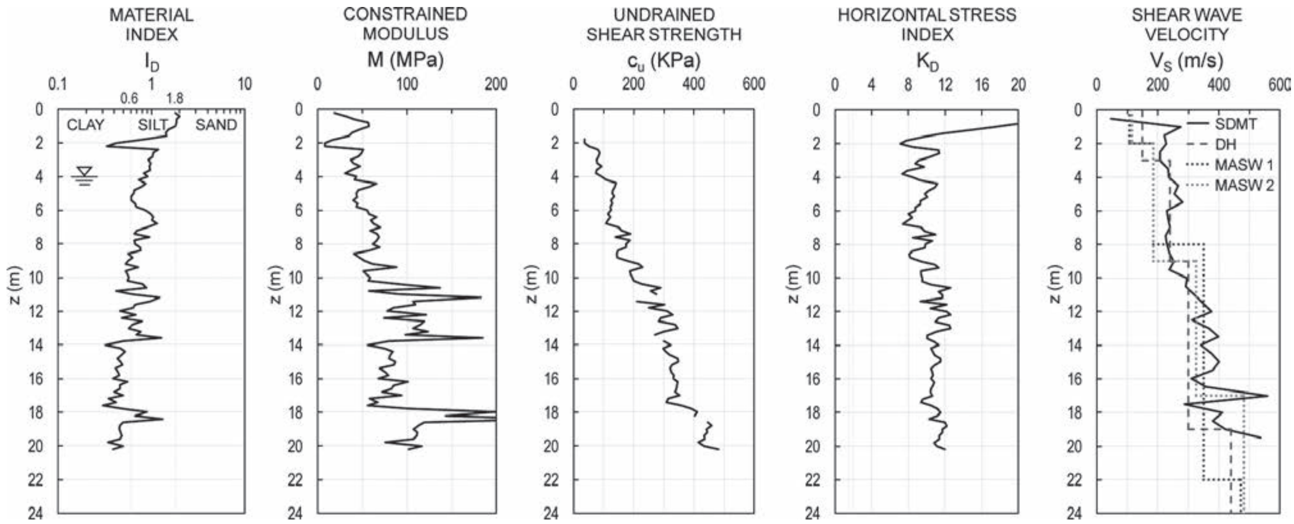

Fig. 9 – SDMT results at the site of Roio Piano (C.A.S.E.), L'Aquila. *On the right:* Comparison of profiles of V_S from SDMT, Down-Hole (Polo Geologico) and MASW (Politecnico di Torino). DH and MASW data from MS–AQ WORKING GROUP (2010); see also SANTUCCI DE MAGISTRIS *et al.* (this journal).

Fig. 9 – Risultati SDMT nel sito di Roio Piano (C.A.S.E.), L'Aquila. A destra: Confronto tra profili di V_S ottenuti da SDMT, Down-Hole (Polo Geologico) e MASW (Politecnico di Torino). Dati DH e MASW da MS–AQ WORKING GROUP (2010); vedi anche SANTUCCI DE MAGISTRIS et al. (in questa rivista).

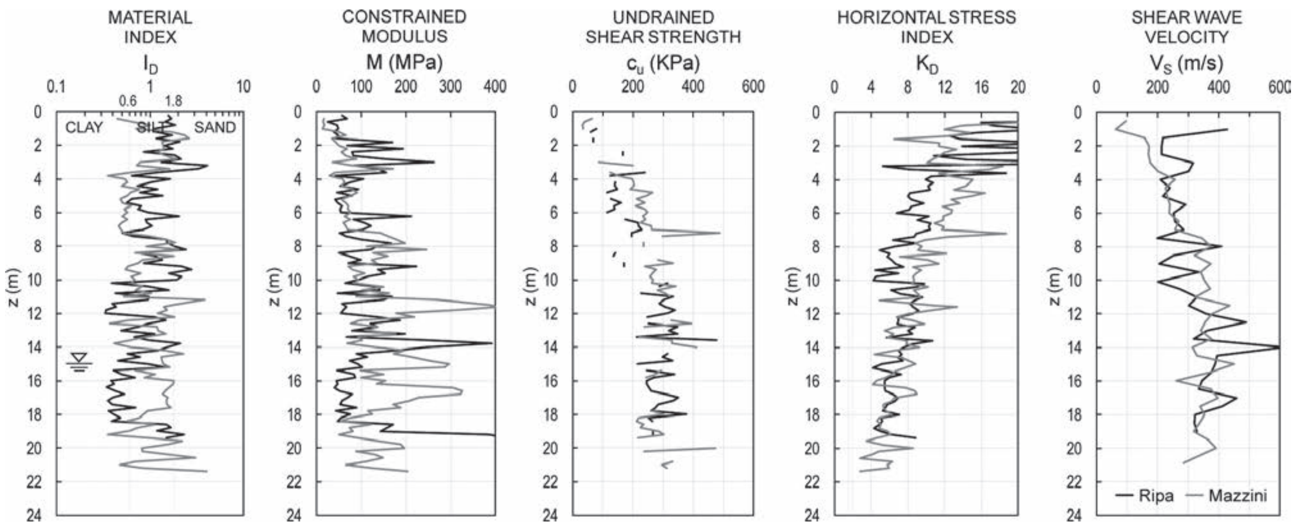

Fig. 10 – SDMT results at two sites in Santa Rufina, Roio, L'Aquila.

Fig. 10 – Risultati SDMT in due siti a Santa Rufina, Roio, L'Aquila.

anola, Roio Piano). The diagrams on the right show the comparison between the V_S profiles obtained by SDMT, by Down-Hole tests (DH), executed by Polo Geologico, and by multi-receiver surface waves tests (MASW), carried out by Politecnico di Torino [see SANTUCCI DE MAGISTRIS *et al.* (this journal) for details]. The results of these tests, entrusted by the Italian Department of Civil Protection, are included in MS–AQ WORKING GROUP (2010). It can be observed that the V_S profiles obtained by SDMT are generally in satisfactory agreement with the V_S profiles obtained by Down-Hole and MASW.

Other SDMT results obtained by the penetration procedure are illustrated in Fig. 10 (Santa Rufina, Roio) and in Fig. 11 (Ponte Rasarolo). In the latter site, located near the Aterno riverside, liquefaction and lateral spreading phenomena were triggered by the April 6, 2009 earthquake, as detected by AYDAN *et al.* (2009). Another case of liquefaction triggered by the earthquake main shock at Vittorito (≈ 45 km far from the epicentre), and analyzed by use of SDMT results, was presented by MONACO *et al.* (2011a).

In general, at all sites investigated by the penetration procedure the maximum testing depth (lim-

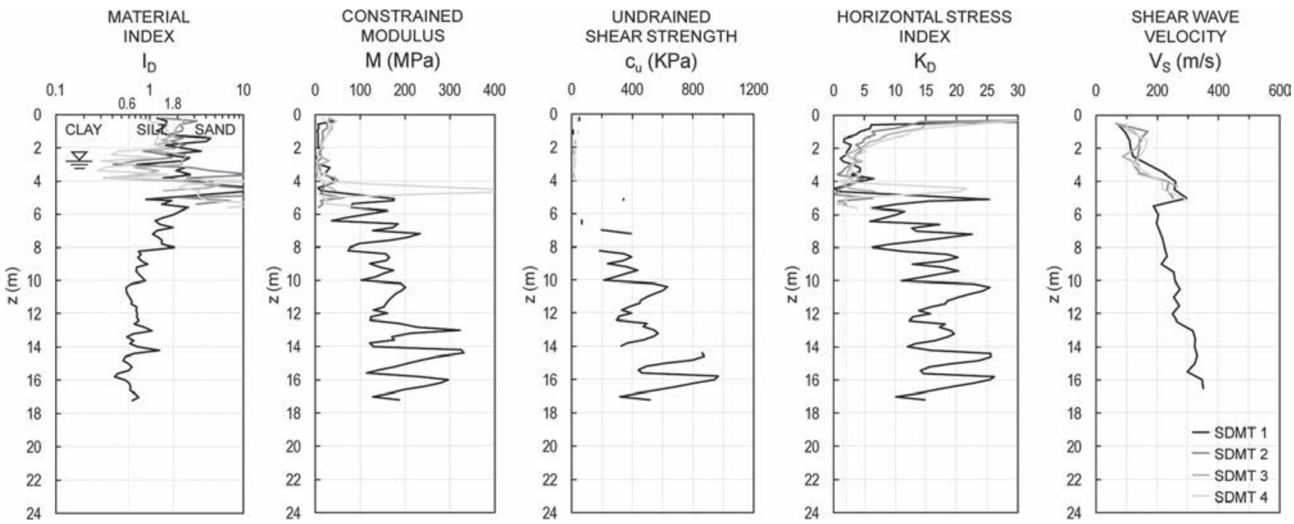

Fig. 11 – SDMT results at the liquefaction site of Ponte Rasarolo, L'Aquila.
Fig. 11 – Risultati SDMT nel sito di liquefazione di Ponte Rasarolo, L'Aquila.

ited by the capacity of the penetrometer rig) was ≈ 16 to 23 m. The measured V_S values seldom exceed 400 m/s within ≈ 20 m depth.

3.3. V_S measurements by the backfilling procedure in non-penetrable soils

Figs 12 to 24 show the profiles of V_S obtained by use of the SDMT seismic module in backfilled boreholes (no DMT parameters), in non-penetrable soils, at various sites in the area of L'Aquila.

In particular, Figs 12 to 19 show the V_S profiles and the schematic stratigraphic profiles at various sites in the city centre (see location in Fig. 3b). At all the sites the upper portion of the subsoil belongs to the "Brecce dell'Aquila" formation. It can be noted that the values of V_S in the breccias (down to a maximum depth of 74 m at Palazzo Camponeschi, Fig. 12) are mostly 600-1000 m/s or higher, generally increasing with depth. It is supposed that the observed dispersion of the measured V_S could possibly reflect some variability in grain size distribution, cementation and/or mechanical properties typical of this material. This assumption relies on "visual experience" rather than on comparisons with experimental results of in situ or laboratory tests. On the other hand, since the breccias typically include calcareous fragments of up to some centimetres of size, irregularly embedded in the sandy-silty matrix (see example in Fig. 5), it is extremely difficult to characterize this material by any in situ method other than geophysical methods, and laboratory testing is precluded by the difficulty of sampling.

Fine-grained residual soils, locally known as "Terre rosse" (red soils), are frequently encountered in the upper ≈ 8 to 15 m of breccias, particularly in

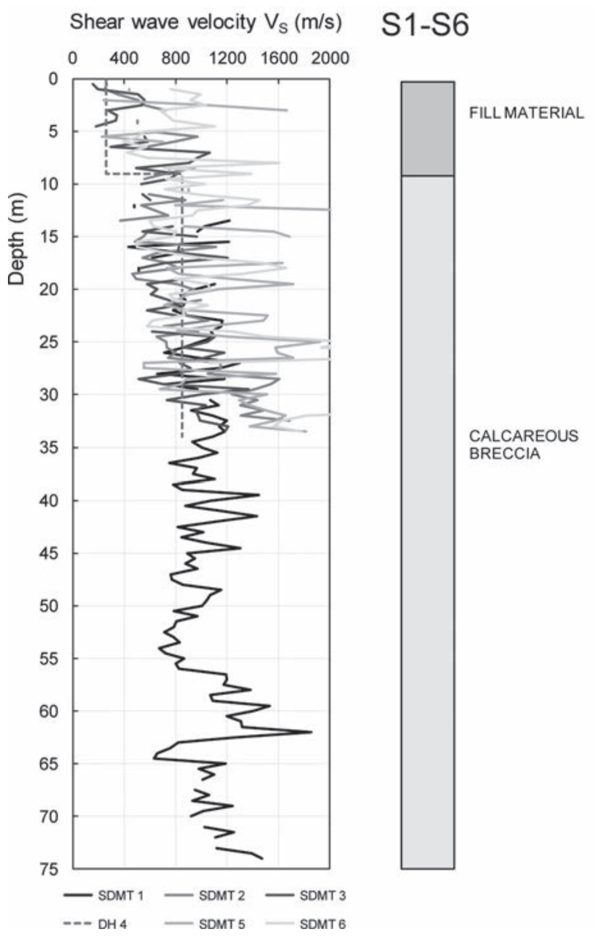

Fig. 12 – Profiles of V_S measured by SDMT in 5 backfilled boreholes, V_S measured by Down-Hole and schematic stratigraphy at the site of Palazzo Camponeschi, L'Aquila.
Fig. 12 – Profili di V_S misurata mediante SDMT in 5 fori riempiti di sabbia, V_S misurata mediante Down-Hole e profilo stratigrafico schematico nel sito di Palazzo Camponeschi, L'Aquila.

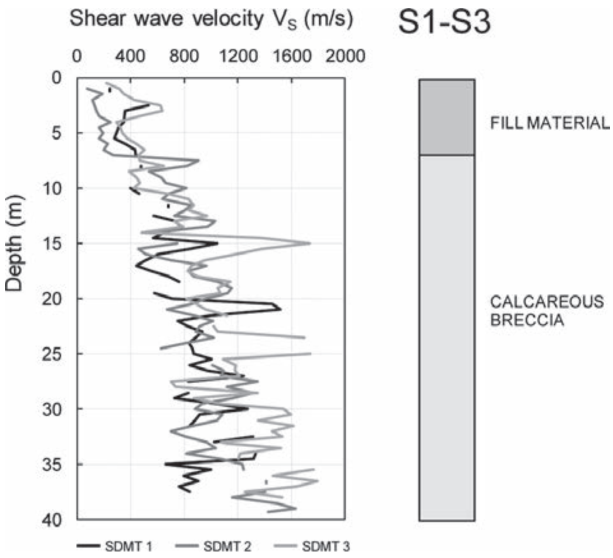

Fig. 13 – Profiles of V_S measured by SDMT in 3 backfilled boreholes and schematic stratigraphy at the site of Palazzo Carli, L'Aquila.

Fig. 13 – Profili di V_S misurata mediante SDMT in 3 fori riempiti di sabbia e profilo stratigrafico schematico nel sito di Palazzo Carli, L'Aquila.

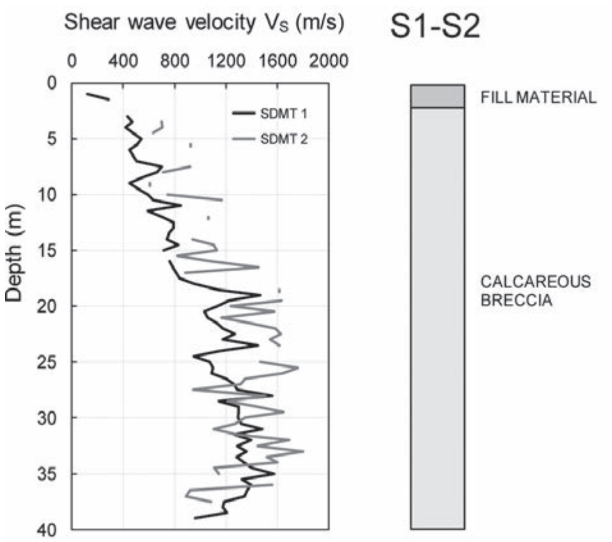

Fig. 14 – Profiles of V_S measured by SDMT in 2 backfilled boreholes and schematic stratigraphy at the site of Palazzo Margherita, L'Aquila.

Fig. 14 – Profili di V_S misurata mediante SDMT in 2 fori riempiti di sabbia e profilo stratigrafico schematico nel sito di Palazzo Margherita, L'Aquila.

the Southern part of the city centre. The V_S values measured in the "Terre rosse" are typically ≈ 400 m/s (see e.g. Figs 17 and 18). Lower values (V_S ≈ 200-300 m/s) have been locally measured in shallow filling materials (in several cases man-made fills discovered in the city centre are supposed to originate from dis-

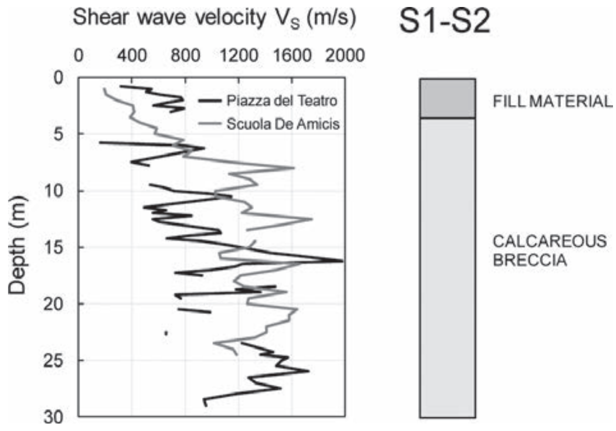

Fig. 15 – Profiles of V_S measured by SDMT in 2 backfilled boreholes and schematic stratigraphy at the site of Piazza del Teatro – Scuola De Amicis, L'Aquila.

Fig. 15 – Profili di V_S misurata mediante SDMT in 2 fori riempiti di sabbia e profilo stratigrafico schematico nel sito di Piazza del Teatro – Scuola De Amicis, L'Aquila.

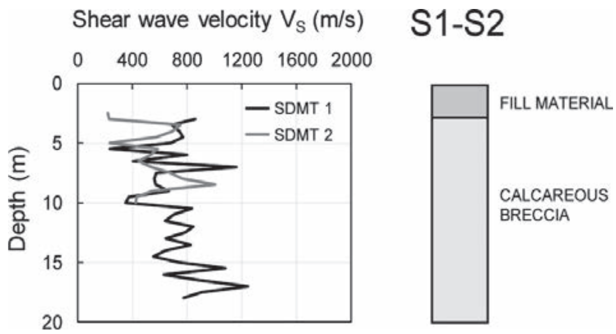

Fig. 16 – Profiles of V_S measured by SDMT in 2 backfilled boreholes and schematic stratigraphy at the site of Complesso Santa Teresa, L'Aquila.

Fig. 16 – Profili di V_S misurata mediante SDMT in 2 fori riempiti di sabbia e profilo stratigrafico schematico nel sito del Complesso Santa Teresa, L'Aquila.

posal of rubbles of masonry buildings destroyed in past earthquakes, namely in the 1703 earthquake).

The lacustrine silty deposit underlying the "Brecce dell'Aquila" was investigated by SDMT at the site of Fontana 99 Cannelle, located at an elevation ≈ 90 m lower than Piazza Duomo, near the South-Western border of the city centre (see Fig. 4). Here the thickness of the breccias reduces to 15-20 m or less (Fig. 19). The backfilling procedure permitted to obtain SDMT measurements down to a depth of 133 m. Below ≈ 100 m depth the signal/noise ratio of the SDMT seismograms was too low to permit the V_S determination 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,

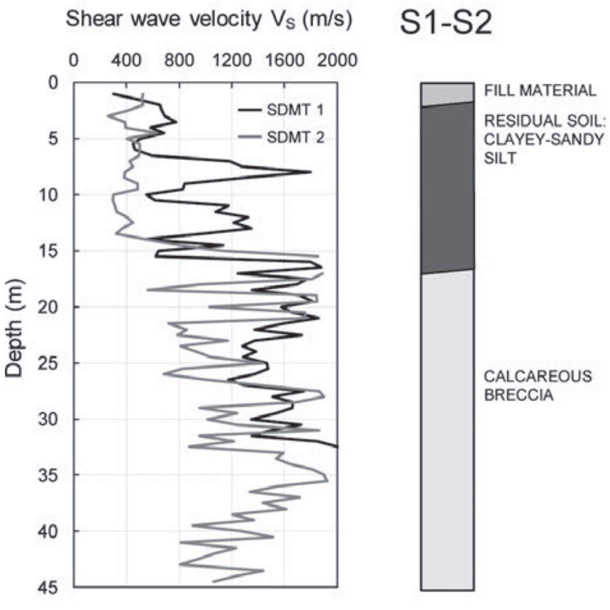

Fig. 17 – Profiles of V_S measured by SDMT in 2 backfilled boreholes and schematic stratigraphy at the site of Palazzo Centi, L'Aquila.

Fig. 17 – Profili di V_S misurata mediante SDMT in 2 fori riempiti di sabbia e profilo stratigrafico schematico nel sito di Palazzo Centi, L'Aquila.

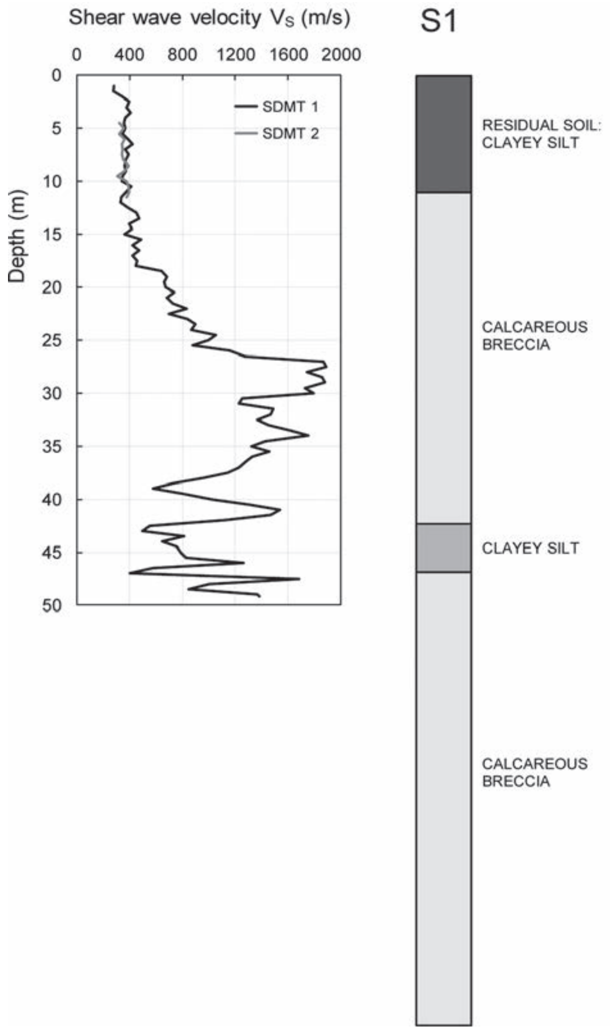

Fig. 18 – Profile of V_S measured by SDMT in a backfilled borehole (89 m) and schematic stratigraphy at the site of Via De Bartholomaeis, L'Aquila.

Fig. 18 – Profilo di V_S misurata mediante SDMT in un foro riempito di sabbia (89 m) e profilo stratigrafico schematico nel sito di Via De Bartholomaeis, L'Aquila.

while the energy of the noise, having a zero mean value, remains about the same). In the same Fig. 19, the profile of V_S measured by a Cross-Hole test (CH) in a site nearby is reported. The CH test, carried out by CARDARELLI AND CERCATO (2010), was performed down to a depth of 78 m at the site of Madonna del Ponte, where the same lacustrine deposit is outcropping, at about 500 m distance and ≈ 15 m lower elevation with respect to Fontana 99 Cannelle. Accounting for the different elevation of the two sites, the V_S measured by SDMT, mostly ranging between 400 and 600-700 m/s, are in reasonable agreement with those obtained by Cross-Hole at Madonna del Ponte.

Figs 20 to 23 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. 3a), in the densely populated districts of Coppito (San Salvatore Hospital, Fig. 20), Pile (Sant'Antonio, Fig. 21), Cansatessa (Via Solaria, Fig. 22) and Pettino (Via Sila Persichelli, Fig. 23). These recently developed residential/commercial districts, generally composed of 3-6 storey reinforced concrete frame buildings, were considerably damaged by the earthquake. The sites investigated in this area are mostly characterized by the presence of coarse-grained soils (calcareous gravel in sandy-silty matrix or sand). The V_S values measured at the above sites generally range between 400-600 m/s and more than 1000 m/s, increasing with depth.

In Fig. 22 the profile of V_S obtained by SDMT is compared to the V_S profile obtained by surface waves tests (MASW) carried out at the same site by IAMC-CNR [MS–AQ WORKING GROUP, 2010]; the two V_S profiles show to be in good agreement between 12.5 m and 17 m depth, while they differ substantially above 12.5 m and below 17 m depth, where the average V_S from SDMT is about 20% lower than V_S from MASW.

At the site of Via Sila Persichelli, Pettino (Fig. 23), characterized by the presence of an upper soft silty clay layer overlying stiff gravel, the profiles of V_S obtained by SDMT 1 and SDMT 3 clearly identified a contrast of shear wave velocity between the upper soft clay layer (V_S ≈ 300 m/s) and the lower gravel layer (V_S ≈ 600-900 m/s) at about 15-17 m depth; this velocity contrast is a potential source of local amplification of the ground motion. In SDMT 2 V_S increases with depth down to about 23-24 m, when the gravel layer is encountered. Such difference in the

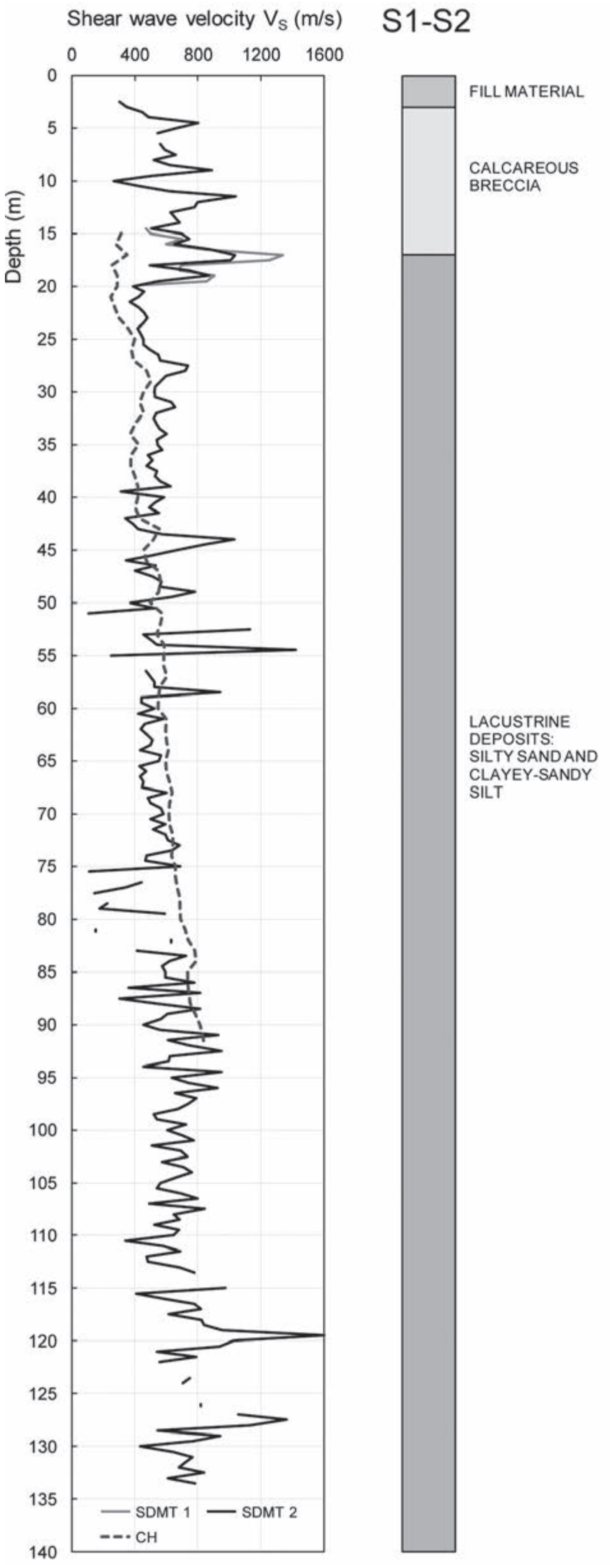

Fig. 19 – Profiles of V_S measured by SDMT in 2 backfilled boreholes, V_S measured by Cross-Hole in a nearby site [CARDARELLI AND CERCATO, 2010] and schematic stratigraphy at the site of Fontana 99 Cannelle, L'Aquila.

Fig. 19 – Profili di V_S misurata mediante SDMT in 2 fori riempiti di sabbia, V_S misurata mediante Cross-Hole in un sito vicino [CARDARELLI AND CERCATO, 2010] e profilo stratigrafico schematico nel sito della Fontana 99 Cannelle, L'Aquila.

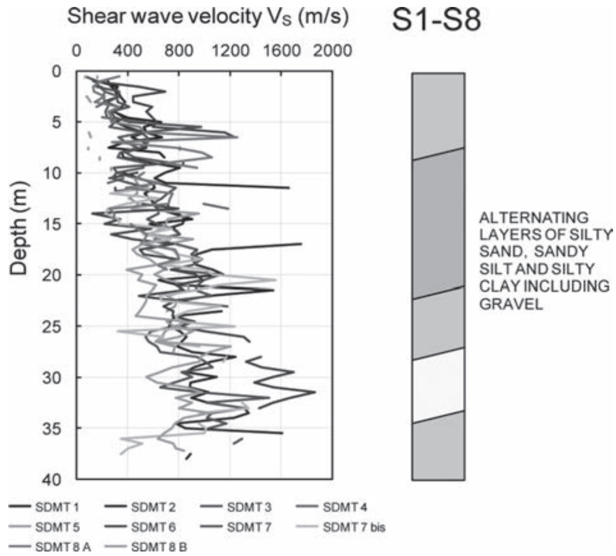

Fig. 20 – Profiles of V_S measured by SDMT in 8 backfilled boreholes and schematic stratigraphy at the site of San Salvatore Hospital (Coppito), L'Aquila.

Fig. 20 – Profili di V_S misurata mediante SDMT in 8 fori riempiti di sabbia e profilo stratigrafico schematico nel sito dell'Ospedale San Salvatore (Coppito), L'Aquila.

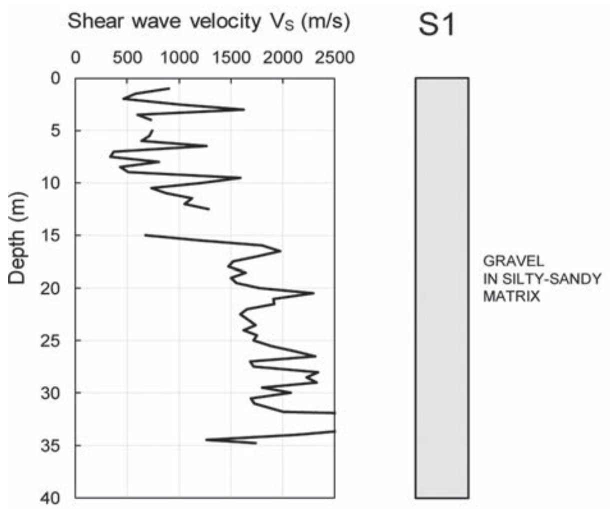

Fig. 21 – Profiles of V_S measured by SDMT in a backfilled borehole and schematic stratigraphy at the site of Sant'Antonio (Pile), L'Aquila.

Fig. 21 – Profili di V_S misurata mediante SDMT in un foro riempito di sabbia e profilo stratigrafico schematico nel sito di Sant'Antonio (Pile), L'Aquila.

V_S profiles at the same site reflects the variability in thickness of the upper soft clay layer (colluvial sediments filling the bottom of buried valleys), which typically in the Pettino area may range from zero, or a few metres, to 20-25 m even within a short distance.

Fig. 24 shows the profiles of V_S obtained by SDMT in two backfilled boreholes at the site of the Fac-

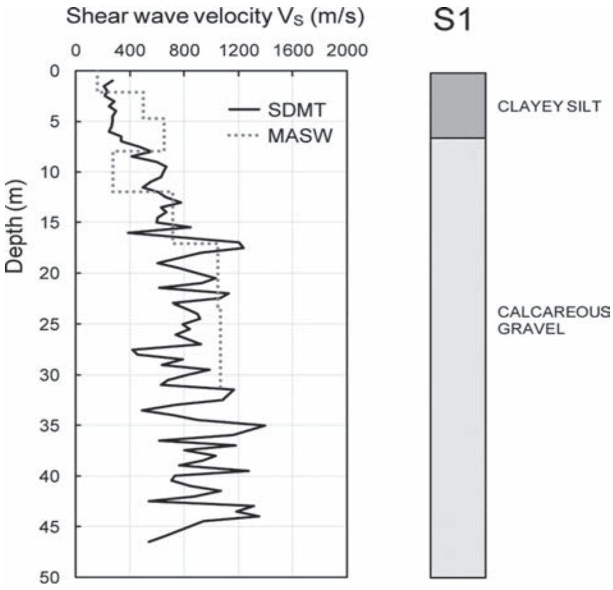

Fig. 22 – Profile of V_S measured by SDMT in a backfilled borehole, V_S measured by MASW [IAMC-CNR, MS–AQ WORKING GROUP, 2010] and schematic stratigraphy at the site of Via Solaria (Cansatessa), L'Aquila.

Fig. 22 – Profilo di V_S misurata mediante SDMT in un foro riempito di sabbia, V_S misurata mediante MASW [IAMC-CNR, MS–AQ WORKING GROUP, 2010] e profilo stratigrafico schematico nel sito di Via Solaria (Cansatessa), L'Aquila.

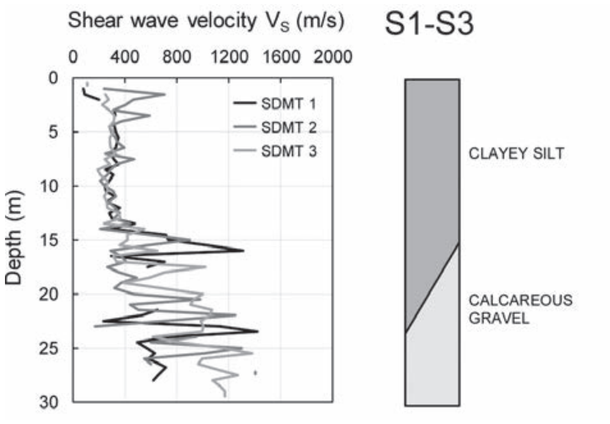

Fig. 23 – Profiles of V_S measured by SDMT in 3 backfilled boreholes and schematic stratigraphy at the site of Via Sila Persichelli (Pettino), L'Aquila.

Fig. 23 – Profili di V_S misurata mediante SDMT in 3 fori riempiti di sabbia e profilo stratigrafico schematico nel sito di Via Sila Persichelli (Pettino), L'Aquila.

ulty of Engineering of the University of L'Aquila (Monteluco di Roio), located at only ≈ 500 m distance from the April 6, 2009 earthquake main shock epicentre (see Fig. 3a) and severely damaged by the earthquake.

Other SDMT results, obtained as part of investigations aimed at the characterization of sites of

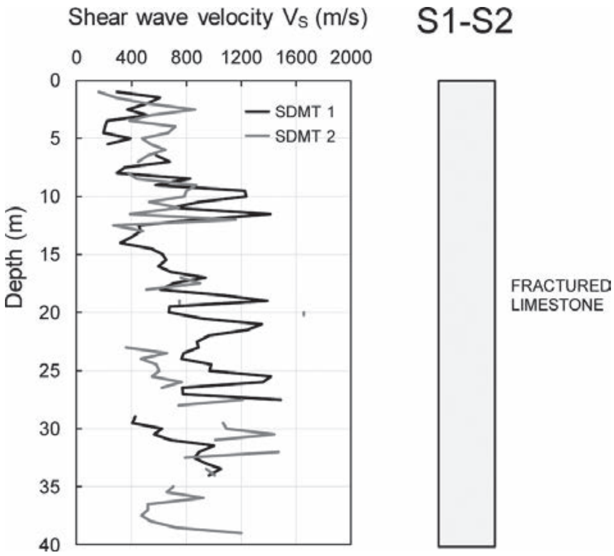

Fig. 24 – Profiles of V_S measured by SDMT in 2 backfilled boreholes and schematic stratigraphy at the site of Monteluco di Roio – Faculty of Engineering, L'Aquila.

Fig. 24 – Profili di V_S misurata mediante SDMT in 2 fori riempiti di sabbia e profilo stratigrafico schematico nel sito di Monteluco di Roio – Facoltà di Ingegneria, L'Aquila.

strong motion stations (part of the Italian Strong Motion Accelerometric Network – RAN) in the area of L'Aquila, are reported elsewhere [e.g. LANZO *et al.*, 2011].

3.4 Evaluation of V_S from mechanical DMT data

In addition to the recent SDMT investigations previously described, the results of several mechanical DMTs carried out in the past in the area of L'Aquila were collected for the seismic microzonation

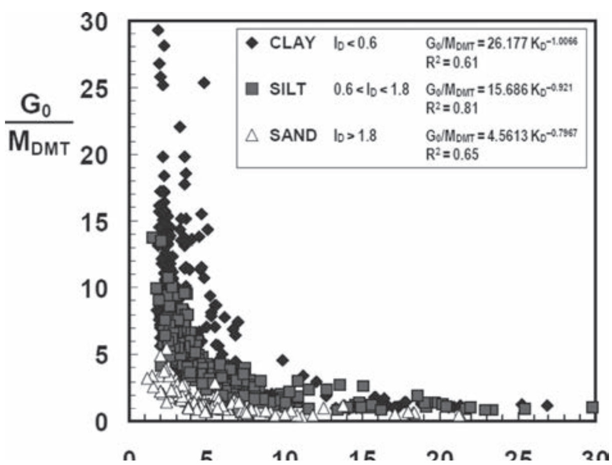

Fig. 25 – Ratio G_0 / M_{DMT} vs. K_D (OCR) for various soil types [MONACO *et al.*, 2009].

Fig. 25 – Rapporto G_0 / M_{DMT} in funzione di K_D (OCR) per diversi tipi di terreno [MONACO et al., 2009].

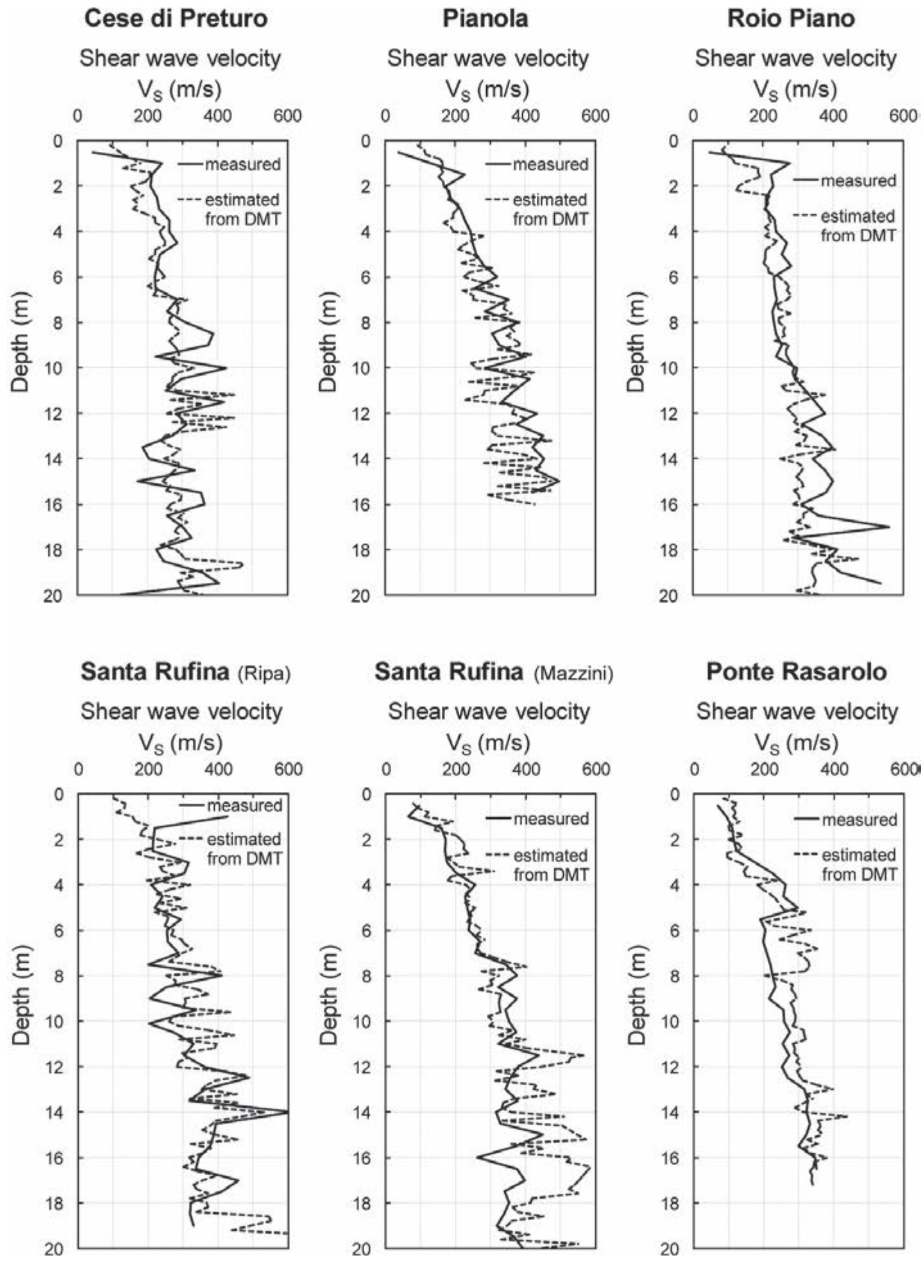

Fig. 26 – Comparison of profiles of V_S measured by SDMT and estimated from DMT data at six sites in the area of L'Aquila.
Fig. 26 – Confronto tra profili di V_S misurati con SDMT e stimati da dati della prova DMT in sei siti nell'area dell'Aquila.

study. These results were used to obtain rough estimates of V_S, at sites where it had not been measured [see MONACO *et al.* (2012); SANTUCCI DE MAGISTRIS *et al.* (this journal)], by use of the correlations in Fig. 25.

Such correlations were established considering that 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}. The latter is obtained from the usual DMT interpretation. The effectiveness of the M_{DMT} estimation has been proved by the good agreement observed in a large number of well documented comparisons between measured and DMT-predicted settlements or moduli [MONACO *et al.,* 2006; MARCHETTI *et al.,* 2008].

The experimental relationship between G_0 and M_{DMT} is illustrated in the diagram in Fig. 25, where the ratio G_0 / M_{DMT} is plotted vs. the DMT horizontal stress index K_D (related to OCR): the values of G_0 and M_{DMT} are derived by SDMT results at 34 different sites, in a variety of soil types [MONACO *et al.,* 2009].

The comparisons shown in Fig. 26 indicate a good agreement between the profiles of V_S measured directly by SDMT (solid line) and V_S estimated from mechanical DMT data (dashed line) obtained in the same SDMT test, using the correlations in Fig. 25, at

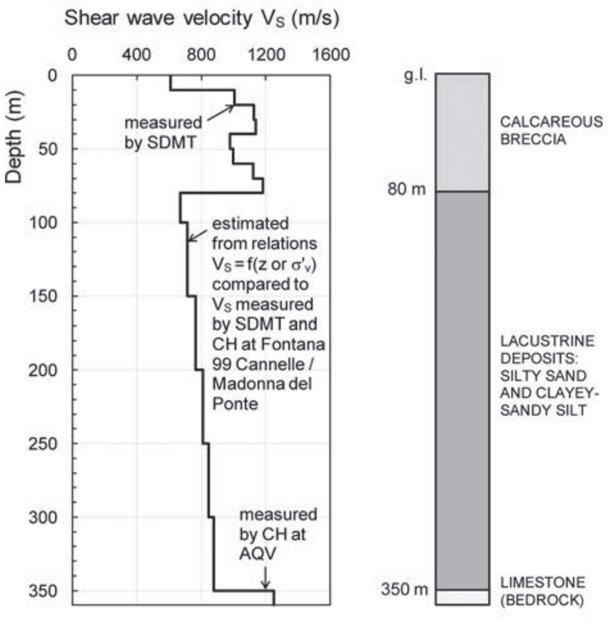

Fig. 27 – Schematic stratigraphy and shear wave velocity profile defined for 1D seismic response analysis at the site of Palazzo Camponeschi, L'Aquila [after MONACO *et al.*, 2011b].

Fig. 27 – Schema stratigrafico e profilo della velocità delle onde di taglio definiti per analisi di risposta sismica locale 1D nel sito di Palazzo Camponeschi, L'Aquila [da MONACO et al., 2011b].

six sites in the area of L'Aquila where SDMT was performed using the penetration procedure. The relative error, calculated as ($V_{S\ measured} - V_{S\ estimated}$) / $V_{S\ measured}$, is about 20% on average.

4. Use of V_S from SDMT for soil characterization in site seismic response analyses

The V_S profiles obtained by SDMT, combined with geological information and data obtained from other investigations, have been used for the soil characterization in seismic response analyses of various sites, located both in L'Aquila city centre and in the surrounding area [MONACO *et al.*, 2011b; MONACO *et al.*, 2011c; FERRARO *et al.*, this journal]. The results of these analyses, in agreement with previous studies [e.g. MAUGERI *et al.*, 2011; MS–AQ WORKING GROUP, 2010], confirm that site effects played an important role in the observed non-uniform damage distribution due to the April 6, 2009 earthquake.

As an example, Fig. 27 illustrates the shear wave velocity profile defined for the seismic response analysis at the site of Palazzo Camponeschi (see location in Figs 3b and 4). As typical of the city centre, the subsoil is characterized by an inversion of the shear wave velocity with depth, at the transition from the upper 80 m thick breccias ($V_S \approx$ 800-1000 m/s) to the underlying lacustrine silts ($V_S \approx$ 600-700 m/s); the bedrock (*geological* and *seismic*) is found at 350 m depth. The profile of V_S in the breccias was defined as an average of five V_S profiles obtained by SDMT in backfilled boreholes to 74 m depth (Fig. 12). In the lower lacustrine silts, in absence of direct measurements, the profile of V_S was estimated as a function of depth or stress level by experimental relationships [CHIARA, 2001; CRESPELLANI *et al.*, 1989]. Such V_S profile was found in reasonable agreement with V_S measured by SDMT and by Cross-Hole at Fontana 99 Cannelle and Madonna del Ponte (Fig. 19), where the same lacustrine formation is encountered at shallow depths. The limestone bedrock was characterized by V_S = 1250 m/s, derived from a Cross-Hole test performed at the site of the strong motion station AQV (a few km West of the city centre), where the bedrock was found at ≈ 50 m depth [DI CAPUA *et al.*, 2009]. Additional information on the input data and the results of the seismic response analysis at Palazzo Camponeschi can be found in MONACO *et al.* (2011b).

5. Conclusions

A large number of seismic dilatometer tests were carried out 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 housing sites (C.A.S.E.), 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 centre 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 performed by the normal penetration procedure only in a limited number of sites. However the backfilled borehole procedure permitted to obtain V_S profiles by use of the SDMT seismic module – likewise a two-receiver Down-Hole test – also in non-penetrable soils, at several sites both in the city centre and in the suburban area of L'Aquila. In some cases the backfilling procedure permitted to obtain V_S measurements down to unusually large depths (≈ 70 to 130 m), by use of the "stacking" technique for interpreting the SDMT seismograms in case of low signal/noise ratio.

The V_S profiles obtained by SDMT were found generally in acceptable agreement with the V_S profiles obtained by other in-hole techniques (Down-Hole, Cross-Hole), while the agreement with the V_S profiles obtained by surface wave tests in some cases is less satisfactory.

As a general rule, it is obviously advisable to directly measure V_S. However, if only mechanical DMT results are available (e.g. from past investigations), rough estimates of V_S (from G_0) can be obtained by correlation with mechanical DMT data.

The V_S profiles obtained by SDMT, combined with geological information and data obtained from other investigations, have been used to define the soil model for numerical seismic response analyses of sites located both in L'Aquila city centre and in the suburban area, characterized by substantially different subsoil conditions.

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Caratterizzazione in sito con dilatometro sismico (SDMT) nella città dell'Aquila

Sommario

Questo articolo presenta una rassegna di risultati ottenuti da un gran numero di prove con dilatometro sismico (SDMT) eseguite nell'area dell'Aquila dopo il terremoto del 6 Aprile 2009. Date le caratteristiche dei terreni comunemente incontrati in quest'area (prevalentemente a grana grossa, non penetrabili), generalmente le prove SDMT sono state eseguite all'interno di fori riempiti di sabbia, per cui è stato possibile misurare solo la velocità di propagazione delle onde di taglio V_S, e non gli altri parametri DMT. I risultati sperimentali illustrati in questo articolo comprendono: (a) risultati SDMT ottenuti con la normale tecnica di penetrazione (in un numero limitato di siti, prevalentemente in limi); (b) profili della sola V_S ottenuti con la tecnica del riempimento di fori; (c) confronti tra profili di V_S ottenuti da SDMT e da altre prove (Down-Hole, Cross-Hole, analisi di onde di superficie); (d) confronti tra V_S misurata da SDMT e stimata da risultati della prova DMT meccanica. I profili di V_S forniti dalla prova SDMT, combinati con informazioni di natura geologica e dati di altre indagini, comprendenti sondaggi profondi fino a 300 m nel centro storico, sono stati utilizzati per la caratterizzazione geotecnica in analisi di risposta sismica locale.