$V_S$ 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 $V_S$ obtenus 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 ceux 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 $M_{DICT}$) 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.
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.
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 $\approx 20-30$ m below the ground surface and overlays a stiff clay layer, followed by dense sand below $\approx 57-60$ m. The groundwater level is found at $\approx 19$ 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 ($\approx 2$ 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 ($\approx 400-800$ m/s) and in the silty layers ($\approx 400-600$ m/s), more uniform in the deep stiff clay ($\approx 500$ m/s, Fig. 5). The "spikes" (high values of $V_s$) frequently observed in the $V_s$ profiles down to $\approx 30$ 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
The results presented in this paper indicate that the seismic dilatometer (SDMT) can be advantageously used for obtaining measurements of \( V_S \) and 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.

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REFERENCES


