20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

V_S profiles provided by SDMT for soil characterization in numerical seismic response analyses

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***Abstract* – The seismic dilatometer (SDMT) is the combination of the standard flat dilatometer (DMT) with a seismic module for measuring the shear wave velocity V_S, a basic input parameter for site seismic response analyses. This paper presents an overview of the SDMT equipment, test procedure and interpretation, as well as examples of SDMT results and related comments.**

I. INTRODUCTION

In the recent years the crucial role of the local ground conditions on the seismic action on constructions has been definitely recognized in current earthquake resistant design practice, also stimulated by the introduction of the Eurocode 8 [1]. A key parameter, at the base of any method for quantifying the influence of the local ground conditions on the seismic action, is the shear wave velocity V_S. According to the EC8 simplified approach, the seismic action can be evaluated using elastic response spectra defined taking into account the "ground types" site classification, based on the equivalent shear wave velocity in the top 30 m of soil ($V_{S,30}$). A more rational approach is based on numerical site seismic response analyses, which require accurate soil input data, above all accurate profiles with depth of V_S in the subsoil down to the bedrock. Several reliable and cost-effective routine in situ techniques for the direct measurement of V_S are available today. This paper is focused on the use of the seismic dilatometer (SDMT). Initially conceived for research, in the recent years the SDMT has gradually entered into use in current site investigation practice, permitting to accumulate a large experience for site characterization in seismic areas.

II. SEISMIC DILATOMETER TEST (SDMT): EQUIPMENT, PROCEDURE, INTERPRETATION

A. General description

The seismic dilatometer (SDMT) is the combination of the mechanical flat dilatometer (DMT), introduced by Marchetti [2], with an add-on seismic module for measuring the shear wave velocity V_S (conceptually similar to the seismic cone penetration test SCPT). First introduced in 1988 [3], the SDMT was subsequently improved at Georgia Tech, Atlanta, USA [4], [5], [6]. A new SDMT system has been recently developed in Italy [7]. The seismic module (Fig. 1) 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 (Figs 2, 3 and 4), 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. 2). 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

ISBN-14: 978-92-990073-2-7

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. 5.

B. SDMT equipment: technical data

Receivers

The receivers are sensors (geophones or accelerometers) which produce a calibrated response to a seismic wave. In the current SDMT configuration the two receivers are one-directional geophones having dimensions small enough to be positioned inside the seismic module, which is formed by a hollow cylindrical element interposed between the base of the push rods and the DMT blade (Fig. 1). Both receivers are fixed to the seismic module, at a vertical distance of 0.5 m, with their active axes aligned in the same parallel horizontal direction. Such orientation is visible and can be checked from the outside. To improve coupling with the soil, the diameter of the seismic module is slightly larger than the connector at the top of the blade.

Seismic source

The seismic source is a system which generates a mechanical perturbation, inducing the propagation of repeatable seismic waves in the soil (Fig. 2). The seismic source is typically composed of a pendulum hammer and an anvil formed by a steel rectangular plate (Fig. 3). To ensure full transmission of the impact energy to the soil, preventing movements of the anvil under the hammer blows, the anvil is loaded by the weight of the truck (by use of the jack system of the push rig) and pressed against the soil. The base of the anvil must be clean and level. Pavement, asphalt etc., if present, must be removed. To maximize the energy transmitted to the soil, the anvil should be isolated from the push rig, e.g. by interposing a rubber sheet on the top of the anvil. The mass of the hammer is typically between 5 and 15 kg. The hammer must hit the anvil in horizontal direction, against one plane vertical side. To avoid, or reduce, the generation of converted waves (i.e. compression waves generated by refraction at interfaces), the anvil should be hit by the hammer in a horizontal direction perpendicular to the line connecting its centre and the intersection of the sounding (or push rods) with the ground surface (Fig. 4), in order to generate horizontally polarized (SH) shear waves. The distance between the SDMT sounding and the impact point of the hammer should be limited to the minimum (e.g. 1-2 m) and measured with an accuracy of 1 cm.

Trigger

The trigger is a source monitoring device which permits to identify the instant of generation of the mechanical perturbation inducing the seismic wave. The trigger is fixed to the hammer or to the anvil. It must have a

Fig. 1. Seismic dilatometer test equipment: DMT blade and seismic module.

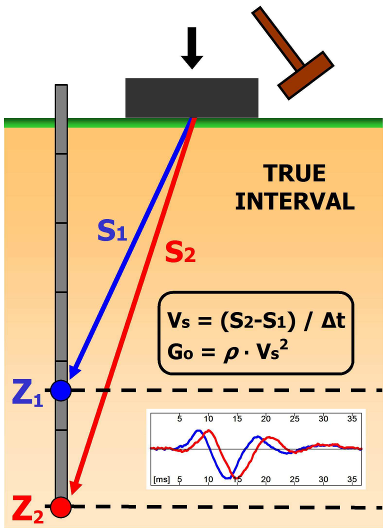


Fig. 2. Schematic seismic dilatometer test layout.

Fig. 3. Shear wave source at the ground surface.

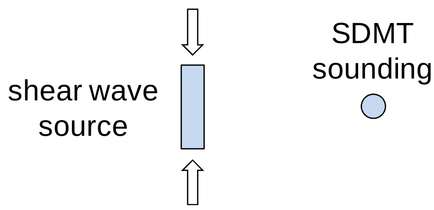


Fig. 4. Schematic plan layout showing the proper orientation of the shear wave source.

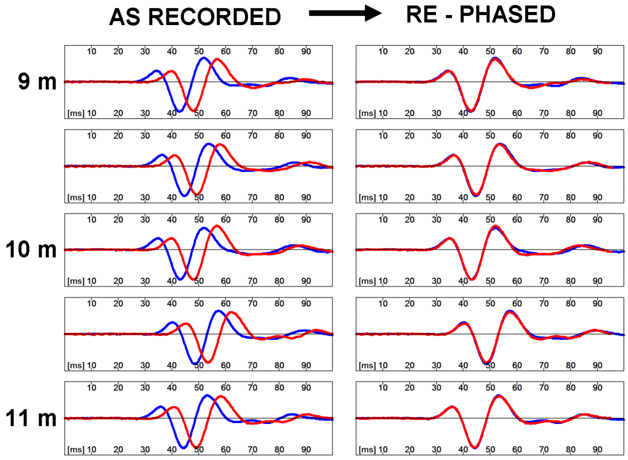


Fig. 5. Example of seismograms obtained by SDMT.

reduced reaction time, typically ≤ 10 µs, and transmit the signal at the contact between the hammer and the anvil (instant of wave generation) to the data acquisition system. In the two-receiver test configuration the trigger is not influent on the interpretation, however it is necessary to start the recording when the hammer hits the anvil.

Data acquisition system

The data acquisition system includes independent amplifiers (one for each receiver) and a multichannel digital recorder, capable to sample with a frequency of at least 50 µs. In the current SDMT configuration the signals acquired by the two receivers are amplified and digitized at depth. In case of weak signals or high noise, the digital system permits to increase the signal/noise ratio by averaging different readings, summing up (stacking) a number of repeated signals generated with the same test configuration and then dividing the sum by the number of the signals. In this way the energy of the signal is summed, while the energy of the noise, having a zero mean value, remains nearly the same.

C. Test procedure

The seismic dilatometer is inserted into the soil taking care that the horizontal active axes of the receivers are parallel to the direction of the hammer blow impact line (Fig. 4). V_S measurements are executed at regular depth intervals, typically every 0.5 m. To limit the disturbance associated to ambient noise, it could be useful to eliminate the sources of vibration and disconnect the rods from the push system. At each test depth the hammer hits the anvil, the trigger transmits the signal which activates the data acquisition system and the time history of the signals is recorded by each receiver. The energization is repeated at least three times. The repeatability of the V_S values can be accepted if the three values obtained after each hammer blow are within the range of ± 3% of the average value, otherwise further hammer blows must be applied until at least 80% of the values are within the above range. An alternative energization procedure could be utilized when it is difficult to discern shear waves from compression waves in the interpretation of the signals. Such procedure consists of applying, at each test depth, the hammer blow in the two opposite horizontal directions along the same line. This procedure permits to generate shear waves characterized by source polarity inversion, which on the other hand does not affect the compression waves. The superposition of the recorded signals permits then to identify more clearly the motion associated to the shear waves.

D. Interpretation of V_S measurements

The technique most commonly used for interpreting the recorded signals is based on the interval velocity method. The velocity of propagation of the shear waves V_S is calculated by the following relation:

$$V_S = \frac{S_2 - S_1}{t_2 - t_1} \qquad (1)$$

where S_2 and S_1 are the straight distances (i.e. the assumed shear wave travelpaths) between the source and the receivers 2 and 1 (Fig. 2), and t_2 and t_1 are the times employed by the wave to cover the distances S_2 and S_1, respectively. At the instant of the energization the two receivers are located at depths Z_1 and Z_2 below the ground surface. The travel time between the two receivers (sensing the same wave), $\Delta t = t_2 - t_1$, is generally obtained by use of the numerical cross-correlation technique. This technique permits to calculate the time delay necessary to superimpose the recordings of the same waveform at the receivers 1 and 2, assuming that the waveform does not suffer significant modifications in frequency during the travelpath between the two receivers. This technique requires high quality of the recorded signals. An example of re-phasing (superposition + translation) of seismograms recorded during a SDMT sounding, to calculate the time delay Δt between the two receivers, is shown in Fig. 5. (A different interpretation technique is required in case of source polarity inversion).

III. SDMT RESULTS

A. Repeatability of V_S measurements

Besides V_S, the seismic dilatometer provides the parameters obtained by the classical flat dilatometer interpretation, see [2] and TC16 Report [8]. Fig. 6 is an example of the typical graphical format of the SDMT output. Such output displays the profile of V_S as well as the profiles of four basic DMT parameters: the material index I_D (indicating soil type), the constrained modulus M, the undrained shear strength c_u (in clay) and the

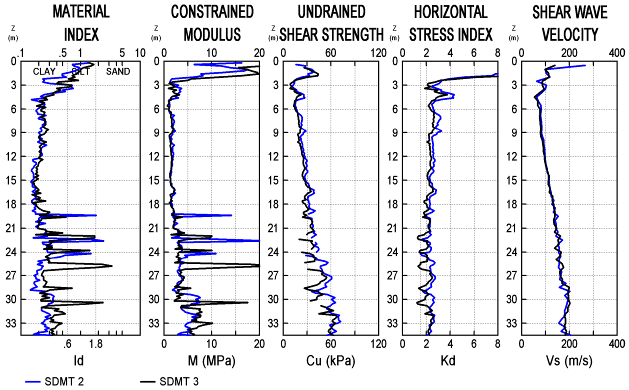


Fig. 6. Superimposed profiles of SDMT results obtained from two adjacent soundings (Fiumicino, Italy)

Table 1. Example of repeatability of V_S measurements by SDMT (Zelazny Most Tailing Dam, Poland)

Z [m]	V_S [m/s]	V_S values [m/s] corresponding to different hammer blows at each depth Z	Coefficient of variation [%]
7.00	179	178,178,180,180,180,179,179,180,180,180	0.50
7.50	231	234,232,232,230,229,231,232,229,230	0.68
8.00	225	227,225,224,225,225,226,226,225,224,224	0.40
8.50	276	276,276,280,273,275,273,271,273,287,281	1.68
9.00	296	291,286,301,292,296,288,301,300,304,303	2.09
9.50	248	244,251,250,247,250,249,250,249,242,248	1.11
10.00	292	292,289,290,293,289,292,289,292,296,295,293	0.79
10.50	320	321,323,320,325,323,325,316,314,308,321	1.61
11.00	291	293,291,293,291,291,290,290,291,290,290	0.38
11.50	321	324,320,320,322,320,322,319,319,320,320	0.48
12.00	309	311,307,311,309,309,311,309,309,307,311	0.50
12.50	286	287,285,285,285,287,285,285,287,287,287	0.35
13.00	265	265,265,265,264,265,265,265,266,265,266,264	0.24
13.50	280	287,276,279,276,276,276,294,275,278,279	2.08
14.00	312	313,312,312,322,310,312,310,310,310,312	1.10
14.50	298	301,298,299,299,298,296,299,298,299,298	0.44
15.00	309	307,309,307,309,309,309,309,309,309,309	0.29

horizontal stress index K_D (related to stress history), calculated with usual DMT interpretation formulae as in [2], [8]. The superimposed profiles shown in Fig. 6 were obtained from two parallel adjacent SDMT soundings. It may be noted from Fig. 6 that the repeatability of the V_S profile is very high, similar to the repeatability of the other DMT parameters.

Table 1 shows, in a different form, another example of repeatability of V_S measurements by SDMT. Each V_S value at a given test depth corresponds to a different hammer blow. The coefficient of variation of V_S is in the range 1-2%. Such repeatability is more than adequate for normal engineering needs.

B. Validation of V_S measurements

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 in [7]. As an example, Fig. 7 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 is in good agreement with V_S profiles obtained by SCPT, Cross-Hole and surface waves tests (SASW) in previous investigations [9]. Fig. 8, based on data reported in [10], shows the comparison between V_S profiles obtained by SDMT, Down-Hole tests (DH) and multi-receiver surface waves tests (MASW) at the site of Roio Piano (OC silty clay) in the area of L'Aquila, Italy, where a large number of sites were investigated by SDMT after the April 6, 2009 earthquake [11]. In this area 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 was less satisfactory.

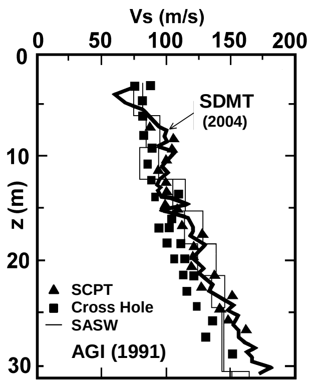


Fig. 7. Comparison of V_S profiles obtained by SDMT and by SCPT, Cross-Hole and SASW (data from AGI 1991, [9]) at the research site of Fucino, Italy [7].

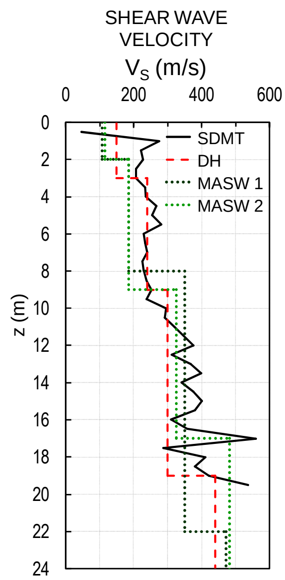
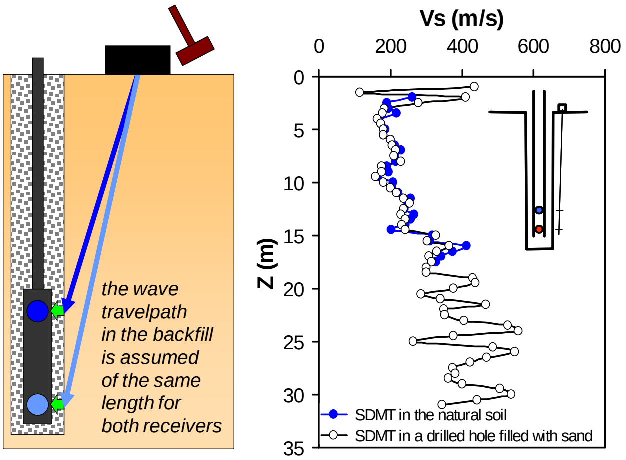


Fig. 8. Comparison of V_S profiles obtained by SDMT, Down-Hole (Polo Geologico) and MASW (Politecnico di Torino) at the site of Roio Piano (C.A.S.E. Project), L'Aquila, Italy (data from [10]).



(a) (b)

Fig. 9. V_S measurements by SDMT in backfilled boreholes in non-penetrable soils [12]. (a) Schematic test layout and basis of the method. (b) Example of validation: comparison of V_S profiles obtained by SDMT in a backfilled borehole and by penetrating the natural soil (Montescaglioso – Ginosa, Italy).

IV. V_S MEASUREMENTS BY SDMT IN BACKFILLED BOREHOLES IN NON-PENETRABLE SOILS

The SDMT standard procedure proves to be an effective, quick, 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. gravel, or even rock) has been devised in [12]. The procedure is the following (Fig. 9a):

1. a borehole is drilled to the required test depth;
2. the borehole is backfilled with clean fine-medium gravel (grain size 5 to 15 mm, no fines content);
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 – 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. 9a), i.e. the time delay Δt does not change.

To validate the method, comparative tests were carried out at sites where both the usual penetration procedure and the backfilling procedure were adoptable. The comparison of the results (see example in Fig. 9b) indicated that the V_S values obtained in the backfilled borehole are nearly coincident with the V_S obtained by penetrating the soil.

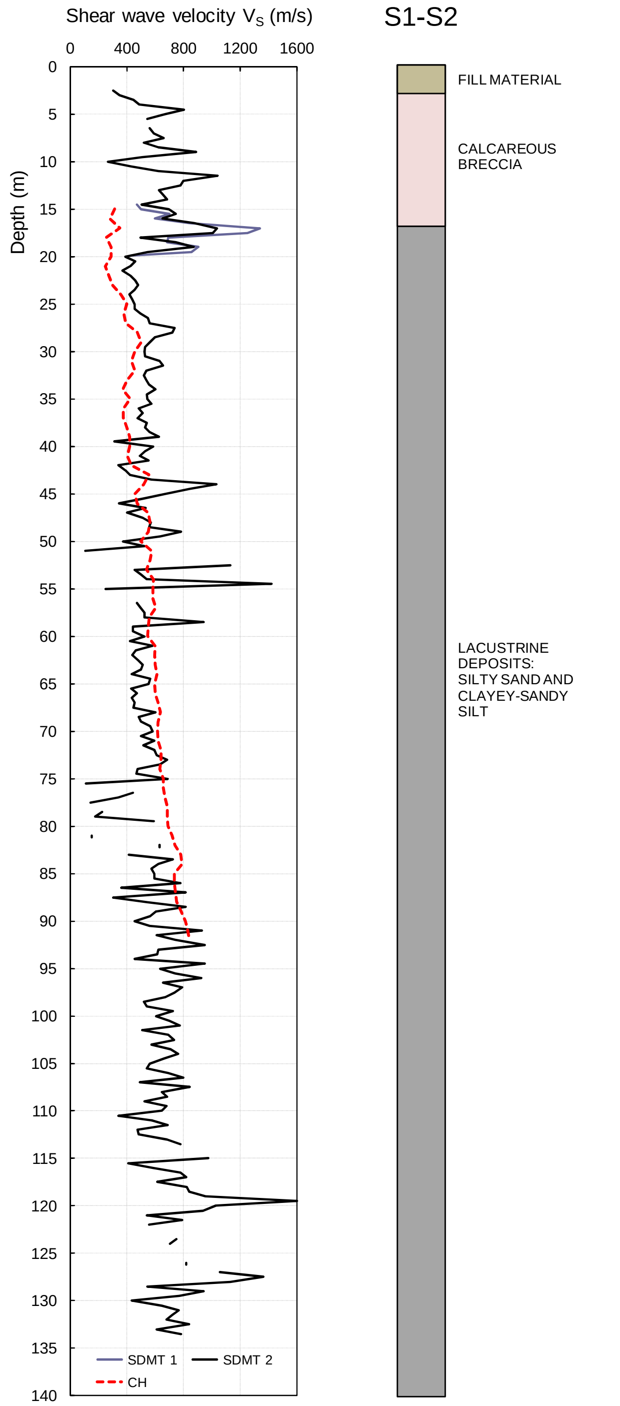


Fig. 10. Profiles of V_S measured by SDMT in 2 backfilled boreholes compared to V_S measured by Cross-Hole in a nearby site [13] and schematic soil profile at the site of Fontana 99 Cannelle, L'Aquila, Italy [11].

Fig. 10 shows an example of V_S profiles obtained by use of the SDMT seismic module in backfilled boreholes, in non-penetrable soils, at the site of Fontana 99 Cannelle, L'Aquila, Italy [11]. In this case V_S measurements were taken down to a very large depth (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, hence V_S was obtained using the stacking technique. In Fig. 10 the profile of V_S measured by a Cross-Hole test (CH) carried out in a site nearby [13] is also reported. The V_S measured by SDMT are in reasonable agreement with those obtained by Cross-Hole.

V. CONCLUSIONS

The seismic dilatometer (SDMT) provides accurate and highly reproducible measurements of the shear wave velocity V_S, a basic input parameter for numerical seismic response analyses. Besides V_S, SDMT provides the usual DMT results for common geotechnical engineering design applications.

The backfilled borehole procedure permits to obtain V_S profiles by use of the SDMT seismic module – likewise a two-receiver Down-Hole test – also in non-penetrable soils. In some cases the backfilling procedure permitted to obtain V_S measurements down to unusually large depths (≈ 130 m), by use of the stacking technique for interpreting the SDMT seismograms in case of low signal/noise ratio.

The accumulated experience indicates that the V_S profiles obtained by SDMT are generally in satisfactory agreement with the V_S profiles obtained by other tests, in particular by other in-hole techniques (Down-Hole, Cross-Hole). The V_S profiles obtained by SDMT, combined with geological information and data obtained from other investigations, provide useful data to define the soil model for numerical seismic response analyses.

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