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The Use of SDMT Data for Local Seismic Response Studies in the Catania Area

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ABSTRACT

Soil stiffness at small strain is a key parameter to solve many geotechnical problems, such as the design of the foundation and the knowledge of the seismic behaviour. There are many methods to perform in-situ soil shear wave velocity measurements: Down Hole test (D-H), Cross Hole test (C-H), Spectral Analysis of Surface Waves (SASW), Multichannel Analysis of Surface Waves (MAWS), etc. Among these methods, the use of Seismic Dilatometer Marchetti Tests (SDMT) to measure the shear wave velocity profile was developed and used in Italy. This test shows good repeatability of the measurements and the possibility to know, at the same time, the mechanical soil characteristics in the static field. In order to evaluate the soil profile of shear wave velocity (V_s), deep site investigations have been undertaken in some Italian sites, prone to high seismic risk. C-H and D-H tests, SDMT and Noise Analysis Surface Waves (NASW) have been carried out. In this paper, the relevance of using the Seismic Dilatometer Marchetti Tests (SDMT) as a basic tool for a comprehensive soil site characterization to carry out a local seismic response study was analyzed.

Keywords: SDMT; local seismic response; shear wave velocity; vertical drained constrained modulus.

1. Introduction

The geotechnical characterization of Catania area by in-situ and laboratory tests has a great importance because the east coast area of Sicily is considered as one of the zones of Italy with greater high seismic risk, basing on the past and current seismic history and on the typology of civil buildings and industrial activities (Cavallaro et al. 1999, 2005, 2006a, 2006b, 2008, 2012, Castelli et al. 2018). The knowledge of soil dynamic properties gives the possibility to preview the soil behaviour during the seismic events.

In the last years, the construction of reinforced concrete buildings, founded on normally consolidated clayey deposits, started in the industrial area of Catania (Sicily, Italy). Thus, there is a significant need to perform dynamic soil property measurements by in laboratory and in-situ tests.

The geotechnical earthquake engineering problems require the evaluation of the dynamic soil properties. The mechanical properties associated with dynamic loading are: shear wave velocity (V_s), shear modulus (G), damping ratio (D), and Poisson's ratio (ν). To determine soil dynamic properties, the current state of practice involves estimating or measuring shear waves velocity V_s in the field, using geophysical methods and estimating or measuring the variation in laboratory of shear modulus G and damping ratio D as a function of shear strain γ.

In this work, an intensive geotechnical site characterization has been performed in Catania area to evaluate geotechnical characteristics of the soil. In-situ tests included the execution of several SDMT tests that have allowed the definition of the initial elastic stiffness at very small strains and in-situ shear strength parameters at high strains. This information has been used to calibrate the parameters of the constitutive model for static and seismic analyses.

The methodology reported in this paper provides a valuable base for the evaluation of the site response analysis or for more complex problems that involve, as example, seismic soil-structure interaction (SSI) effects (Cavallaro et al. 2024; Castelli et al. 2024).

2. Soil general characterization

The M6 industrial building site is located in the industrial area of Catania. To determine the geological profile and the geotechnical characteristics of the soil, in-situ tests such as boreholes (n. 23), cone penetration tests (n. 7 tests), standard penetrations tests (n. 1 test), down-hole seismic tests (n. 2 tests) and seismic dilatometer Marchetti test (n. 1 test) have been carried out. The obtained profile shows that the underground soil is constituted mainly by clayey-silt and silty-clay up to a depth of 35-40 meters from ground surface. The water table, determined by piezometers, is located at around 1.5 meters below the ground surface.

Among the in-situ tests, down-hole seismic tests have been performed up to a depth of 36 meters and the cone penetration dissipation tests CPTU (n. 4 tests) have been performed up to a depth of 60 meters, with the pore pressure measurement for the dissipation tests. In particular, starting from the ground level, the following layers have been found:

A. superficial thin layer from ground level to 6 m of clayey sandy silt,
B. a thick layer (to 6 - 12 m depth) of alternance of silty clay and clayey silt,
C. a layer (to 12 - 23 m depth) of dark gray silty clay,
D. a layer (to 23 - 27 m depth) of brown silty fine sand,
E. a layer (to 27 - 28.5 m depth) of clayey silt and silty clay,
F. a layer (to 28.5 - 30.5 m depth) of sandy clayey silt,
G. a layer (to 30.5 - 32.5 m depth) of sandy gravel,
H. a layer (to 3.25 - 34 m depth) of brown-grey silty sand,
I. a layer (to 34 - 35.5 m depth) of fine gravel,
J. a layer (to 35.5 - 40 m depth) of alternance of blue grey clay and brown sandy silt,
K. a layer (to 40 - 45 m depth) of blue grey silty clay.

From the soil profile, it can be highlighted that the soil layer has the same nature in all the boreholes but the thickness of each layer can be significantly different from one boreholes to another.

The index properties and the mechanical characteristics of the soil have been evaluated from laboratory tests carried on undisturbed soil samples, with the aim to compare the values of the geotechnical parameters determined by laboratory tests with those derived from in-situ tests.

Due to the seismicity and the geotechnical properties of the area, the soil deformability has been investigated both in static conditions by oedometer tests and in dynamic conditions by resonant column tests.

The mechanical characteristics of the soil foundation derived from the laboratory tests are shown, as function of depth, in Fig. 1. The index tests classified the soil as clayey-silt and silty-clay with the following average parameters: liquidity limit w_L varies from 43 up 84 %, plasticity limit w_P is about 25 - 46 %, consistence index IC varies from 0.42 up 1.90. The values of the natural moisture content w_n prevalently range between 32 and 72 % as depth increasing, while the soil unit weight is equal around to 17 kN/m^3.

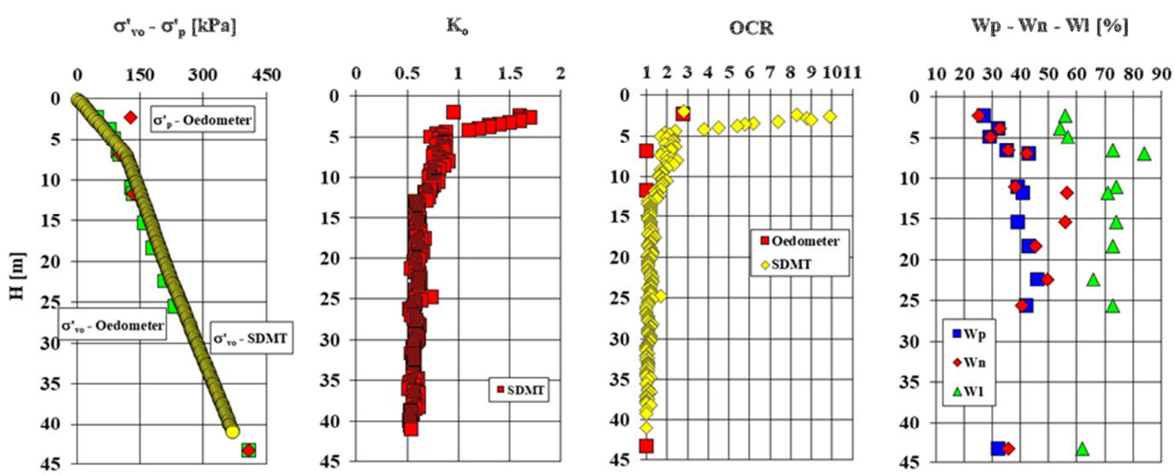

Figure 1. Stress history from in-situ and laboratory tests.

Fig. 2 shows the plasticity properties of numerous soil samples taken in the clayey-silt and silty-clay formation in the industrial area of Catania. The soil deposits can be classified as MH-OH inorganic silts and organic clays of low plasticity.

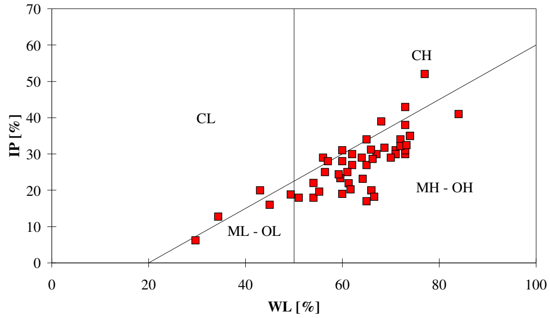

Figure 2. Plasticity chart.

The variability of the grain size distribution is somehow confirmed by the material index, I_D, evaluated by flat dilatometer tests (SDMT) carried out in the same formation. The clay fraction (CF) is predominantly in the range of 2 - 54 %. This percentage decreases to 0 - 2 % at the depth of 95 m where a sand fraction of 4 - 9 % is observed. The gravel fraction is always zero. The silt fraction is in the range of about 50 - 100 %.

The good degree of homogeneity of the deposit is confirmed by comparing the cone penetration resistance q_c from mechanical cone penetration tests (CPT) performed at different locations over the investigated area. The variation of q_c with depth clearly shows the very poor mechanical characteristics of soil. Typical values of q_c are in the range of 0.01 to 0.49

MPa. The soil deposits can be classified as inorganic silt of high compressibility and organic clay.

The preconsolidation pressure σ'_p and the overconsolidation ratio OCR = σ'_p / σ'_{vo} were evaluated from the 24 hours compression curves of 5 incremental loading (IL) oedometer tests, Fig. 1. Moreover, a SDMT was used to assess OCR and the coefficient of earth pressure at rest K_o following the procedure suggested by Marchetti (1980). The OCR values obtained from SDMT range from 1 to 10 (K_o = 0.5 to 1) with an average value equal to 1.2 up to about 10 for the 40 m deep sounding. The OCR values inferred from oedometer tests are lower than those obtained from in-situ tests, as shown from Fig. 1c.

One possible explanation of these differences could be that lower values of the preconsolidation pressure σ'_p are obtained in the laboratory because of sample disturbance, as shown by Cavallaro et al., 2008.

Typical range of physical characteristics, index properties and strength parameters of the deposit are reported in Table 1.

Table 1. Mechanical range characteristics for Catania STM M6 area.

Site	γ [kN/m^3]	e	c_u [kPa]	c' [kPa]	ϕ' [°]
STM M6	16.6-20.2	0.56-1.51	28.75-203.61	2.41-21.7	16-18

where: c_u (Undrained shear strength), c' (Cohesion) and ϕ' (Angle of shear resistance) were calculated from and C-U (7 tests) and C-D (4 tests) Triaxial Tests.

3. Dynamic soil properties

The SDMT provides a simple means for determining the initial elastic stiffness at very small strains and in-situ shear strength parameters at high strains in natural soil deposits (Marchetti 2008).

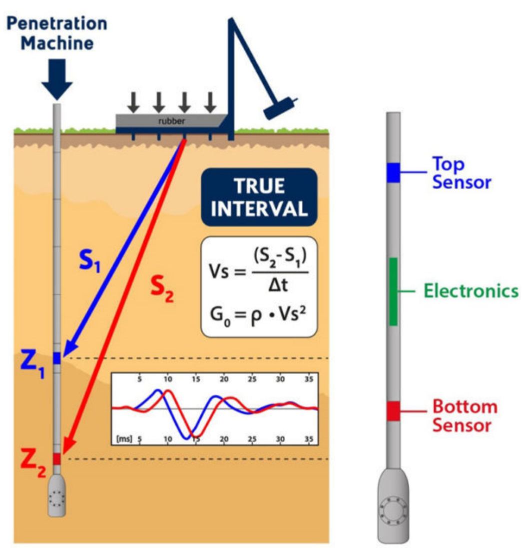

Figure 3. SDMT scheme for the measure of Vs.

Source waves are generated by striking a horizontal plank at the surface that is oriented parallel to the axis of a geophone connects by a co-axial cable with an oscilloscope (Martin and Mayne 1997, 1998). The measured arrival times at successive depths provide pseudo interval V_s profiles for horizontally polarized vertically propagating shear waves (Fig. 3).

Numerous DMT and SDMT tests have been performed in the seismic area of Catania (Castelli et al. 2016, Cavallato et al. 2015) and were also used in offshore condition by Cavallaro et al. (2013a, 2013b).

The small strain shear modulus G_o is determined by the theory of elasticity by the well-known relationship:

$$G_0 = \rho V_S{}^2 \tag{1}$$

where: ρ = mass density.

The results obtained from the SDMT tests are plotted with the depth in Figure 4 where:

- Id: Material Index; gives information on soil type (sand, silt, clay);

- M: Vertical Drained Constrained Modulus, estimated by SDMT using the correlation M = $R_M \cdot E_D$, where R_M is a function primarily of K_D (Horizontal Stress Index). Since K_D incorporates the effects of the horizontal stresses σ_h and stress history, then also M incorporates, through K_D, such effects. The capability of taking into account σ_h is important, since high σ_h dramatically reduce settlements (Massarsch 1994). For this reason, E_D (Dilatometer Modulus), in general, should not be used as such, because it lacks the stress history information contained in K_D, but should first be combined with K_D to obtain M. Note that E_D (despite the symbol) should not be confused with the Young's modulus, E. If required, E can be derived from M via theory of elasticity (E ≅ 0.8 · M for ν = 0.20 - 0.30). Furthermore, the relationship used to calculate R_M depends on the values assumed by I_D (Material Index). Therefore, it is possible to observe in Figure 4 how the values assumed by M highlight the presence of a silty layer on the surface strata and at a depth of approximately 11 m.

- C_u: Undrained Shear Strength;

- K_d: Horizontal Stress Index; the profile of Kd is similar in shape to the profile of the overconsolidation ratio OCR. K_d = 2 indicates in clays OCR = 1, K_d > 2 indicates overconsolidation. A first glance at the K_d profile is helpful to "understand" the deposit;

- V_s: Shear Waves Velocity.

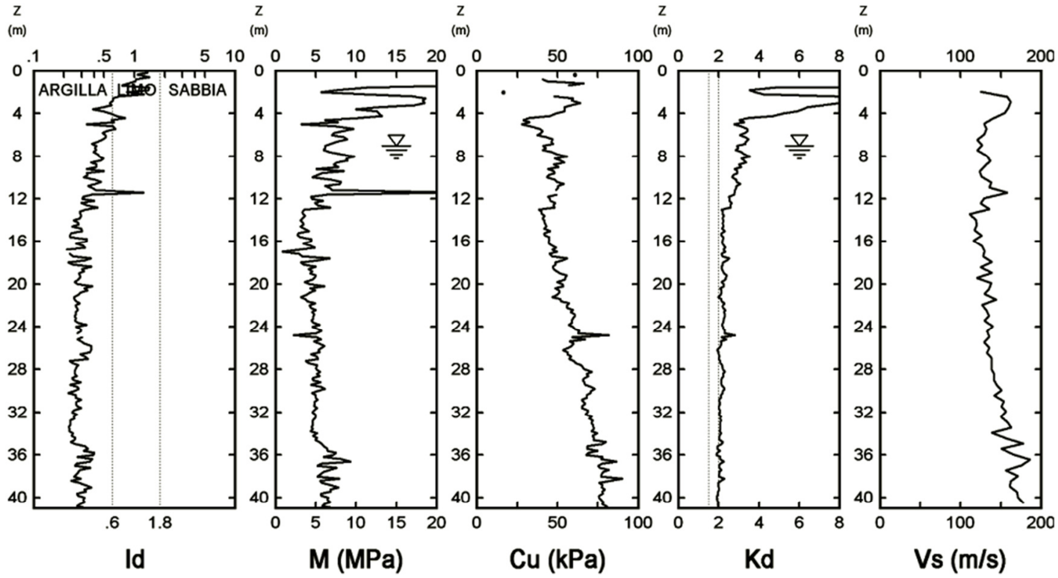

Figure 4. Summary of SDMTs in STM M6 area.

The Poisson ratio variation with depth, obtained from a Down Hole (D-H) test oscillates around 0.49.

Fig. 5 shows the values of V_s obtained in-situ from a D-H test and SDMT and those measured in the laboratory from RCT performed on undisturbed solid cylindrical specimens which were isotropically reconsolidated to the best estimate of the in-situ mean effective stress.

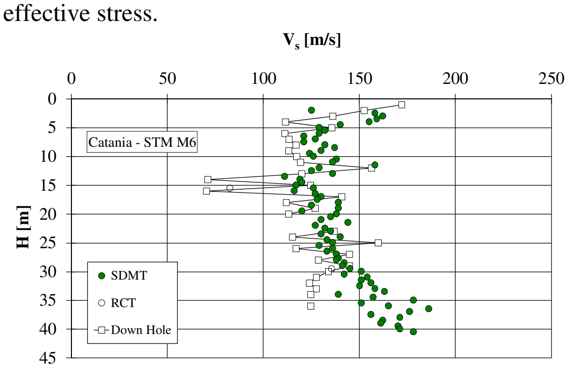

Figure 5. V_s by D-H, SDMT and RCT.

Quite a good agreement exists between the laboratory and in-situ test results. On average the ratio of G_o (Lab) to G_o (Field) by SDMT and DH was equal to about 0.90 at the depth of 29.5 m.

The experimental results of specimens obtained by RCT were used to determine the empirical parameters of the equation proposed by Yokota et al. (1981) (Fig. 6) to describe the shear modulus decay with shear strain level:

$$\frac{G(\gamma)}{G_0} = \frac{1}{1+\alpha\gamma(\%)^{\beta}} \quad (2)$$

in which:

$G(\gamma)$ = strain dependent shear modulus;

γ = shear strain;

α, β = soil constants.

Equation (2) allows the complete shear modulus degradation to be considered with strain level (Maugeri 1995).

The values of α = 7.15 and β = 1.223 were obtained for STM M6 clay by Carrubba and Maugeri (1988).

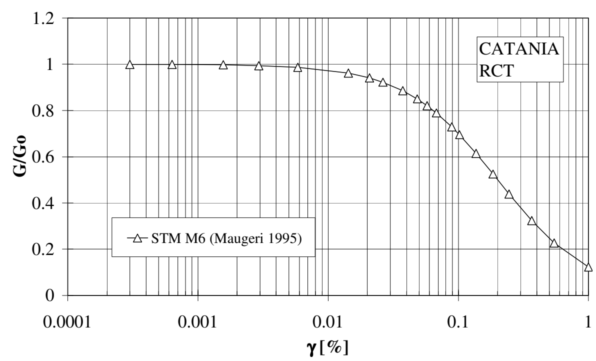

Figure 6. G/G_o-γ curves from RCT tests.

As suggested by Yokota et al. (1981), the inverse variation of damping ratio with respect to the normalized shear modulus has an exponential form as that reported in Figure 7 for the central area of Catania (Maugeri 1995):

$$D(\gamma)(\%) = \eta \, exp\left[-\lambda \frac{G(\gamma)}{G_0}\right] \quad (3)$$

in which: $D(\gamma)$ = strain dependent damping ratio; γ = shear strain; η, λ = soil constants.

The values of η = 28.12 and λ = 2.50 were obtained for STM M6 clay by Carrubba and Maugeri (1988).

Equation (3) assumes maximum value D_{max} = 28.12 % for $G(\gamma)/G_o$ = 0 and minimum value D_{min} = 2.30 % for $G(\gamma)/G_o$ = 1.

Therefore, Eq. (3) can be re-written in the following normalised form:

$$\frac{D(\gamma)}{D(\gamma)_{max}} = exp\left[-\lambda \frac{G(\gamma)}{G_0}\right] \quad (4)$$

These parameters were obtained from the damping values assessed by means of the steady-state method.

Moreover, in Figure 8, Maugeri 1995 proposed a comparison between the results obtained for the clay of Catania (Carrubba and Maugeri 1988) and those proposed by other authors Hara (1973), Yokota (1981), Tatsuoka (in Iwasaki (1997)) and Athanasopouls (1995) to derive G-γ curves from SDMT (Cavallaro and Grasso 2021).

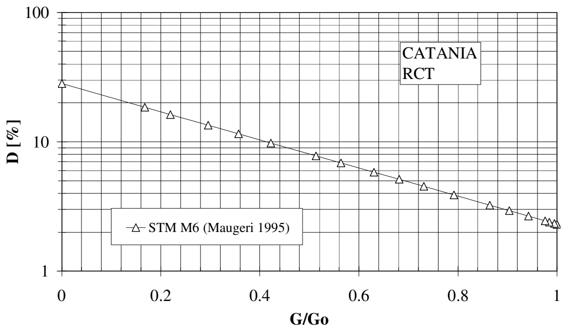

Figure 7. D-G/G_o curves from RCT tests.

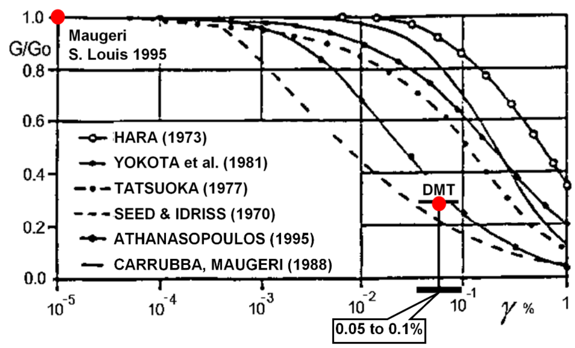

Figure 8. Tentative method for deriving G-γ curves from SDMT proposed by Maugeri (1995) and adapted by Marchetti (2008).

4. SDMT data for non-linear analyses

The non-linear soil behaviour has been simulated by the Hardening Soil model with small-strain stiffness (HSsmall). The HSsmall model, implemented in the finite element code PLAXIS, is based on the Hardening soil model (HS) with the addition of two parameters that describe the variation of stiffness with strain.

The HS model requires three stiffness moduli at the reference pressure, p^{ref}, of 100 kPa: E_{50}^{ref}, E_{ur}^{ref} and E_{oed}^{ref}. All moduli are stress-level dependent, according to the following relationships:

$$E_{oed} = E_{oed}{}^{ref}\left(\frac{\sigma'_1}{p^{ref}}\right)^m \tag{5}$$

$$E_{50} = E_{50}{}^{ref}\left(\frac{\sigma'_3}{p^{ref}}\right)^m \tag{6}$$

$$E_{ur} = E_{ur}{}^{ref}\left(\frac{\sigma'_3}{p^{ref}}\right)^m \tag{7}$$

where E_{50}^{ref} is the secant stiffness in standard drained triaxial test, E_{ur}^{ref} is the unloading/reloading stiffness, E_{oed}^{ref} is the tangent stiffness for primary oedometer loading, σ'_1 and σ'_3 are the major and minor principal effective stresses and m is the power for stress-level dependency of stiffness.

Monaco and Marchetti (2004) explained how the seismic dilatometer test (SDMT) can be used to determine the stiffness parameters. Based on an intensive literature survey carried out by Schanz and Vermeer (1997), they assumed E_{oed} equal to the constrained modulus, M. This approach was also used by Arroyo et al. (2008) and Cox and Mayne (2015).

In this study, the parameters for soil stiffness have been obtained from the Seismic Dilatometer Marchetti Test (SDMT) performed in the M6 industrial building site. The tangent stiffness modulus, E_{oed}^{ref}, has been imposed equal to the value of the constrained modulus dilatometer modulus, M=7 MPa (at p_{ref} = 100 kPa), as reported in Fig. 4. Moreover, the following ratios have been adopted:

$$E_{50}{}^{ref} = E_{oed}{}^{ref} \tag{8}$$

$$E_{ur}{}^{ref} = 3\,E_{oed}{}^{ref} \tag{9}$$

The exponent, m, and the Poisson's ratio for unloading-reloading, ν_{ur}, have been assumed equal to 0.5 and 0.2, respectively.

In order to describe the variation of stiffness with strain, two additional parameters were added in the HSsmall: the reference shear modulus at very small strain, G_0^{ref}, and shear strain level $\gamma_{0.7}$ at which the secant shear modulus G_S is reduced to 72.2 % of G_0. The stress dependency of the shear modulus G_0 is taken into account with the power law:

$$G_0 = G_0{}^{ref}\left(\frac{\sigma'_3}{p^{ref}}\right)^m \tag{10}$$

The value of $G_0{}^{ref}$ is given by Eq. (2), in which V_S is the shear wave velocity obtained from SDMT test (at p_{ref} = 100 kPa) (Fig. 5). The value of $\gamma_{0.7}$ has been taken from the G/Go-γ curve (Fig. 6). The strength parameters have been derived directly from C-D Triaxial Tests (Table 1). In the HSsmall, the tangent shear modulus, G_t, is given by the following equation:

$$G_t = \frac{G_0}{\left(1+0.385\frac{\gamma}{\gamma_{0.7}}\right)^2} \tag{11}$$

The comparison between the HSsmall model and the G/Go- γ curve (Fig. 6) is presented in Fig. 9. Table 2 reports the input parameters of the HSsmall model model for the M6 industrial building site.

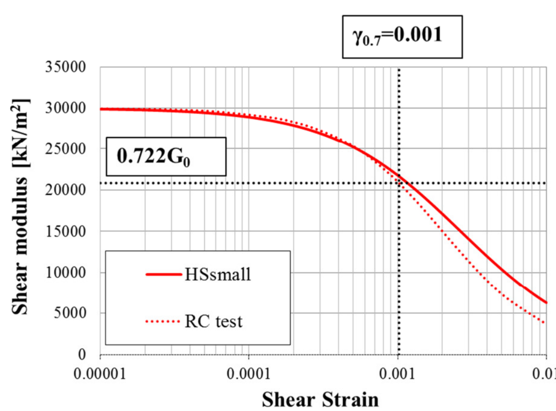

Figure 9. Comparison between the HS small model and the RC test.

Table 2. Input parameters of the HS small model for the M6 industrial building site.

Parameter	Value	Unit
γ	18	$[kN/m^3]$
c'	10	kN/m^2
φ'	17	°
E_{50}^{ref}	7000	kN/m^2
E_{oed}^{ref}	7000	kN/m^2
E_{ur}^{ref}	21000	kN/m^2
p^{ref}	100	kN/m^2
m	0.5	-
G_0^{ref}	30000	kN/m^2
$\gamma_{0.7}$	0.001	-

5. Conclusions

In this study, information concerning the geotechnical characterization from SDMT data for the evaluation of the site response analysis have been delineated. SDMT data has been collected in the area of Catania, in South-Eastern Sicily (Italy). It was shaken by several strong earthquakes in the past that produced significant damages.

The Hardening Soil model with small-strain stiffness (HSsmall) has been employed to simulate the non-linear soil behaviour. It is an advanced constitutive model implemented in the finite element code PLAXIS. The HSsmall is a modification of the Hardening soil model (HS) model that accounts for increased stiffness of soils at small strains. The SDMT data has been employed to determine the three stiffness controlling parameters using the constrained modulus, M. Moreover, the initial reference shear modulus at very small strains has been obtained by SDMT test from the shear wave velocity, VS.

This work illustrates the potential of the SDMT test as an in-situ test for the soil site characterization useful for performing site response analyses.

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