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Preliminary results of P-wave and S-wave measurements by seismic dilatometer test (SPDMT) in Mirandola (Italy)

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ABSTRACT: A trial seismic dilatometer-V_P (SPDMT) has been recently developed to measure the compressional wave velocity V_P, in addition to the shear wave velocity V_S and to the DMT geotechnical parameters. The new SPDMT is the combination of the traditional mechanical flat dilatometer (DMT) with an appropriate seismic module placed above the DMT blade. The SPDMT module consist in a probe outfitted with two receivers for measuring the P-wave velocity, along with two receivers for measuring the S-wave velocity. The paper describes the SPDMT equipment, the test procedure and the interpretation of V_P and V_S measurements, together with some considerations on the potential geotechnical applications which can benefit from the contemporary measurement of the two propagation velocities. Finally, the paper illustrates preliminary results of P-wave and S-wave measurements by SPDMT compared to several cross-hole, down-hole and suspension logging data at the Mirandola test site (Italy), a soft alluvial site which was investigated within the InterPACIFIC (Intercomparison of methods for site parameter and velocity profile characterization) project.

1 INTRODUCTION

During the last decades, there has been a considerable shift from laboratory testing to in situ testing at a point that, today, in situ testing often represents the major part of a geotechnical investigation. Therefore the incoming need of acquiring multiple parameters of the soil stratigraphy with the use of the same investigation tool. In this respect the addition of one or more seismic receivers (geophones or accelerometers) to traditional CPT cone or DMT blade has become a standard practice. These new testing procedures are addressed as the seismic cone penetrometer test (SCPT - Robertson et al. 1986) or the seismic dilatometer test (SDMT - Marchetti et al. 2008), respectively. These tests provide the measurement of the shear wave velocity V_S, in addition to the usual CPT or DMT parameters, extending the scope of site characterization. Recommendations given in recent State-of-the-Art papers (e.g. Mayne et al. 2009) indicate that direct-push in situ tests, such as SCPT and SDMT, are, at intermediate investigation depths, fast and very convenient tests for routine site investigations if compared to other invasive seismic tests.

This paper introduces a trial seismic dilatometer-V_P (SPDMT), recently developed to measure also the compressional wave velocity V_P, together with the common DMT geotechnical parameters and shear wave velocity V_S. The new equipment is the combination of the traditional mechanical flat dilatometer (DMT) with a seismic module placed above the DMT blade. Accurate in situ P-wave and S-wave velocity profiles can give a significant support to the geotechnical characterization in both static and dynamic analyses where the small strain elastic parameters are input variables into the models (Finn 1984). Moreover, porosity evaluation and liquefaction assessment can be performed based on these data.

The InterPACIFIC (Intercomparison of methods for site parameter and velocity profile characterization) project provided a valuable case study to compare SPDMT results to independent cross-hole (CH), down-hole (DH) and suspension logging data at the Mirandola test site (Italy) and to verify the reliability of the new tool particularly concerning the P-wave velocity measurement.

2 THE SEISMIC DILATOMETER WITH COMPRESSION WAVE MEASUREMENTS (SPDMT)

The trial seismic dilatometer-V_P (SPDMT) is the combination of the traditional mechanical flat dilatometer (DMT) with a SPDMT seismic module placed above the DMT blade (Figures 1a, 1b). The new system has been recently developed in Italy and it is an upgrade of the seismic dilatometer (SDMT) introduced by Marchetti et al. (2008). The SPDMT module is a probe outfitted with two uniaxial (vertical) geophones, spaced 0.604 m, for measuring the P-wave velocity V_P, along with two uniaxial (horizontal) geophones, spaced 0.500 m, for measuring the S-wave velocity V_S. Geophones have appropriate frequency and sensitivity characteristics to determine the seismic wave train arrival according to ASTM D7400-14 (2014). Two different seismic sources are adopted: an impulsive source, such as a 8 kg-hammer, hits vertically a steel squared base to produce identifiable compressional waves; a pendulum hammer (≈ 10 kg) 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, in order to offer the highest sensitivity to the generated shear wave.

The P-wave and the S-wave seismic sources are connected to two different external triggers to record respectively the response of the P-wave geophones and of the S-wave geophones. The signal is amplified and digitized at depth. The recording system consists of different channels, one for each geophone, having identical phase characteristics and adjustable gain control.

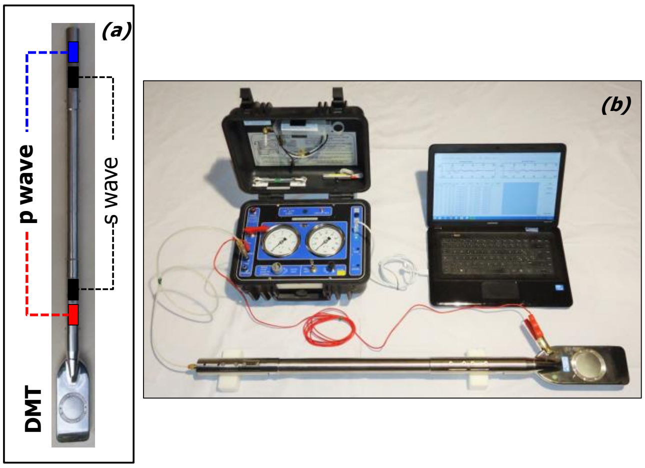

Figure 1. Trial seismic dilatometer-VP (SPDMT): (a) DMT blade and SPDMT module; (b) SPDMT equipment.

The interpretation of the seismic waves arrival times can rely both on the *direct method*, considering the whole set of travel-times at different depths or on the *true-interval* considering for each realization of the test the time delay between two receivers. In the first case the arrival time at each receiver position during penetration is determined by first break picking (Tp). Then all the arrival times are corrected to account for the ray-path inclination:

$$Tc = \left(\frac{SD}{d}\right) \cdot Tp \qquad (1)$$

where SD is the source distance and d is the depth for each receiver position. All the corrected arrival times Tc are then plotted as a function of depth and homogeneous velocity intervals are searched with interpolation of linear branches of the travel time curve. This first interpretation approach is commonly used in the analysis of down-hole data (Auld 1977). This method is convenient when subsoil layering has to be determined. The interpretation reduces inaccuracy in the travel time determinations by mediating among several arrival times over homogeneous velocity layers. In the second case, seismic velocity is obtained as the ratio between the difference in distance between the source and the two receivers (SD_2-SD_1) and the delay of the arrival of the impulse from the first to the second receiver (Δt). 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 *direct method* 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 velocity measurements is considerably improved. The determination of the delay in the seismograms can be based both on the direct picking of the first arrival times in the recorded traces or on the cross-correlation algorithm. This second approach is generally better conditioned being based on a wide portion of the two seismograms – in particular the initial waves – rather than on the first break or specific marker points in the seismogram.

2.1 *Potential geotechnical applications*

The use of the SPDMT dilatometer allows the measurement of the compressional wave velocity V_P, in addition to the shear wave velocity V_S and to the DMT geotechnical parameters obtained using current DMT correlations (Marchetti 1980, Marchetti et al. 2001), by means of the material index I_D (soil type), the constrained modulus M, the undrained shear strength c_u

and the horizontal stress index K_D (related to the overconsolidation ratio). Beyond the usual geotechnical applications provided by the seismic dilatometer (SDMT), the seismic dilatometer-V_P (SPDMT) can the potentially support site scale porosity evaluation and the liquefaction assessment using V_P and V_S measurements, commonly obtained from in situ geophysical surveys, such as cross hole (CH) and down-hole (DH) tests.

According to Foti et al. (2002) and Foti & Lancellotta (2004) the theory of linear poroelasto-dynamics in the low-frequency limit, developed by Biot (1956a, 1956b), can profitably be used for determining the porosity n in fluid-saturated porous media from measured P-wave and S-wave velocities. The determination of the porosity from CH, DH or SPDMT tests has particular relevance in coarse materials, which are difficult to sample. However this procedure gives a simple but effective way to estimate the porosity in situ in fine and coarse soils.

Moreover in situ P-wave and S-wave velocities have the potential to identify the degree of saturation of soils, in terms of saturation ratio S_r and pore pressure coefficient B, and hence the liquefaction resistance of a partially saturated sand. According to Tsukamoto et al. (2002) V_P tends to increase from about 500 m/s to about 1800 m/s when the B-value increases from 0.00 to 0.95 corresponding, respectively, to the saturation ratio S_r of about 90 % and 100 %. Results of cyclic loading tests on partially saturated sands indicated the cyclic resistance ratio *CRR* tends to increase significantly with a decrease in V_P, particularly when P-wave velocity become less than 500 m/s and where the B-value drops to less than 0.1 with a saturation ratio S_r of 90 %. Alternatively CRR begins to increase sharply when the ratio V_P/V_S drops to a value of about 3. Conventional liquefiability assessment, carried out according to the "simplified procedure" by Seed & Idriss (1971), is modified introducing a partial saturation factor *PSF* inferred from compression wave velocity V_P or the ratio V_P/V_S, to correct the cyclic resistance ratio *CRR* derived from SPDMT or other in situ geotechnical or geophysical investigations. Examples can be found in EQC (2013) and Amoroso et al. (2015).

3 MIRANDOLA TEST SITE (ITALY)

3.1 *Interpacific project*

The InterPACIFIC project (Garofalo et al. 2016) was aimed at assessing the reliability, resolution, and variability of geophysical methods (invasive borehole methods and non-invasive surface wave methods) in estimating the shear wave velocity profile for seismic ground response analyses. A series of blind tests has been organized in which several participants performed both invasive and non-invasive techniques at each site without any *a priori* information about the site. Three different subsoil conditions were selected as test sites. The present study is focused on invasive tests performed at the Mirandola test site by means of DH, CH and suspension logging methods and is aimed at comparing the results of SPDMT data within the comparable depths.

Mirandola is located in the Po river plain. The Secchia river, a stream of the Po river, flows north-south on the west side of the test site. The area was affected by a couple of strong earthquakes in May 2012 (Anzidei et al. 2012). The station of the Italian Accelerometric Network placed in Mirandola provided strong-motion records in the vicinity of the epicenter for both shocks. For this reason, Emilia Romagna Region planned a specific site investigation. In particular two boreholes placed at 6.8 m from each other were drilled to a depth of 125 m to reach the geological and seismic bedrock, and DH and CH tests were performed by different teams. A SPDMT sounding was also carried out up to roughly 20 m depth in the nearby area. The site is characterized mainly by alluvial deposits with an alternating sequence of silty-clayey layers of alluvial plain and sandy horizons. V_S and V_P estimations are generally in good agreement over the entire investigation depth. The geological substratum consists of marine and transitional deposits of lower-middle Pleistocene age. It was found at a depth of 118 m in the borehole and it was consistently identified by seismic borehole methods. The boreholes detected the water table at a depth of approximately 4 m below the ground surface as suggested also by P-wave velocity values.

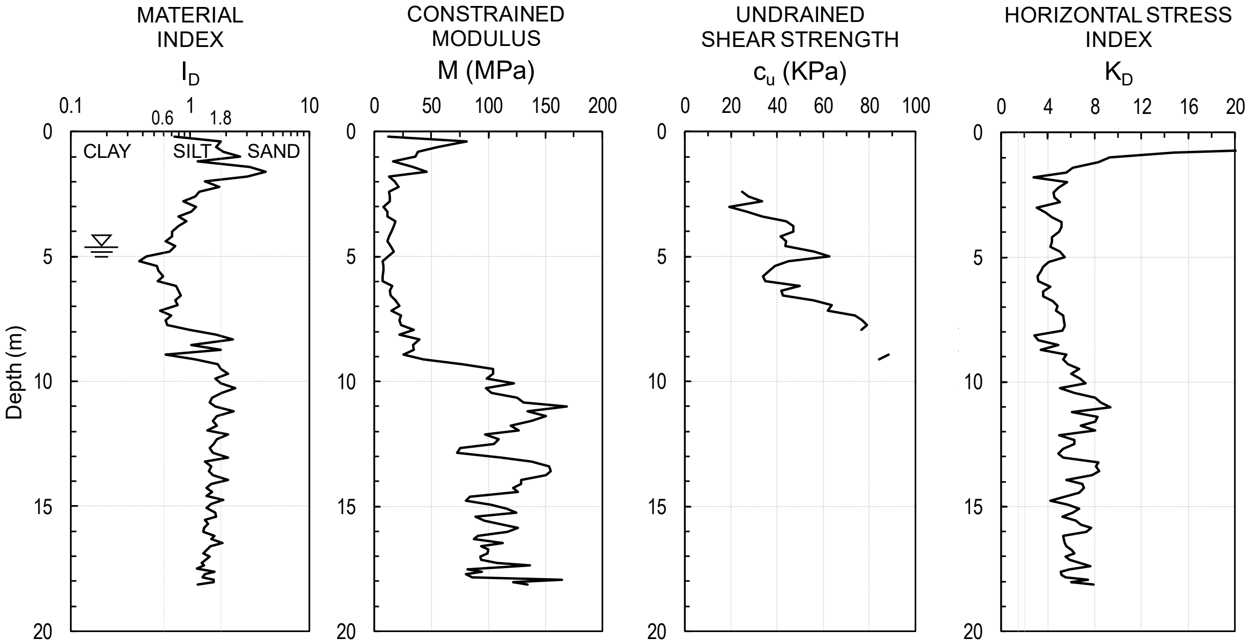

Figure 2. Geotechnical parameters from SPDMT profiles at Mirandola test site.

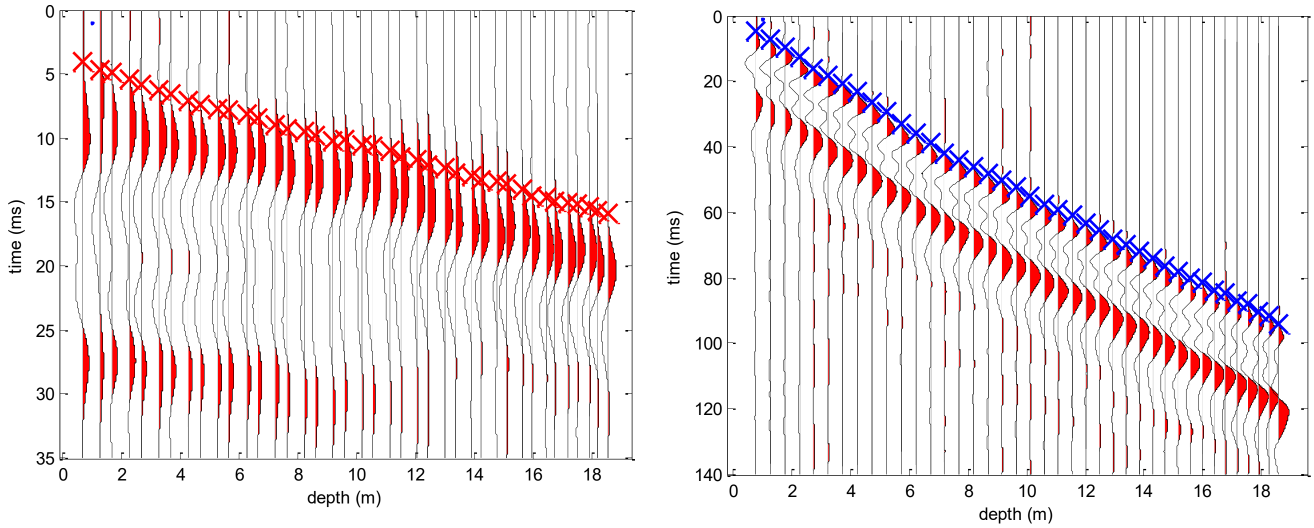

Figure 3. SPDMT recorded seismic traces at Mirandola test site for P-waves (left) and S-waves (rigth).

3.2 SPDMT survey

The profiles with depth of the DMT parameters at Mirandola test site are reported in Figure 2, in terms of material index I_D (indicating soil type), constrained modulus M, undrained shear strength c_u, and horizontal stress index K_D (related to stress history/OCR), obtained using common DMT interpretation formulae (Marchetti 1980, Marchetti et al. 2001). The ground water level was detected at 4.6 m depth by means of the C-readings (see Marchetti et al. 2001). According to the lithological classification based on I_D, the Mirandola test site is characterized by silty sand and sandy silt (i.e. $I_D > 1.2$) in the upper 3.6 m depth, and then a silty clayey and clayey silty layer with low stiffness and strength parameters is encountered up to 7.7 m depth. A lens of silt and sandy silt is found between 7.7 m and 9.1 m depth before entering in a succession of silty sand and sandy silt characterized by high geotechnical properties. These lithologies partially correspond to the geological borehole log, considering that I_D is not a grain size distribution index but it infers the mechanical soil behaviour.

For seismic wave velocity determination the S-wave pendulum hammer was 0.8 m far from the rods, while the P-wave impulsive source was located at 1.5 m from SDMT axis. The data recording equipment was able to record 700 samples at a sampling time of 50 µs and 200 µs respectively for P-wave and S-wave, using two different external triggers. Recorded seismic traces for all the sensors and for both methods are reported in Figure 3 together with the first break picking used in the determination of velocities. For both seismic waves, a high quality of the traces has been obtained after appropriate filtering of the raw data. Nevertheless travel time determination for P-waves resulted difficult due to the time resolution required for a correct determination and due to the oscillating nature of the arrival times in some portion of the stratigraphy (particularly for the first 5 m from the ground surface).

3.1 Comparisons of the results

At Mirandola test site V_S and V_P values from SPDMT are compared to the DH, CH and suspension logging profiles provided by the InterPACIFIC teams as shown in Figure 4. Shear wave velocity data estimated from the trial SPDMT are in very good agreement with the other invasive results with all the interpretation methods considered. The *true-interval* velocity analysis by means of the cross-correlation of seismic traces provided more stable results with respect to the first break picking. Instead, compression wave values from SPDMT are only in broad accordance with the InterPACIFIC interpretations. An higher variability in the *true-interval* velocity can be observed in the data reflecting the lower resolution in time delay determination due to the higher velocity of P-waves. Particularly in the first 5 m investigation depth cross-correlation of seismic traces provided very coarse result not reported in the figure. Conversely the *direct method* interpretation, mediating the inaccuracies over wide intervals is able to provide a reference profile which is more in agreement with other available data. Results can be therefore considered acceptable considering also the seasonal fluctuations of the ground water table that can create some variability in the partial/full saturation of the upper portion of the soil deposit (5.0-7.5m).

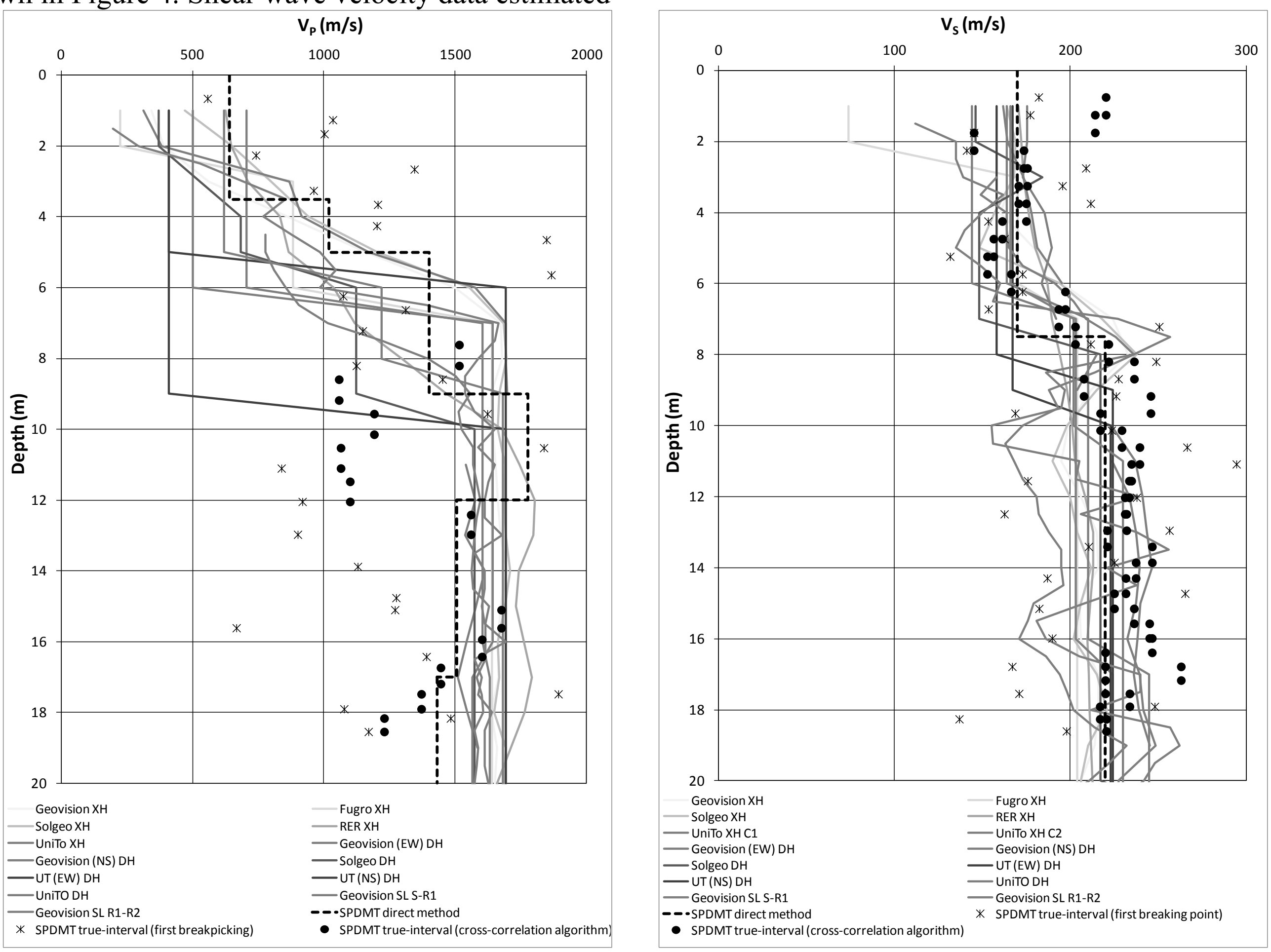

Figure 4. Comparisons between CH, DH suspension logging results of the InterPACIFIC project (grey lines, Garofalo et al. 2016) and SPDMT results (black line and symbols) in terms of V_S and V_P values at Mirandola test site.

4 CONCLUSIONS

This article reports on the first application a trial seismic dilatometer-V_P (SPDMT) recently developed to measure the compressional wave velocity V_P, in addition to the shear wave velocity V_S and to the DMT geotechnical parameters. Results have confirmed the high reliability of V_S determination from the SDMT test and an acceptable agreement in terms of V_P.

Further tests are required to improve the quality of acquired P-wave traces by improving the sensors response in order to increase reliability also of true interval determinations. Trials are ongoing to reduce eventual presence of tube waves by mechanically disconnecting the SPDMT seismic module from the rods.

5 ACKNOWLEDGEMENTS

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