V_S measurements by seismic dilatometer (SDMT) in non-penetrable soils

Mesures de V_S par le dilatomètre sismique (SDMT) dans sols non pénétrables

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ABSTRACT

This paper illustrates the procedure for obtaining measurements of the shear wave velocity V_S by seismic dilatometer (SDMT) in backfilled boreholes in non-penetrable soils. 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. The SDMT equipment/test procedure and the borehole backfilling technique are briefly described. The validation of the method by comparison of parallel profiles of V_S obtained in the "virgin" soil and in a backfilled borehole is presented. V_S profiles obtained by SDMT in backfilled boreholes at two test sites in central Italy, Sulmona (coarse gravel) and L'Aquila (calcareous breccia), are compared to V_S profiles obtained by the traditional Down-Hole technique and related to the stratigraphic profiles of the subsoil.

RÉSUMÉ

Cet article décrit la procédure pour obtenir des mesures de la vitesse des ondes de cisaillement V_S par le dilatomètre sismique (SDMT) dans forages remblayés avec du sable dans sols non pénétrables. La possibilité d'une telle mesure descend du fait que le chemin de l'onde de cisaillement de la surface au récepteur supérieur et inférieur inclut un court chemin dans le remblai de longueur très semblable pour les deux récepteurs. L'équipement et la procédure de l'essai par SDMT et la technique de remblayage du forage sont brièvement décrites. La validation de la méthode par la comparaison des profils parallèles de V_S obtenu dans le sol "vierge" et dans un forage remblayé est présentée. Les profils de V_S obtenus par SDMT dans forages remblayés à deux sites d'essai en l'Italie centrale, Sulmona (gravier grossier) et L'Aquila (brèche calcaire), sont comparés à les profils de V_S obtenus par la technique Down-Hole traditionnelle et mise en relation avec les profils stratigraphiques du sous-sol.

Keywords : seismic dilatometer SDMT, shear wave velocity V_S, non-penetrable soils

1 INTRODUCTION

The seismic dilatometer (SDMT) is the combination of the traditional "mechanical" Flat Dilatometer (DMT) introduced by Marchetti (1980) with a seismic module placed above the DMT blade. The SDMT module is a probe provided with two receivers, spaced 0.5 m, for measuring the shear wave velocity V_S. From V_S the small strain shear modulus G_0 may be determined using the theory of elasticity. The engineering application of such technique follows from different motivations:

- V_S and G_0 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.
- Seismic site classification using directly V_S rather than the SPT blow count N_{SPT} or the undrained shear strength s_u (as required e.g. by the Eurocode 8 and by EC8-inspired national technical codes).
- Availability of the usual DMT results (e.g. constrained modulus M_{DMT}) for common design applications (e.g. settlement predictions).

The SDMT equipment and test procedure are briefly described in the paper. Detailed information and comments on SDMT results and applications can be found in previous papers, in particular in Marchetti et al. (2008). (Information on the mechanical DMT can be found in the comprehensive report by the ISSMGE Technical Committee TC16 2001).

This paper is focused essentially on the procedure for obtaining profiles of V_S by SDMT in backfilled boreholes in non-penetrable soils. In particular the paper presents the results of V_S measurements obtained by SDMT in backfilled boreholes at various test sites located in the old centres of the towns of Sulmona and L'Aquila, in a highly seismic region in central Italy. The subsoil at the investigated sites is predominantly coarse gravel (Sulmona) and calcareous breccia (L'Aquila). SDMT testing was part of site investigation programs carried out to determine fundamental soil parameters required for seismic microzonation, prediction of the site seismic response and design of retrofitting of historic buildings.

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. Initially conceived for research, the SDMT is gradually entering into use in current site investigation practice. 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, provided 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

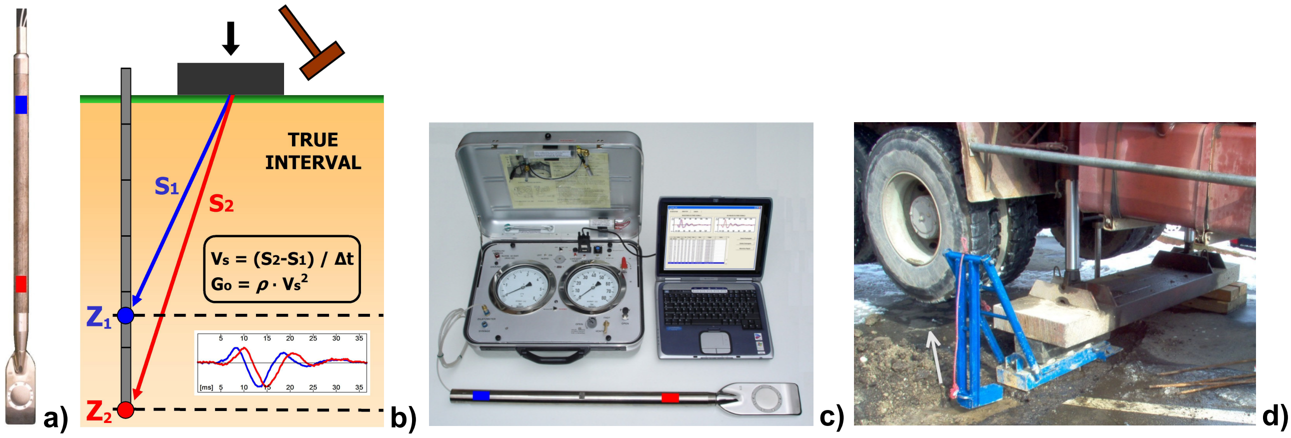

Figure 1. (a) DMT blade and seismic module. (b) Schematic layout of the seismic dilatometer test. (c) Seismic dilatometer equipment. (d) Shear wave source at the surface.

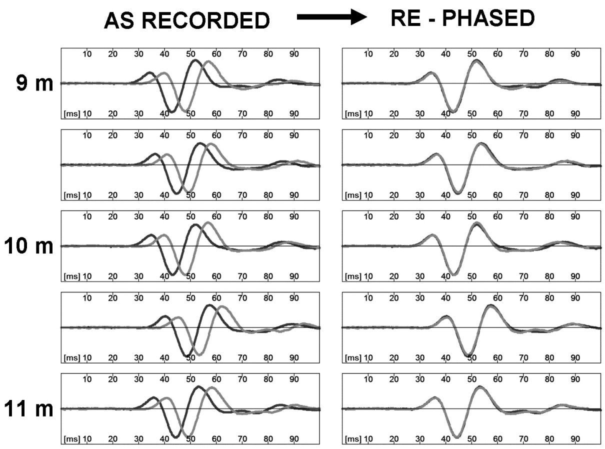

Figure 2. Example of seismograms obtained by SDMT at the site of Fucino (Italy)

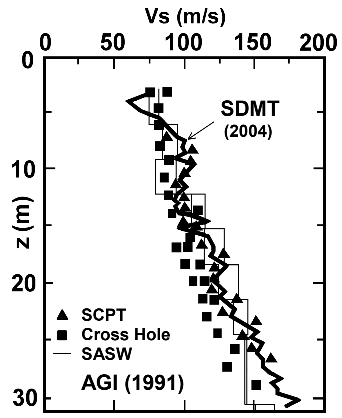

Figure 3. Comparison of V_S profiles obtained by SDMT and by SCPT, Cross-Hole and SASW (AGI 1991) at the research site of Fucino (Italy)

(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 which hits horizontally a steel rectangular base pressed vertically against the soil (by the weight of the truck) and oriented with its long axis parallel to the axis of the receivers, so that they can offer the highest sensitivity to the generated shear wave.

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

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 3 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. 3) 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).

3 V_S BY SDMT IN NON-PENETRABLE SOILS

In cases where the soil is too hard to penetrate (e.g. gravel), or even in rock, V_S measurements can be obtained by SDMTs carried out inside boreholes backfilled with sand (only V_S – no DMT measurements). 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.

The procedure is the following:

(1) A borehole, cased or uncased, is drilled by use of a drill rig to the required test depth.

(2) The borehole is then backfilled with clean coarse sand – fine gravel (grain size 1-2 to 4-5 mm, no fines) by pouring the sand from the top of the borehole. The filling operation is carried out for depth intervals of maximum length equal to the length of a single section of the casing (e.g. 1.5 m), ensuring each time that the bottom of the casing is maintained below the top of the filling. The volume of the poured sand and the level of the backfill inside the borehole are systematically measured. If necessary water is poured from the top of the borehole to facilitate sinking and densification of the sand (these operations minimize the risk that voids in the backfill may later reduce the contact between the seismic probe and the soil, required for obtaining accurate measurements of V_S). After filling each 1.5 m depth interval the casing is lifted, avoiding rotation. This sequence is repeated until the borehole is completely filled with sand.

(3) The SDMT is then inserted and advanced into the backfilled borehole in the usual way, e.g. by use of a penetrometer rig (carefully positioned in correspondence of the borehole) and V_S measurements are carried out every 0.5 m of depth. No DMT measurements – meaningless in the backfill soil – are taken in this case.

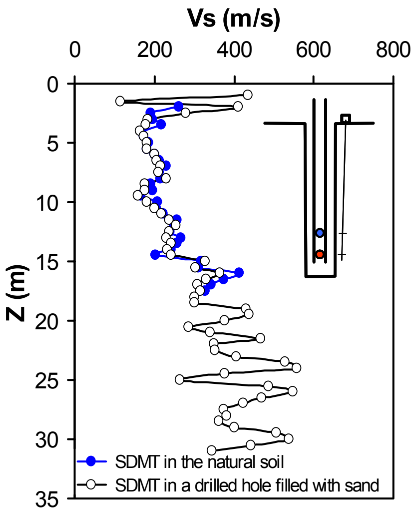

Figure 4. Comparison of V_S profiles obtained by SDMT in the natural soil and in a backfilled borehole at the site of Montescaglioso – Ginosa (Matera), Italy

Comparative tests at various sites indicate that the values of V_S obtained in a backfilled borehole are nearly coincident with the V_S obtained by penetrating the "virgin" soil. Figure 4 shows the comparison between the profiles of V_S obtained, at the same site, by penetrating the "virgin" soil and in an adjacent borehole filled with sand. The good agreement observed between the two V_S profiles (Fig. 4) supports the reliability of V_S values obtained by this procedure.

4 V_S MEASUREMENTS BY SDMT IN BACKFILLED BOREHOLES AT VARIOUS TEST SITES

4.1 *Sulmona site*

SDMT tests at Sulmona were carried out in December 2006 – January 2007, in combination with other seismic tests (Down-Hole, microtremor measurements). The site investigation program was part of a research project aimed at the second level seismic microzonation of the town of Sulmona, funded by Regione Abruzzo in cooperation with the Comune di Sulmona and involving researchers of the University of L'Aquila, the University of Rome "La Sapienza" (Dipartimento Scienze della Terra) and the Dipartimento della Protezione Civile – Servizio Sismico Nazionale (see research report by Totani et al. 2007).

The subsoil in the old town centre of Sulmona is generally constituted by an upper layer of calcareous medium to coarse well-graded gravel in sandy matrix, including layers of sandy and clayey silts. The gravel extends to a depth of ≈ 20-30 m below the ground surface and overlays a stiff clay layer, followed by dense sand below ≈ 57-60 m. The groundwater level is found at ≈ 19 to 25 m depth.

Due to the predominance of "non-penetrable" coarse gravel in the upper 20-30 m, V_S measurements by SDMT were carried out in boreholes filled with sand according to the above outlined procedure. Three boreholes were executed at different locations in the old town centre of Sulmona: Villa Comunale (30 m depth), Scuola Masciangioli (30 m) and Largo Tommasi (60 m). Figure 5 shows the profile of V_S obtained by SDMT down to a depth of 60 m in the backfilled borehole S3 (Largo Tommasi). The stratigraphic profile of the subsoil is shown alongside. Figures 6 and 7 show the profiles of V_S obtained by SDMT down to 30 m in the backfilled boreholes S1 (Villa Comunale) and S2 (Scuola Masciangioli), the stratigraphic profiles of the subsoil and the profiles of V_S obtained by Down-Hole tests carried out in adjacent boreholes (≈ 2 m distance) by researchers of the University of Rome "La Sapienza". Comments:

(a) The values of V_S obtained by SDMT are in keeping with V_S values expected for the soil types recognized in the borehole logs (Figs. 5 to 7).

(b) The V_S values by SDMT are significantly dispersed in gravel (≈ 400-800 m/s) and in the silty layers (≈ 400-600 m/s), more uniform in the deep stiff clay (≈ 500 m/s, Fig. 5). The "spikes" (high values of V_S) frequently observed in the V_S profiles down to ≈ 30 m may possibly reflect a variable degree of cementation / composition / grain size of the gravel.

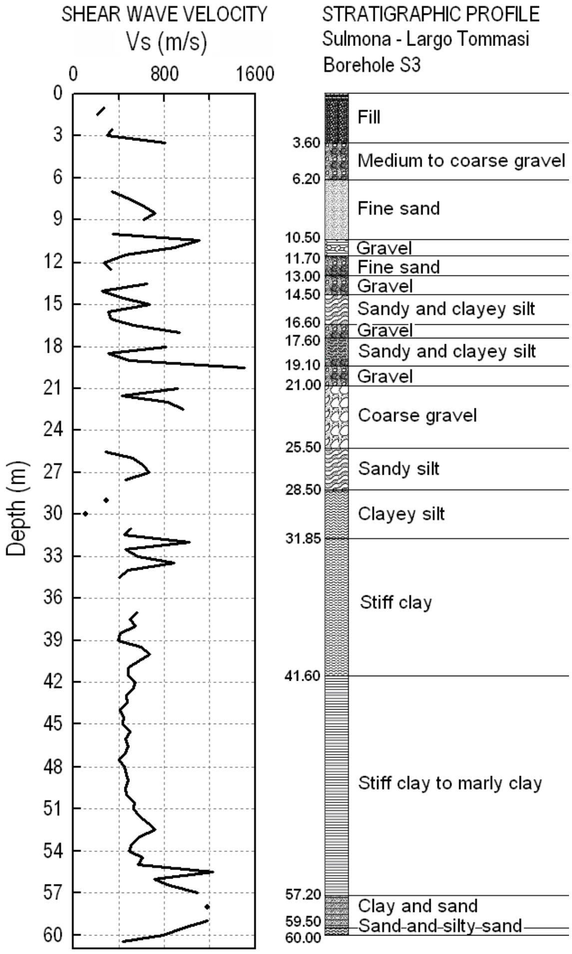

Figure 5. Sulmona (Largo Tommasi) – Profile of V_S obtained by SDMT in backfilled borehole and stratigraphic profile

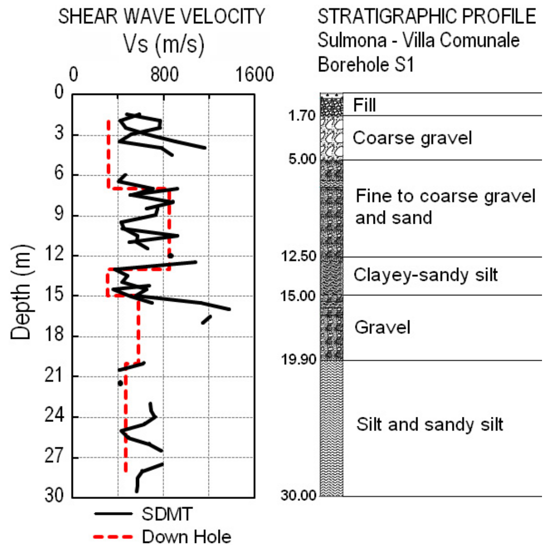

Figure 6. Sulmona (Villa Comunale) – Profiles of V_S by SDMT in backfilled borehole, V_S by Down-Hole and stratigraphic profile

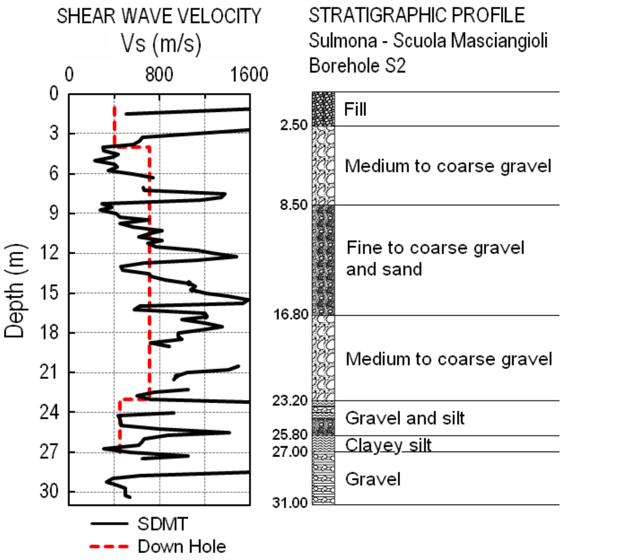

Figure 7. Sulmona (Scuola Masciangioli) – Profiles of V_S by SDMT in backfilled borehole, V_S by Down-Hole and stratigraphic profile

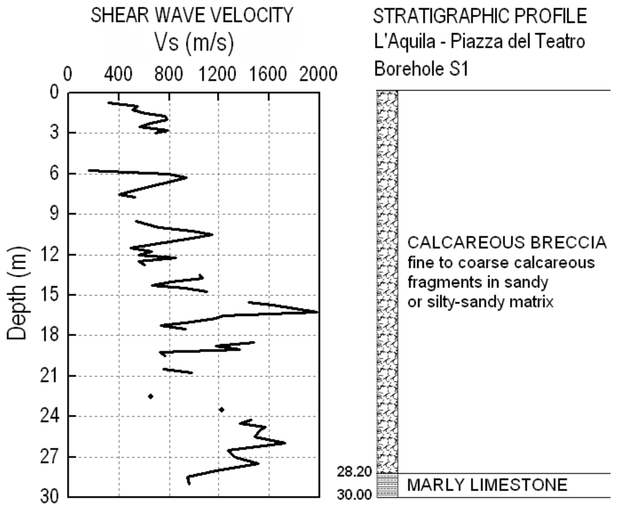

Figure 8. L'Aquila (Piazza del Teatro) – Profile of V_S obtained by SDMT in backfilled borehole and stratigraphic profile

(c) The values of V_S obtained by SDMT are substantially in agreement with the V_S obtained by Down-Hole (Figs. 6 and 7). However the *true-interval* V_S measurements obtained by SDMT every 0.5 m of depth (every 0.25 m in the borehole S2, Fig. 7) provide more detailed and realistic profiles of V_S compared to the *pseudo-interval* Down-Hole technique (V_S measurements every 1 m), which in this case had produced constant values of V_S over several metres of depth.

4.2 *L'Aquila site*

One SDMT test in a backfilled borehole to 30 m depth was carried out in the old town centre of L'Aquila (Piazza del Teatro) in April 2008. The subsoil in this area is generally constituted by an upper thick layer of calcareous breccia (fine to coarse calcareous fragments generally in sandy or silty-sandy matrix). At the test site of Piazza del Teatro the breccia extends to a depth of ≈ 28 m below the ground surface, where marly limestone is encountered. The mechanical properties of the calcareous breccia are known to be highly variable, mostly depending on the variable degree of cementation.

Figure 8 shows the profile of V_S obtained by SDMT (every 0.25 m of depth) and the stratigraphic profile of the subsoil at L'Aquila – Piazza del Teatro. Also in this case the values of V_S obtained by SDMT are in keeping with V_S values expected for the soil types recognized in the borehole log. The values of V_S in the breccia are very high (≈ 600-1000 m/s) and increase with depth. The dispersion of the V_S values possibly reflects the variability in soil properties due to the variability in sandy or silty-sandy matrix and cementation typical of this material.

5 CONCLUSIONS

The results presented in this paper indicate that the seismic dilatometer (SDMT) can be advantageously used for obtaining measurements of V_S (and of the small strain shear modulus G_0 determined from V_S) in backfilled boreholes in non-penetrable soils, commonly encountered in many seismic areas, e.g. in the Apennines regions in Italy. 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.

Comparisons at various sites, presented in this paper, indicate that the *true-interval* V_S measurements obtained by SDMT in backfilled boreholes, typically every 0.5 m of depth, provide more detailed and realistic profiles of V_S compared to traditional techniques (e.g. *pseudo-interval* Down-Hole method). Hence the SDMT could be an alternative/integration to commonly used techniques to obtain reliable and detailed V_S profiles in hard soils/soft rocks.

ACKNOWLEDGMENTS

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