Soil Characterization of Catania Harbour by the Seismic Dilatometer Marchetti Test (SDMT)

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Keywords: Harbour, seismic risk, small shear modulus, damping.

ABSTRACT: The city of Catania, located on the eastern zone of Sicily, is prone to high seismic risk. The Catania harbour is an important tourist, industrial and commercial harbour of Italy. For site characterisation of soil, deep site investigations have been undertaken. Borings and seismic dilatometer Marchetti tests (SDMT) have been performed, with the aim to evaluate the soil profile of shear waves velocity (V_s). Moreover, the following laboratory tests were carried out on undisturbed samples retrieved with an 86 mm diameter Shelby sampler: oedometer tests, direct shear tests, triaxial tests and resonant column tests. The available data enabled one to compare the shear waves velocity profile obtained by empirical correlations and seismic dilatometer Marchetti tests (SDMT). The influence on stiffness decay curves G-γ and damping curves D-γ, as well as on shear strength, was evaluated by means of laboratory tests.

1 INTRODUCTION

Currently the Catania harbour is subject to modernization works. The works include construction of a large dock in the port, a work that will serve to move towards the beach of Playa commercial traffic and all containers that currently prevent the transit of citizens within the port. The result will be to return the port to the city and move the customs area in an area that will make use of the services and major infrastructure projects.

Site characterization is needed for evaluation of consolidation settlements of the sea bottom and of the material used to fill the area, as well as the stability of the quay wall and the seismic behaviour of the Catania harbour.

In order to study the dynamic characteristics of soils in the Catania harbour area, laboratory and in situ investigations have been carried out to obtain soil profiles with special attention being paid to the variation of the shear modulus G and damping ratio D with depth. Seismic dilatometer tests (SDMT) have been also carried out in the zone of the harbour area, with the aim of an accurate geotechnical characterisation, including the evaluation of the soil shear wave velocity V_s profile, as well as the profile of the horizontal stress index K_D. Moreover, the following investigations in the laboratory were carried out on undisturbed samples: oedometer tests, direct shear tests, triaxial tests and resonant column tests (RCT). This paper tries to summarize the geotechnical information in a comprehensive way in order to provide a case record of site characterization for the modernization works in a port area. Similar geotechnical study was also successful performed for significant historical test sites (Cavallaro et al. 1999a, 2003, 2004, 2013a).

2 GEOLOGY AND SEISMICITY OF THE AREA

The study are lies eastern Sicily, which is characterized by the presence of Mount Etna. This rests on top of two major structural units (Lentini et al. 1987): the Foreland Ibleo plateau and the Apennine-Maghrebian Chain, which is a system of aquifer sin south-verging tectonic scales.

The Foreland Iblean is the northern edge of the African plate and is characterized by a succession Meso-Cenozoic, mainly carbonate, repeatedly

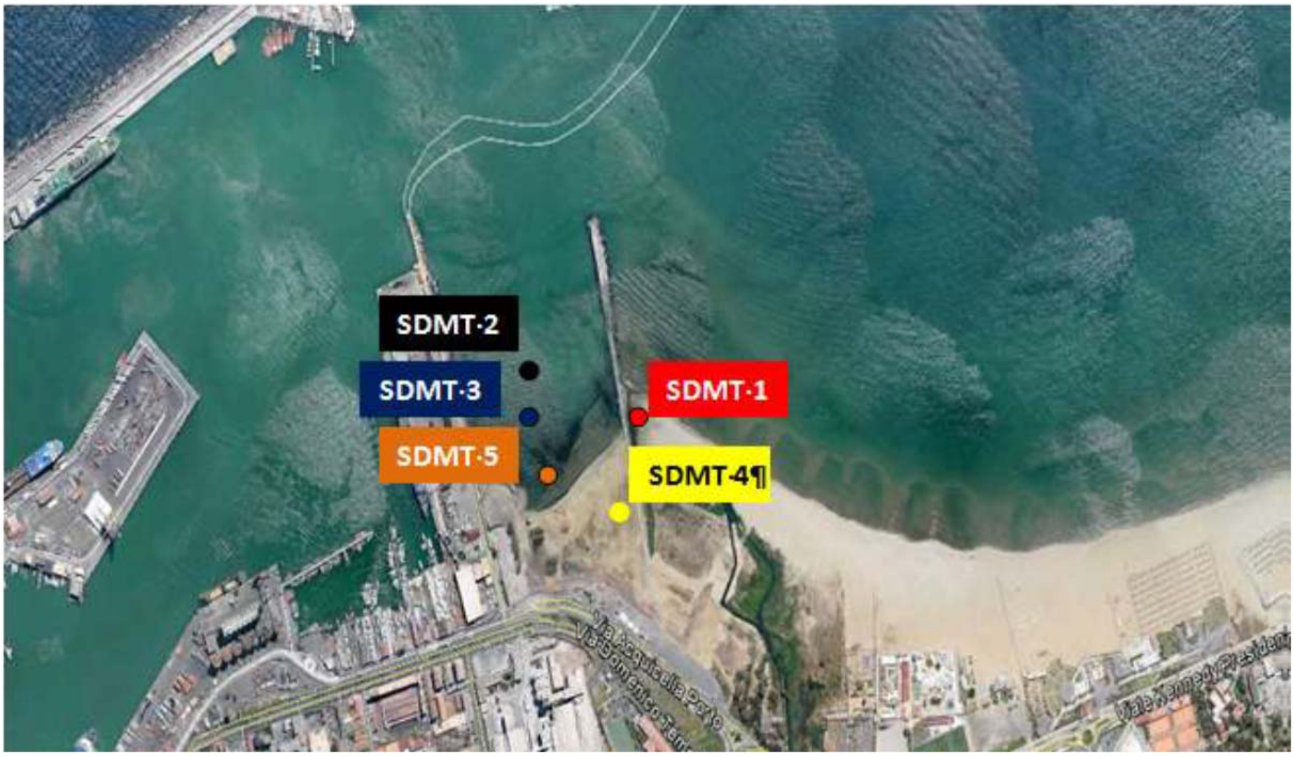


Fig. 1. Layout of investigation area with locations of the SDMTs.

interspersed with basic volcanic; the most recent deposits (Quaternary) are based on two sedimentary cycles and affect only the depression sand the edges of the plateau Iblean.

The city of Catania is located on the east coast of Sicily, which is one of the most seismically active areas in Italy. Various disastrous earthquakes have struck the east coast of Sicily, with a Medvedev Sponheuer Karnik (MSK) intensity from IX to XI in the last 900 years (Postpischl 1985, Azzaro et al. 1999). In particular, the seismic events of February 1169 and January 1693 destroyed almost completely the city of Catania with intensity X-XI MSK and estimated magnitude between 7.0 and 7.4 (Boschi et al. 1995).

The earthquake of January 11, 1693 is considered one of the biggest earthquakes occurred in Italy. It is supposed that more than 1500 aftershocks occurred along a period of more than two years after the main shock. This earthquake, with an intensity of XI degree on the MSK scale in many centers, struck a vast territory of south-eastern Sicily and caused the partial, and in many cases total, destruction of 57 cities and 40,000 casualties.

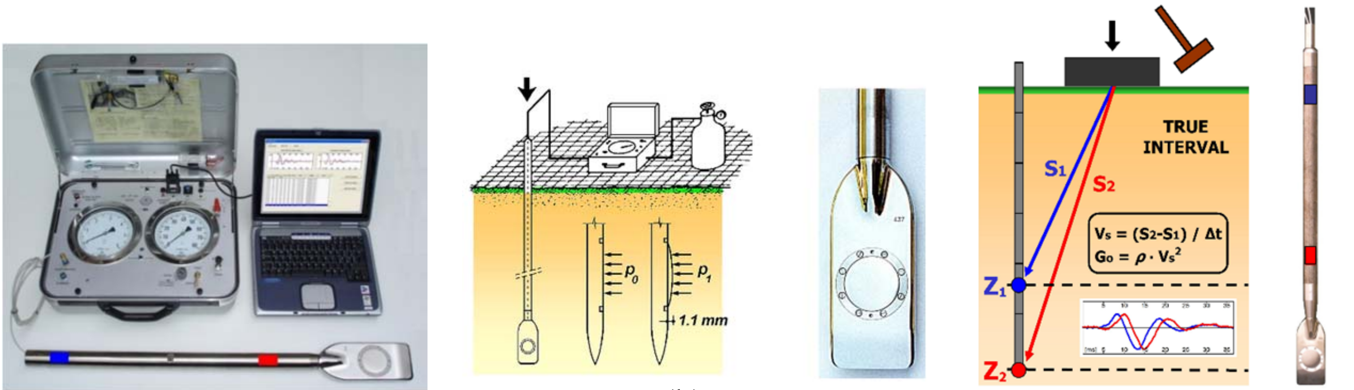
From 1000 A.D. to date, just four other earthquakes in the area have exceeded an estimated local Richter magnitude 5.8: the July 7 1125, the December 10 1542, the January 9 1693 and the February 20 1818 events (Azzaro and Barbano 2000). The other seismic events, which damaged Catania, such as the March 1536, April 1698, December 1716 and December 1990 earthquakes, generally produced minor effects, with collapses in degraded buildings. The recent earthquake on December 13, 1990 namely “the St. Lucia earthquake” struck Eastern Sicily with a local Richter Magnitude M_L = 5.6 caused 19 victims and severe damages to buildings and infrastructures (De Rubeis et al. 1991).

Seismicity is mainly distributed in two sectors: along the coast, where the events have also reached a surface Richter Magnitude $M_S \geq 7.0$, and inland with earthquakes with $M_S \leq 5.5$.

3 INVESTIGATION PROGRAMME AND BASIC SOIL PROPERTIES

The investigated area has plane dimensions of 400000 m^2 and maximum depth of 50 m. The area pertaining to the boreholes program and the locations of the field tests are shown in Fig. 1.

The Catania harbour site 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).



(a) (b) (c)

Fig. 2. Seismic dilatometer equipment (a). Schematic layout of the flat dilatometer test (b) and of the seismic dilatometer test (c).

From the soil profile can be highlight the soil layer have a nearly same nature in all the boreholes.

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 to the geotechnical properties of the area, the soil deformability have been investigated both in static conditions by direct shear tests and triaxial tests and in dynamic conditions by resonant column tests.

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 γ is prevalently in the range between 16.7 to 20.0 kN/m^3, 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 φ' ranged 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 %.

4 SHEAR MODULUS BY IN SITU TESTS

The SDMT (Marchetti et al. 2008, Monaco et al. 2009) provides a simple means for determining the initial elastic stiffness at very small strains and in situ shear strength parameters at intermediate level of strains in natural soil deposits (Cavallaro 1999b, Cavallaro et al. 2012). This apparatus was also used in offshore condition by Cavallaro et al. (2013b, 2013c).

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 and Mayne 1997, 1998; Mayne et al. 1999).

A new SDMT system has been recently developed in Italy. The seismic modulus is a cylindrical instrumented tube, located above the DMT blade (Marchetti 1980), housing two receivers at a distance of 0.50 m (see Fig. 2). 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).

Moreover the pair 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.

The adoption of the "true interval" configuration considerably enhances the repeatability in the V_s measurement (observed repeatability $V_s \approx 1$ - 2 %).

V_s is obtained as the ratio between the difference in distance between the source and the two receivers (S2 - S1) and the delay of the arrival of the impulse from the first to the second receiver (Δt). V_s measurements are obtained every 0.5 m of depth.

The shear wave source at the surface is a pendulum hammer (≈ 10 kg) which 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, so that they can offer the highest sensitivity to the generated shear wave.

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. In Fig. 2 it is shown the

SDMT scheme for the measure of V_s while Fig. 3 shows an example of seismograms obtained by SDMT at various test depths at the site of Catania harbour (it is a good practice to plot side by-side the seismograms as recorded and re-phased according to the calculated delay). V_s may be converted into the initial shear modulus G_o by the theory of elasticity by the well-known relationships:

$$G_o = \rho V_s^2 \tag{1}$$

where: ρ = mass density.

The combined knowledge of G_o and of the one-dimensional modulus M (from DMT) may be helpful in the construction of the G-γ modulus degradation curves (Cavallaro et al. 2006a).

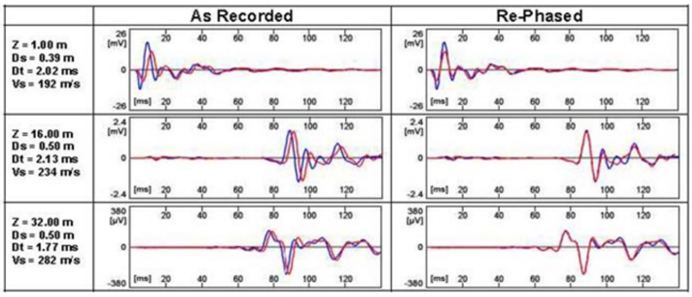


Fig. 3. Example of seismograms obtained by SDMT at the site of Catania Harbour, Italy.

A summary of SDMT parameters are shown in Fig. 4 where:

- I_d: Material Index; gives information on soil type (sand, silt, clay);
- φ': Angle of Shear Resistance;
- K_d: Horizontal Stress Index; 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 "understand" the deposit;

- V_s: Shear Waves Velocity.

Fig. 5 shows shear wave velocity profiles obtained from SDMTs in different boreholes.

It was also possible to evaluate the small strain shear modulus G_o in the Catania harbour area by means of the following empirical correlations available in literature based on laboratory test results or seismic Marchetti dilatometer tests results.

a) Jamiolkowski et al. (1995)

$$G_o = \frac{600 \cdot \sigma'^{0.5}_m p_a^{0.5}}{e^{1.3}} \tag{2}$$

where: $\sigma'_m = (\sigma'_v + 2\,\sigma'_h)/3$ effective medium stress with σ'_v = effective vertical normal stress and σ'_h = effective horizontal normal stress; p_a = 1 bar is a reference pressure; e = void ratio index; G_o, σ'_m and p_a are expressed in the same unit.

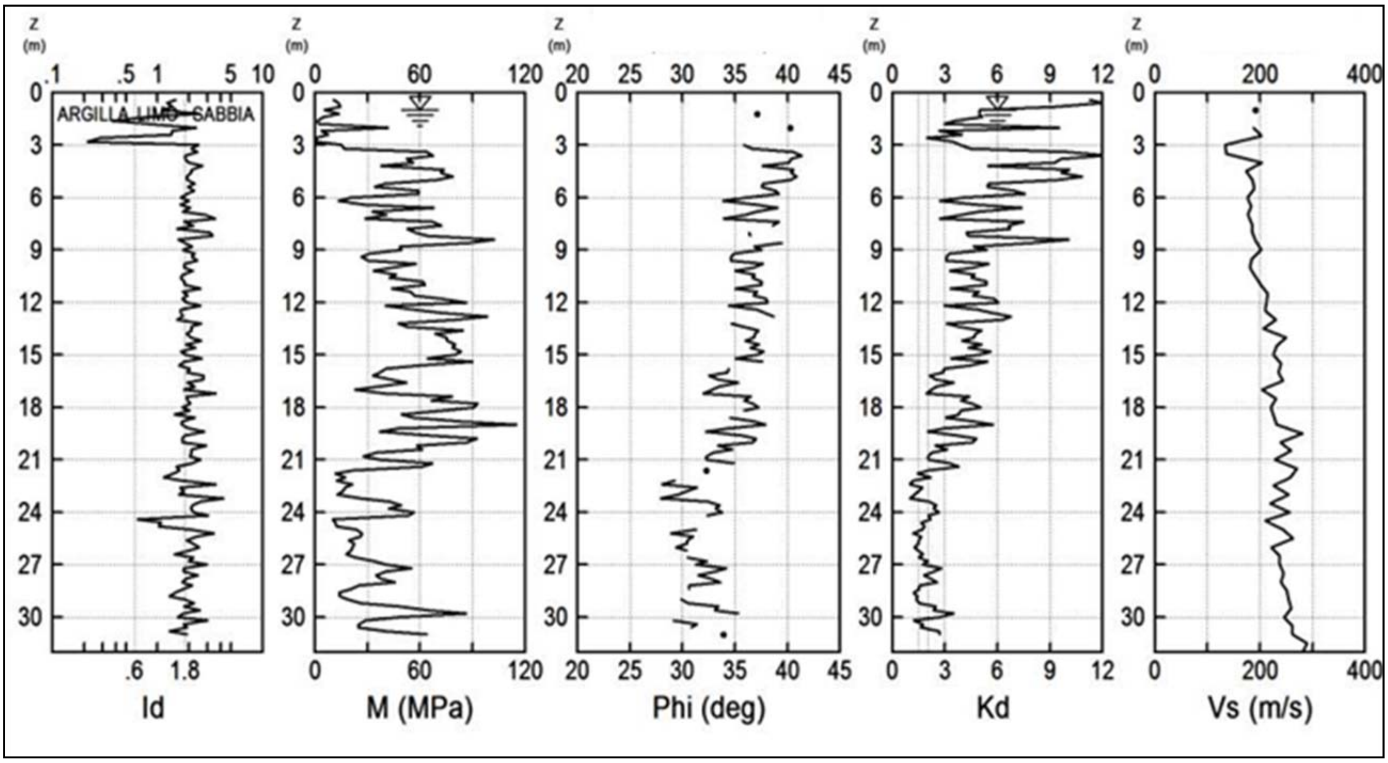


Fig. 4. Results of the SDMTs in terms of geotechnical parameters.

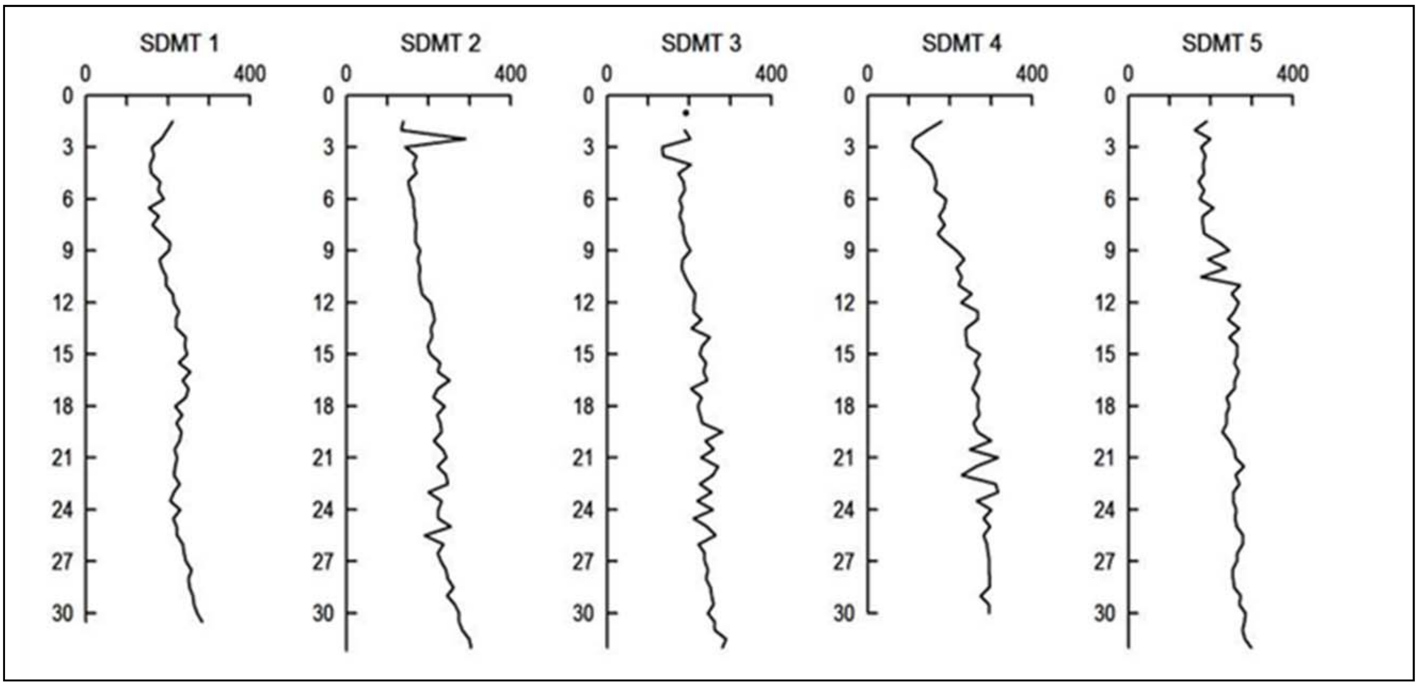


Fig. 5. Shear wave velocity profiles obtained from SDMT.

The values for parameters, which appear in eq. (2) are equal to the average values that result from laboratory tests performed on quaternary Italian clays and reconstituted sands. A similar equation was proposed by Shibuya and Tanaka (1996) for Holocene clay deposits.

b) Hryciw (1990)

$$G_o = \frac{530}{(\sigma'_v/p_a)^{0.25}} \frac{\gamma_D/\gamma_w - 1}{2.7 - \gamma_D/\gamma_w} K_o^{0.25} \cdot (\sigma'_v \cdot p_a)^{0.5} \quad (3)$$

where: G_o, σ'_v and p_a are expressed in the same unit; p_a = 1 bar is a reference pressure; γ_D and K_o are respectively the unit weight and the coefficient of earth pressure at rest, as inferred from SDMT results according to Marchetti (1980).

Fig. 6 shows the values of G_o obtained in situ from a SDMT and those obtained by means of the empirical correlations.

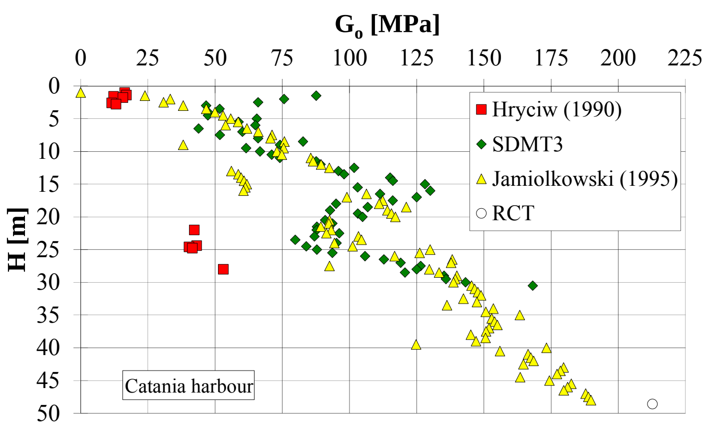


Fig. 6. G_o from SDMT and by empirical correlations

On the whole, equation (2) seems to provide the most accurate trend of G_o with depth, as can be seen in Fig. 6. A good agreement exists between empirical correlations and SDMT. However, the method by Hryciw (1990) was not capable of detecting the SDMT results for sandy soil as can be seen in Fig. 6.

Fig. 6 shows also the value of G_o measured in the laboratory from RCT performed on undisturbed solid cylindrical specimens. In the case of laboratory tests, the G_o values are determined at shear strain levels of less than 0.001 %.

Quite a good agreement exists between the laboratory test results and empirical correlations. On average the ratio of G_o(Emp. Corr.) to G_o(Lab) was equal to about 0.89 at the depth of 48.6 m.

5 SHEAR MODULUS AND DAMPING RATIO BY LABORATORY TESTS

Shear modulus G and damping ratio D of Catania harbour deposits were obtained in the laboratory from resonant column tests (RCT). A resonant column/torsional shear apparatus (Lo Presti et al. 1993, Capilleri et al. 2009) was used for this purpose.

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

For RCTs, the damping ratio was determined using the amplitude decay method and it was obtained during the decrement of free vibration.

The laboratory test conditions for cohesive soils retrieved at 48.6 m depth and the obtained small strain shear modulus G_o are listed in Table 2. The undisturbed specimens were 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 the cylindrical specimens are: radius = 50 mm and height = 100 mm (Cavallaro et al. 1999c, Cavallaro et al. 2006b).

Table 2. Test conditions for Catania harbour specimens.

Borehole Sample	Test No.	σ'_{vc} [kPa]	γ [kN/m^3]	W_n [%]	e	RCT	G_o [MPa]
SDMT3-N5	1	100	18.43	35.85	0.920	U	198
SDMT3-N5	2	200	18.43	35.85	0.711	U	211
SDMT3-N5	3	300	18.43	35.85	0.685	U	213

where: U = Undrained., G_o from RCT.

The experimental results of specimens (Fig. 7) from sand silty soil of Catania harbour area were used to determine the empirical parameters of the equation proposed by Yokota et al. (1981) to describe the shear modulus decay with shear strain level:

$$\frac{G(\gamma)}{G_o} = \frac{1}{1+\alpha\gamma(\%)^{\beta}} \tag{4}$$

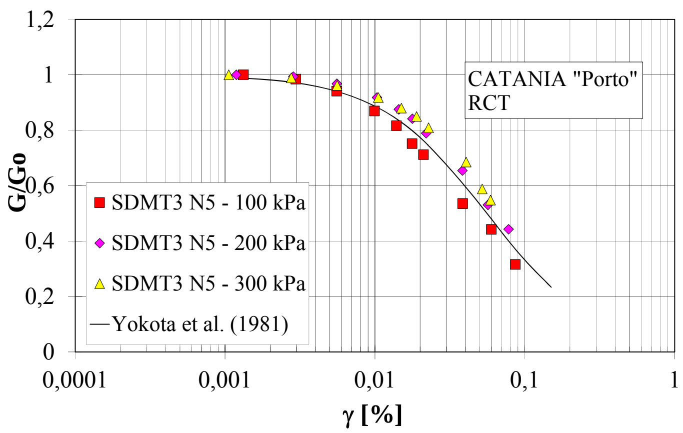


Fig. 7. G/G_o- γ curves from RCT for Catania harbour area.

The values of α = 32 and β = 1.2 were obtained for Catania harbour soil.

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 reported in Fig. 8 for cohesive soil:

$$D(\gamma)(\%) = \eta \cdot \exp\left[-\lambda \cdot \frac{G(\gamma)}{G_o}\right] \tag{5}$$

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

The values of η = 4.7 and λ = 1.1 were obtained for the Catania harbour area.

Equation (5) assumes maximum value D_{max} = 3.77% for $G(\gamma)/G_o$ = 0.2 and minimum value D_{min} = 1.56% for $G(\gamma)/G_o$ = 1.

Therefore, equation (5) can be re-written in the following normalized form:

$$\frac{D(\gamma)}{D(\gamma)_{max}} = \exp\left[-\lambda \cdot \frac{G(\gamma)}{G_o}\right] \tag{6}$$

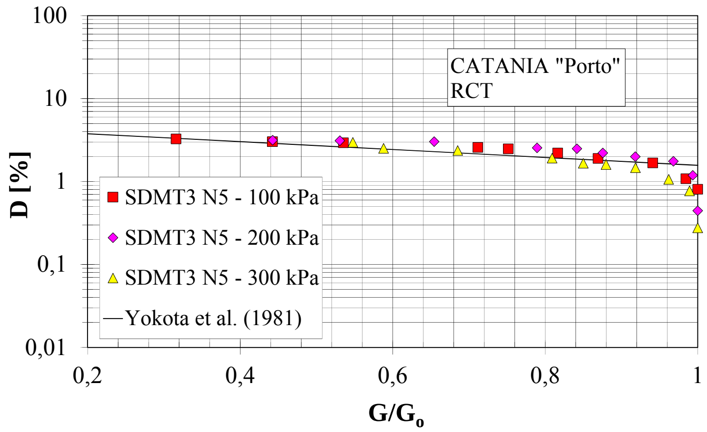


Fig. 8. D-G/G_o curves from RCTs.

6 CONCLUSIONS

A site characterization for the design and the execution of the modernization works of Catania harbor 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 32 meters, the results show a very detailed soil characterization profiles of the more relevant soil properties, such as the material index (I_d), the dilatometric modulus M from which the oedometer modulus can be evaluated, the angle of shear resistance φ' for sand silty soil, the shear wave velocity V_s, the horizontal stress index K_D.
- the small strain shear modulus obtained by the shear wave velocity profiles by SDMT compare well with Jamiolkowski et al. (1995) empirical correlation and resonant column test results at small strain;
- for the evaluation of shear modulus at intermediate strain, resonant column tests have been performed;
- the results interpreted by the equations suggested by Yokota et al. (1981) describe the shear modulus decay with shear strain level and the inverse

variation of damping ratio with respect to the normalized shear modulus.

7 IN MEMORY

November 1, 2015 Prof Michele Maugeri died killed by an incurable disease. Unforgettable will remain his enthusiasm and his great ability as a scholar and scientist. The co-authors of this paper started with him have decided to conclude the work in memory of the great master.

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