

# SDMT Soil Testing for the Local Site Response Analysis

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**Abstract** – To evaluate the basic data for a seismic response analysis it is possible to use many direct methods to obtain the shear wave velocity profile of the soil: Down Hole, Cross Hole, SASW, MASW, etc. Among these methods, recently the use of Seismic Dilatometer Marchetti Tests (SDMT), to measure the shear wave velocity profile, was developed and used in Italy. The SDMT 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 this paper some test sites at Catania city, prone to high seismic risk, were studied to know the dynamic soil profile, among them are the "Piana di Catania - STM M6", "Monte Po", "San Giuseppe la Rena", "Villa Comunale - Bellini Garden" and "Catania Harbour" sites. Seismic Dilatometer Marchetti Tests (SDMT) have been carried out with the aim to evaluate the soil profile of shear waves velocity ( $V_s$ ) in the perspective of site effects evaluation.

## I. INTRODUCTION

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 [1]. The knowledge of soil dynamic properties gives the possibility to preview the soil behavior during the seismic events. A number of field and laboratory techniques have been developed over the last 35 years to measure the dynamic properties of soils [2-3].

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 ( $\nu$ ). 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  $\gamma$ .

To the aim of soil dynamic characterization, in situ tests are available such as Down-Hole, Cross-Hole, SASW and Seismic Dilatometer Marchetti Tests (SDMT) and in laboratory tests such as Resonant Column (RCT) and Cyclic Torsional Shear Tests (CLTST).

In this paper the results obtained by SDMT and RCT were studied to evaluate the basic data for a seismic response analysis of Catania area.

## II. BASIC SOIL PROPERTIES

Laboratory tests have been performed on undisturbed samples retrieved by means of an 86 mm Shelby tube sampler.

The investigation programme was performed in five different areas of Catania:

1. the "Piana di Catania (STM - M6)" site in the S-E zone of the city [4-5];
2. the "Monte Po" site in the N-W zone of the city [6-7];
3. the "San Giuseppe la Rena" site along the southern coast line of the city [8];
4. the "Villa Comunale - Bellini Garden" site in the central area of the city [9-10];
5. the "Catania Harbour" site in the Sud area of the city [10].

In the "Piana di Catania (STM - M6)" area [11], 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 values of the natural moisture content,  $w_n$ , range from between 22 and 56 %. Characteristic values for the Atterberg limits are:  $w_L = 54 - 84$  % and  $w_p = 27 - 46$  %, with a plasticity index of  $PI = 22 - 41$  %.

In the "Monte Po Hill" the area [6-7] is related to a layered soil made by a succession of Terreforti clays, sands and volcanic coarse. Generally, a thin layer of altered soil can be observed in the area with thickness ranging from 0 to about 1 m. Then, four different unit can

be recognized: a layer of medium-stiff alluvial silt of medium plasticity with thickness ranging from 50 cm to 4 m; a layer of very sandy gravel which was detected only in some boreholes with thickness ranging from 25 cm to about 4 m; a formation of conglomerate and sand with thickness ranging from 50 cm to about 3 m; finally a layer of clay of upper plasticity range locally representing the sub-grade. In the Catania "Monte Po Hill" area, the clay fraction (CF) is predominantly in the range of 28 - 44 %. This percentage decreases to 17 % at the depth of 7 m where a sand fraction of 42 % is observed. The gravel fraction is always zero. The silt fraction is in the range of about 3 - 42 %.

The "San Giuseppe la Rena" area [8], in the south zone of Catania, is characterized by fine sands with presence of silt at greater depth.

The "Villa Comunale - Bellini Garden" area [9-10] is related to clayey soil in the central area, the deposits mainly consist of silty clay with a natural moisture content  $w_n$  of between 20 and 27 %.

The "Catania Harbour" site [10] consists of a layer of yellow sands of bottom (to 0- 2 m depth), a layer of black sands slightly silty (to 2 - 10 m depth), a layer of black silty sands with intervals lava sands (to 10 - 16 m depth), a layer of organogenic sands with sandy silt (to 16 - 50 m depth). The index tests classified the soil as a sand or silty sand and as a sandy silt in the lower layers with the following average parameters: soil unit weight  $\gamma$  is prevalently in the range between 16.7 to 20.0 kN/m<sup>3</sup>, specific weight unit  $G_s$  is about 2.46 - 2.72, void index  $e$  is about 0.635 - 0.916, cohesion  $c'$  varies from 1.00 up 65.00 kPa, angle of shear resistance  $\phi'$  ranges from 21° up 39°. As regard the lower layers liquidity limit  $w_L$  varies from 60 up 78 %, plasticity limit  $w_p$  is about 41 - 30 %, consistence index IC is higher than 1. The values of the natural moisture content  $w_n$  prevalently range between 21 and 28 %.

### III. STIFFNESS AND DAMPING RATIO

Shear modulus  $G$  and damping ratio  $D$  of Catania test sites deposits were obtained in the laboratory from resonant column tests (RCT). A resonant column/torsional shear apparatus [9] was used for this purpose.

The Resonant Column test for determining modulus and damping characteristics of soil is based on the theory of waves propagation. Either compression waves or shear waves can be propagated through the soil specimen from which either Young's modulus or shear modulus can be determined. In a Resonant Column apparatus the excitation frequency is adjusted until the specimen experience resonance. The modulus is computed from the resonant frequency and the geometric properties of the specimen and driving apparatus. A measure of the damping ratio can be obtained by either of two methods,

amplitude decay or steady state methods.

$G$  is the unload-reload shear modulus evaluated from RCT, while  $G_0$  is the maximum value or also "plateau" value as observed in the  $G$ - $\log(\gamma)$  plot. Generally  $G$  is constant until a certain strain limit is exceeded. This limit is called elastic threshold shear strain ( $\gamma_t^e$ ) and it is believed that soils behave elastically at strains smaller than  $\gamma_t^e$ . The elastic stiffness at  $\gamma < \gamma_t^e$  is thus the already defined  $G_0$ .

For Catania RCTs the damping ratio was determined using two different procedures: following the steady-state method, the damping ratio was obtained during the resonance condition of the sample; following the amplitude decay method it was obtained during the decrement of free vibration.

Nineteen Resonant Column (RCT) tests have been performed by using the same apparatus to evaluate the shear modulus  $G$  and damping ratio  $D$  of the municipal area of Catania soil.

The laboratory test conditions and the obtained small strain shear modulus  $G_0$  are listed in Table 1.

Table 1. Test condition for Catania soil specimens.

Site	Test No.	H [m]	$\sigma'_{vc}$ [kPa]	$e$	PI	$G_0$ [MPa]	RCT
1	1	6.95	70	0.999	18.81	32	U
1	2	11.15	106	1.093	25.03	17	U
1	3	22.75	240	1.056	19.65	28	U
1	4	35.50	240	0.724	20.26	17	U
1	5	56.00	400	0.970	28.66	32	U
2	1	20.70	211	0.873	31	61	U
3	1	-	38	0.721	-	71	U
3	2	-	57	0.711	-	79	U
3	3	-	105	0.685	-	113	U
3	4	-	39	0.796	-	62	U
3	5	-	55	0.765	-	60	U
3	6	-	102	0.769	-	82	U
4	1	17.00	172	0.582	26.05	-	U
4	2	22.00	246	0.653	28.60	64	U
4	3	35.70	375	0.695	20.02	77	U
4	4	39.00	411		31.40	93	U
5	1	48.60	100	0.920	18.71	198	U
5	2	48.60	200	0.711	18.71	211	U
5	3	48.60	300	0.685	18.71	213	U

where: U = Undrained, H = sample depth.

Generally the undisturbed specimens were first isotropically reconsolidated to the best estimate of the in situ effective stress and then subjected to RCT (Resonant Column Test).

For "Catania Harbor" sample an undisturbed specimens was isotropically reconsolidated to three different reference effective stress. The same specimen was subject to RCT after a rest period of 24 hrs.

The size of solid cylindrical specimens are Radius = 25 mm and Height = 100 mm.

Figure 1 shows the results of RCTs normalised by dividing the shear modulus  $G(\gamma)$  for the initial value  $G_0$  at very low strain.

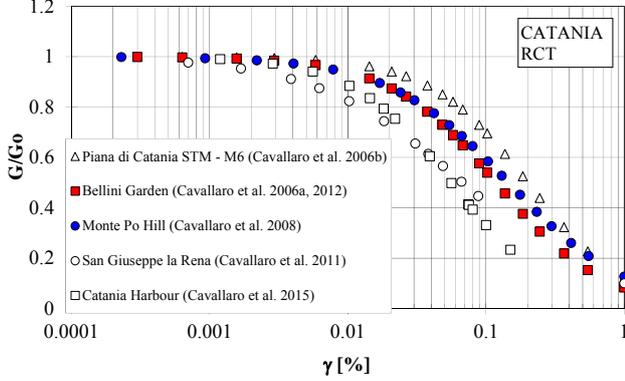


Figure 1.  $G/G_0$ - $\gamma$  curves from RCT.

The experimental results of specimens were used to determine the empirical parameters of the equation proposed by [12] to describe the shear modulus decay with shear strain level:

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

The expression (1) allows the complete shear modulus degradation to be considered with strain level. The values of  $\alpha$  and  $\beta$  were obtained for the five test sites of Catania city.

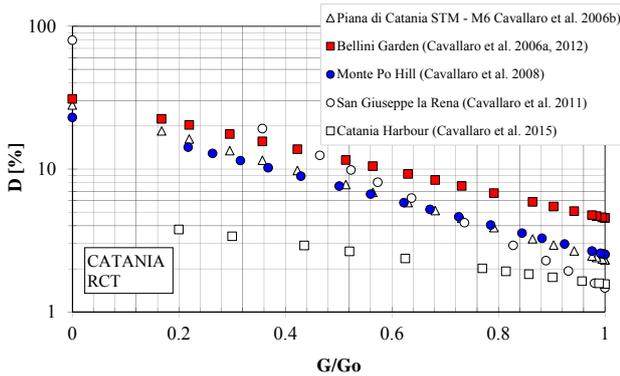


Figure 2.  $D$ - $G/G_0$  curves from RCT.

As suggested by [12], the inverse variation of damping ratio in respect to the normalized shear modulus has an exponential form, like that reported in Figure 2:

$$D(\gamma)(\%) = \eta \cdot \exp\left[-\lambda \cdot \frac{G(\gamma)}{G_0}\right] \quad (2)$$

in which:  $D(\gamma)$  = strain dependent damping ratio;  $\gamma$  = shear strain and  $\eta$ ,  $\lambda$  = soil constants. The values of  $\eta$  and  $\lambda$  were obtained for the five test sites of Catania city. For the "Piana di Catania (STM - M6)" site equation (2) assumes the maximum value  $D_{\max} = 28.12$  % for  $G(\gamma)/G_0 = 0$  and a minimum value  $D_{\min} = 2.30$  % for  $G(\gamma)/G_0 = 1$ . For the "Monte Po" site equation (2) assumes the maximum value  $D_{\max} = 23$  % for  $G(\gamma)/G_0 = 0$  and a minimum value  $D_{\min} = 2.52$  % for  $G(\gamma)/G_0 = 1$ . For the "San Giuseppe la Rena" site equation (2) assumes the maximum value  $D_{\max} = 80$  % for  $G(\gamma)/G_0 = 0$  and a minimum value  $D_{\min} = 1.46$  % for  $G(\gamma)/G_0 = 1$ . For the "Villa Comunale - Bellini Garden" site equation (2) assumes the maximum value  $D_{\max} = 31$  % for  $G(\gamma)/G_0 = 0$  and a minimum value  $D_{\min} = 4.54$  % for  $G(\gamma)/G_0 = 1$ . For the "Catania Harbour" site equation (2) assumes the maximum value  $D_{\max} = 3.77$  % for  $G(\gamma)/G_0 = 0.2$  and a minimum value  $D_{\min} = 1.56$  % for  $G(\gamma)/G_0 = 1$ .

Therefore, equation (2) can be re-written in the following normalised form:

$$\frac{D(\gamma)}{D(\gamma)_{\max}} = \exp\left[-\lambda \cdot \frac{G(\gamma)}{G_0}\right] \quad (3)$$

The expressions (1) and (3) were used by [1-11].

The values of empirical parameters of equations, (2) and (3) are reported in Table 2.

Table 2. Soil constants for the municipal area of Catania.

Site	$\alpha$	$\beta$	$\eta$	$\lambda$
1	7.15	1.223	19.87	2.16
2	6.9	1	23	2.21
3	9	0.815	80	4
4	11	1.119	31	1.921
5	32	1.2	4.7	1.1

#### IV. SHEAR WAVE VELOCITY AND STIFFNESS BY DOWN HOLE TESTS (DH) AND SEISMIC DILATOMETER MARCHETTI TESTS (SDMT)

It is well known that the initial stiffness is a fundamental soil property relevant to the prediction of amplification effects of earthquakes and, therefore, required inputs for seismic response analysis include small-strain shear modulus,  $G_0$ , for each layer.

This parameter is directly related to small-strain shear wave velocity,  $V_s$ , by:

$$G_0 = \rho V_s^2 \quad (4)$$

where:  
 $\rho$  = mass density of soil.

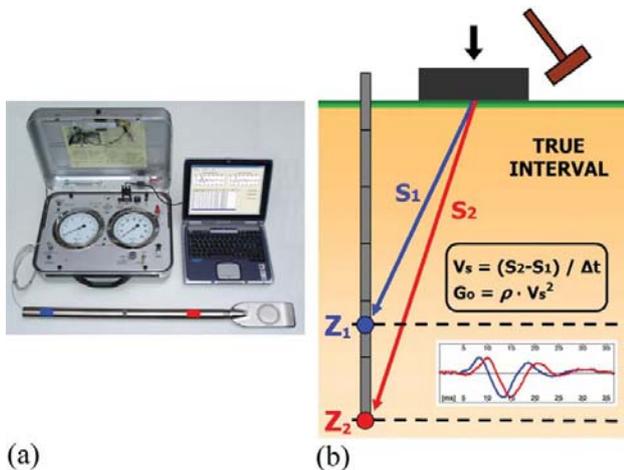


Figure 3. Seismic dilatometer test: (a) SDMT equipment (blade and seismic module); (b) Schematic test layout.

The current state of practice for determining  $G_0$  involves estimating or measuring  $V_s$  in the field. Among the various measurement techniques, it is common opinion that the most accurate testing technique is the cross-hole test but it is often a current practice to consider the down-hole test as a reliable solution for standard engineering problems.

The down-hole tests were performed according to conventional approaches, with surface sources and 1-D geophones embedded in the receiver borehole. The small strain ( $\gamma \leq 0.001\%$ ) shear modulus,  $G_0$ , was determined from SDMT and Down Hole (D-H) tests. The Seismic Dilatometer Marchetti Test (SDMT) is an instrument resulting from the combination of the DMT blade [13-16]

with a modulus measuring the shear wave velocity. The seismic module is an instrumented tube, located above the blade (see Figure 3), housing two receivers at a distance of 0.50 m. The test configuration "two receivers"/"true interval" avoids the problem connected with the possible inaccurate determination of the "first arrival" time sometimes met with the "pseudo interval" configuration (just one receiver). Also the pair of seismograms at the two receivers corresponds to the same blow, rather than at two successive blows - not necessarily identical. The adoption of the "true interval" configuration considerably enhances the repeatability in the  $V_s$  measurement.

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.

Source waves are generated by striking a horizontal plank at the surface that is oriented parallel to the axis of a geophone connected to a co-axial cable with an acquisition system [17-18]. The measured arrival times at successive depths provide pseudo interval  $V_s$  profiles for horizontally polarized vertically propagating shear waves.  $V_s$  may be converted into the initial shear modulus  $G_0$ .

The combined knowledge of  $G_0$  and the one dimensional modulus  $M$  (from DMT) may be helpful in the construction of the  $G$ - $\gamma$  modulus degradation curves. The  $V_s$  determinations are executed at 0.50 m depth intervals. A summary of SDMTs parameters is shown in Figure 4 for "Piana di Catania (STM - M6)" area and in Figure 5 for "Catania Harbour" area where:

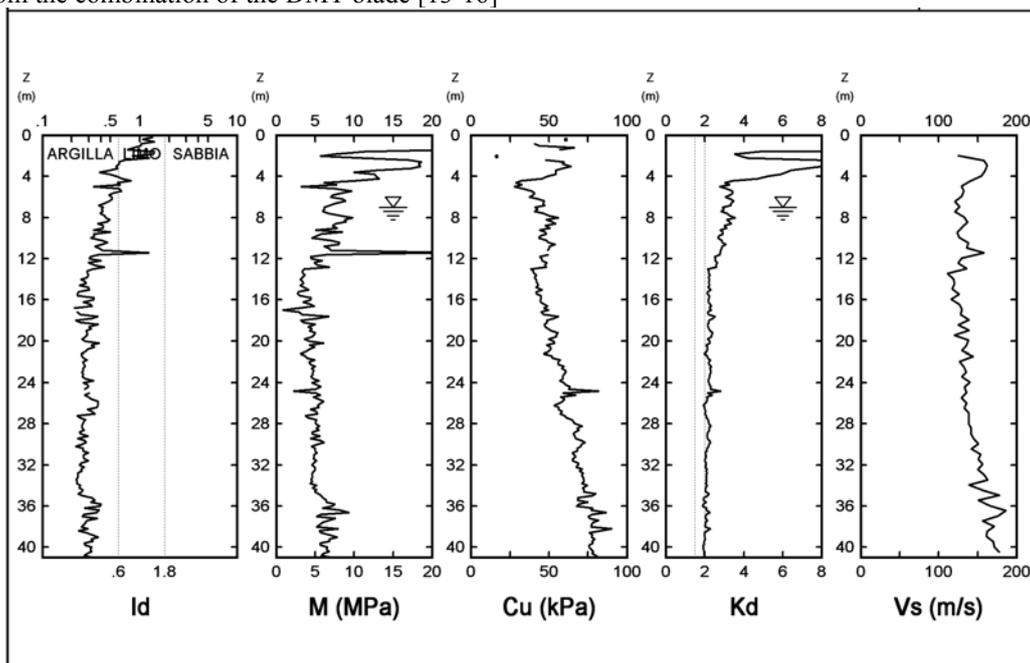


Figure 4. Summary of SDMT results in "Piana di Catania (STM - M6)" area.

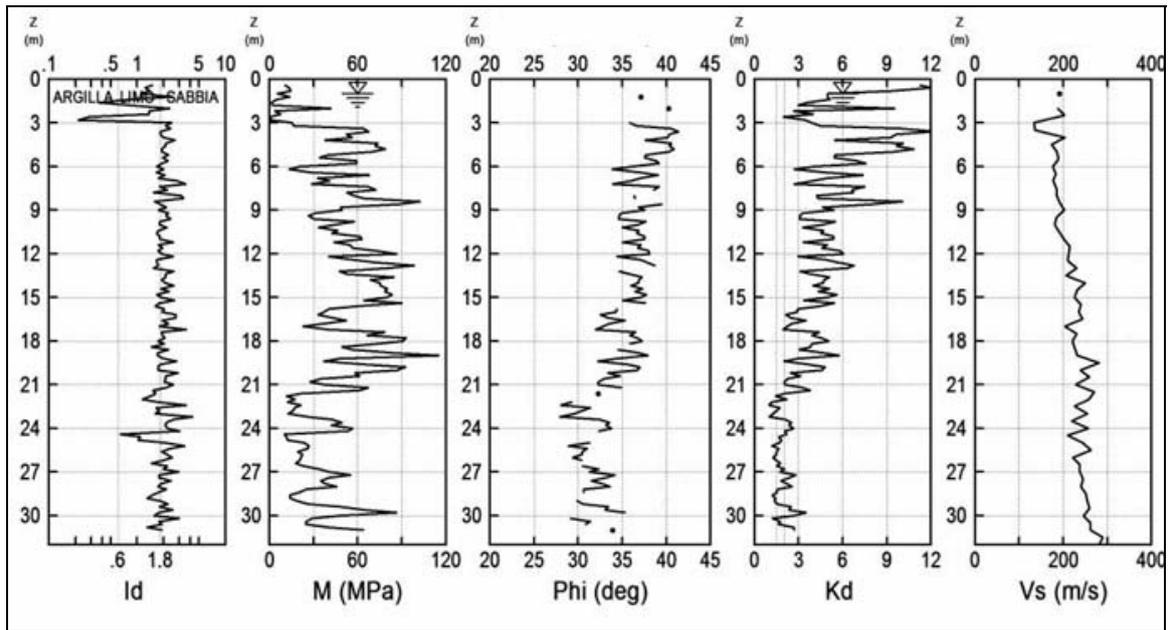


Figure 5. Summary of SDMT results in "Catania Harbour" area.

Id: Material Index; gives information on soil type (sand, silt, clay); M: Vertical Drained Constrained Modulus;  $C_u$ : Undrained Shear Strength;  $\phi'$  Angle of Shear Resistance;  $K_d$ : Horizontal Stress Index;  $V_s$ : Shear Waves Velocity. The profile of  $K_d$  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 define the deposit characteristics.

## V. CONCLUSIONS

A site characterization to evaluate the basic data for a seismic response analysis for Catania city has been presented in this paper, with particular reference to SDMTs.

On the basis of the data shown it is possible to draw the following conclusions:

- SDMTs were performed up to a depth of 40 meters; the results show a very detailed soil characterisation profiles of the more relevant soil properties, such as the material index (Id), the constrained modulus M and the dilatometer modulus  $E_d$ , the angle of shear resistance  $\phi'$  for sandy silty soil and undrained shear strength  $C_u$  for clayey soil, the shear wave velocity  $V_s$ , the horizontal stress index  $K_d$ .
- for the evaluation of shear modulus at small strain, Resonant Column tests have been performed;
- the results interpreted by the equations suggested by [12] describe the shear modulus decay with shear strain level and the inverse variation of damping ratio with respect to the normalized shear modulus. Results allowed also seismic geotechnical hazard evaluation in

the city of Catania (Italy) [19-26] also for soil-structure interaction [27-30] and for the retrofitting of buildings [31-35].

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