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"STATIC AND DYNAMIC PROPERTIES OF SOILS IN CATANIA (ITALY)"

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ABSTRACT
The analysis of the historical reports and previous research projects allowed us to describe high-level seismic risk scenarios for the city of Catania, located on the eastern coast of Sicily (Italy). The geotechnical zonation of the subsoil of the city of Catania suggests a high seismic hazard added to a soil amplification of the ground motion. To this aim field and laboratory tests allowed the definition of a geotechnical characterisation in the city of Catania. For the site characterisation of soils deep site investigations have been undertaken. Borings and dynamic in situ tests have been performed in some selected test sites with the aim to evaluate the soil profiles of shear wave velocity and to retrieve undisturbed samples for laboratory tests. The testing programme consisted of standard classification tests, Oedometer tests, Direct shear tests, Resonant Column and Torsional shear tests. Two equations to draw the complete shear modulus degradation with strain level and the inverse variation of damping ratio with normalized shear modulus respectively have been also proposed. Shear wave velocity profiles experimentally obtained were compared with both in situ and laboratory tests.

1. INTRODUCTION

Site characterization is a crucial point in the evaluation of site response analysis of soils [Castelli et al., 2016d; Castelli and Maugeri, 2008; Castelli et al., 2008a, 2008b; Castelli and Lentini, 2013; Castelli and Lentini, 2016; Castelli et al., 2017; Cavallaro, 2006b, 2008a, 2008b]. In order to study the dynamic characteristics of soils in three Catania test sites, 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 Marchetti Tests (SDMT) have been also carried out in the area of the "National Institute of Geophysics and Volcanology" building (INGV) and in the "Madre Teresa di Calcutta" building school (CD MTC), with the aim of an accurate geotechnical characterisation, including the evaluation of the shear wave velocity V_s profile, as well as the profile of the horizontal stress index K_d.

Shear wave velocity has been measured by different tests. The soil profiles in terms of the shear modulus G_0 and in terms of the shear wave velocity V_s have been evaluated and compared by different in situ tests. The redundancy of measurements is very useful, for instance, for site response and liquefaction analyses of the city of Catania [Castelli et al., 2016c], which can be based either on V_s values or K_d values. Boreholes were driven and undisturbed samples were retrieved for laboratory tests. Because of their relevance on the estimation of local ground shaking and site effects, data from in-hole geophysical surveys (Down-Hole and Seismic

Dilatometer Marchetti Test) have been examined with special attention, particularly for S wave velocity measurements. It must be noted that the shear wave velocity V_s was evaluated on the basis of both empirical correlations with in situ or laboratory tests and a few direct measurements. Moreover, the following investigations in the laboratory were carried out on undisturbed samples: direct shear tests, triaxial tests, Cyclic Loading Torsional Shear Tests (CLTST) 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 data for site characterization and for the mitigation of seismic risk within structural improvement of buildings [Abate et al., 2016; Abate et al., 2017a; 2017b; Grassi and Massimino, 2009]. Similar geotechnical studies were also successful performed for significant historical test sites (Castelli et al. 2016a, 2016d, 2016e; 2016f; Cavallaro et al. 1999b, 2003, 2004a, 2004b, 2013a).

2. GEOLOGY AND SEISMICITY OF THE AREA

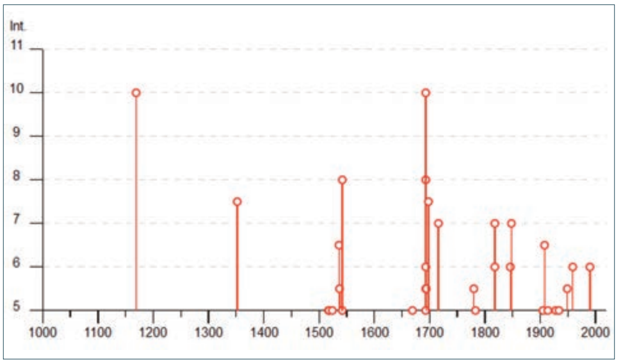
The study was performed in eastern Sicily, which is characterized by the presence of Mount Etna Volcano. This rests on top of two major structural units [Lentini et al., 1982; Pappalardo et al., 2016]: the Foreland Iblean plateau and the Apennine-Maghrebian Chain. The Foreland Iblean plateau is the northern edge of the African plate and is characterized by a succession of Meso-Cenozoic, mainly carbonate, repeatedly interspersed with basic volcanic rock. 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 struck the east coast of Sicily, with a (MSK) intensity from IX to XI in the last 900 years [Postpischl, 1985; Azzaro et al., 1999; Locati et al., 2016]. In particular, the seismic events of February 20, 1169 and January 11, 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; Gizzi, 2006]. 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., just four other earthquakes in the area 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 [Barbano et al., 2010], see Figure 1. Some of these events probably produced historical tsunamis (1693 and 1908 events) along the Ionian coast of Sicily [Barbano et al., 2010].

The other seismic events, which damaged the city of Catania, such as the March 1536, the April 1698, the December 1716 and the 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 and 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 $M_S \leq 5.5$ [Panzera et al., 2011a].

Graph 1 shows the seismic history of the city of Catania in the Italian Macroseismic Database DBMI15 [Locati et al., 2016] during the time window of years 1000-2014, starting from the fixed macroseismic intensity of VI MCS. Intensity data of DBMI15 derive from studies by authors from various institutions, both in Italy and bordering countries.

For these reasons several examples of site response analyses by 1-D modeling and microtremor measurements have been performed in the urban area of Catania [Lombardo et al., 2001; Panzera et al., 2011b, 2015; Sgarlato et al., 2011].



GRAPH 1. Seismic history of the city of Catania in the Italian Macroseismic Database DBMI15 during the time window 1000-2014.

3. SITE CHARACTERIZATION PROGRAMME AND BASIC GEOTECHNICAL SOIL PROPERTIES

The static and dynamic geotechnical study of soils in the city of Catania was performed in three investigation tests sites: the “National Institute of Geophysics

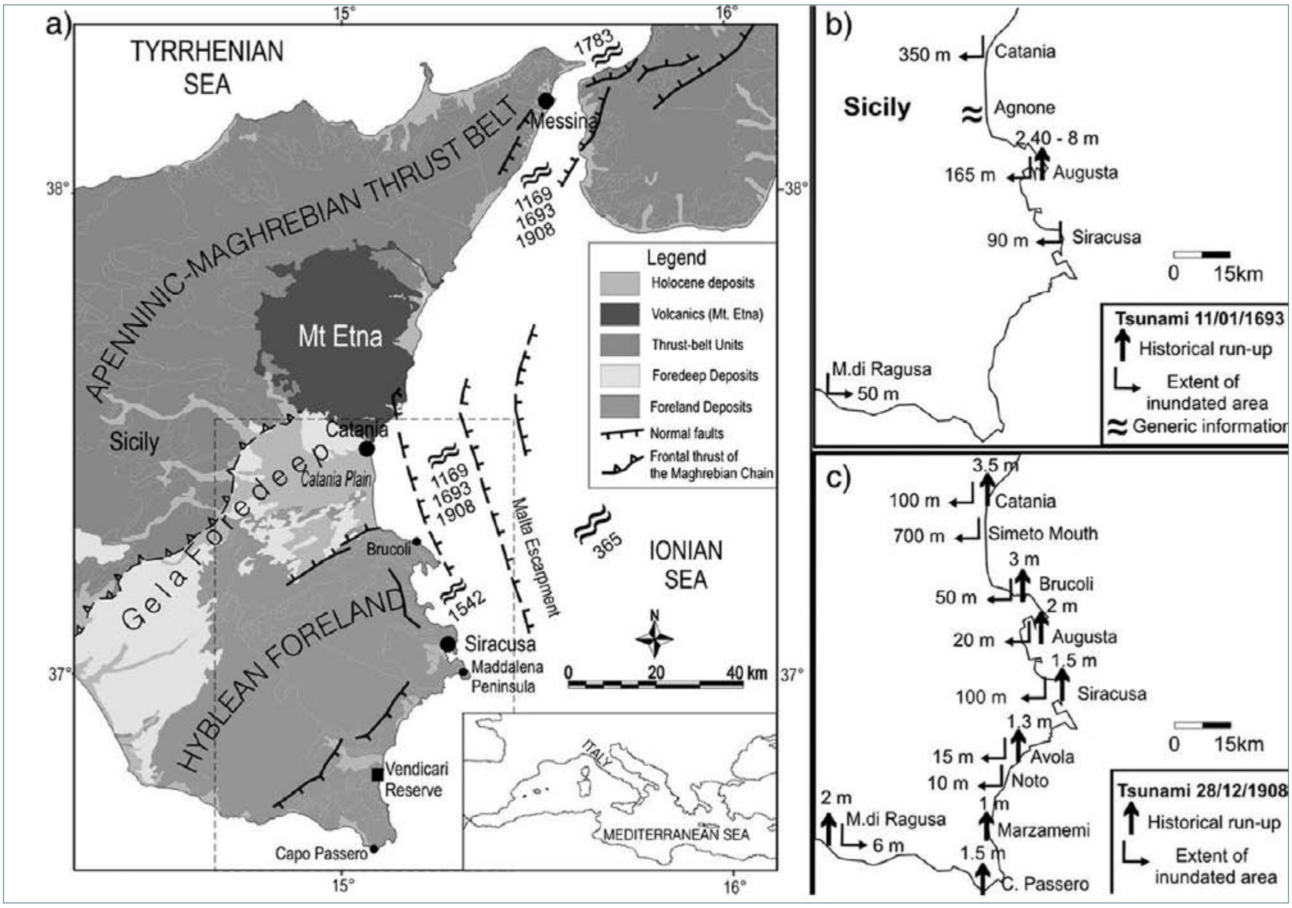


FIGURE 1. Map of seismotectonic features of South-Eastern Sicily, with indication of 1693 and 1908 historical tsunamis, after Barbano et al. [2010].

and Volcanology" (INGV) in the central area of the city, the "Nazario Sauro building School" (IC NS) in the western area of the city and the "Madre Teresa di Calcutta School" (CD MTC) in Tremestieri Etneo Municipality in the northern area of the city. The investigation studied depth reached a maximum depth of 80 m for INGV, of 40 m for IC NS and of 30 m for CD MTC. Laboratory tests have been performed on undisturbed samples retrieved by means of a 101 mm tube sampler [Cavallaro et al., 2007].

To evaluate the geotechnical characteristics of soils the following in situ and laboratory tests were performed in the tests located in the city of Catania:

- INGV: n. 3 Boreholes, n. 3 Standard Penetration test (SPT), n. 2 Down-Hole tests (DHT), n. 1 Cross-Hole tests (CHT), n. 1 Seismic Dilatometer Marchetti Test (SDMT), n. 6 Direct Shear Tests (DST), n. 2 Consolidated Undrained Triaxial Tests (CUT_XT), n. 2 Unconsolidated Undrained Triaxial Tests (UUT_XT), n. 2 Cyclic Loading Torsional Shear Tests (CLTST), n. 4 Resonant Column Test (RCT).
- IC NS: n. 2 Boreholes, n. 2 Seismic Dilatometer Marchetti Tests (SDMT), n. 6 Direct Shear Tests (DST), n. 3 Unconfined Uniaxial Compression Tests.
- CD MTC: n. 1 Boreholes, n. 1 Seismic Dilatometer Marchetti Test (SDMT), n. 3 Direct Shear Tests (DST), n. 1 Unconfined Uniaxial Compression Tests.

The "National Institute of Geophysics and Volcanology" (INGV) area mainly consists:

S1: a paving slabs of basalt (to 0.00 - 0.15 m depth), a layer of backfill (to 0.15 - 1.50 m depth), a layer of brown to dark yellow sandy silt slightly clayey with included centimeter limestone (to 1.50 - 5.10 m depth), a layer of yellow - orange sand with included sandstone gravels (to 5.10 - 5.40 m depth), a layer of brown to dark yellow sandy silt slightly clayey with included centimeter limestone (to 5.40 - 6.70 m depth), a layer of yellow ochre to grey clay slightly silty (to 6.70 - 9.50 m depth), a layer of grey - blue clay slightly silty with included decimeter dark black sand lenses (to 9.50 - 60.00 m depth).

S2: a paving slabs of basalt (to 0.00 - 0.15 m depth), a layer of backfill (to 0.15 - 1.50 m depth), a layer of brown to dark yellow sandy silt slightly clayey with included centimeter limestone (to

FIGURE 2. Layout of tests sites geotechnical boreholes: a) "National Institute of Geophysics and Volcanology" (INGV): S1, S2, S3; b) "Nazario Sauro building School" (IC NS): S1, S2; c) "Madre Teresa di Calcutta School" (CD MTC): S1.

1.50 - 6.00 m depth), a layer of yellow - orange sand with included sandstone gravels (to 6.00 - 6.90 m depth), a layer of yellow ochre to grey clay slightly silty (to 6.90 - 8.50 m depth), a layer of grey - blue clay slightly silty with included decimeter dark black sand lenses (to 8.50 - 80.00 m depth).

S3: a paving slabs of basalt (to 0.00 - 0.15 m depth), a layer of backfill (to 0.15 - 2.60 m depth), a layer of brown to dark yellow sandy silt slightly clayey with included centimeter limestone (to 2.60 - 8.60 m depth), a layer of yellow ochre to grey clay slightly silt (to 8.60 - 12.00 m depth), a layer of grey - blue clay slightly silty with included decimeter dark black sand lenses (to 12.00 - 60.00 m depth).

The "Nazario Sauro building School" (IC NS) area mainly consists:

S1: a layer of topsoil (to 0.00 - 1.00 m depth), a layer of fractured basaltic rock with included dark grey vacuoles (to 1.00 - 4.50 m depth), a layer of smoke grey sand and volcanic breach (to 4.50 - 13.30 m depth), a layer of compact basaltic rock with included light to dark fractures (to 13.30 - 25.20 m depth), a layer of sand and volcanic breach with included highly oxidized basaltic blocks (to 25.20 - 32.20 m depth), a layer of sand and smoke grey volcanic breach (to 32.20 - 40.00 m depth).

S2: a layer of backfill (to 0.00 - 2.80 m depth), a layer of fractured basaltic rock with included dark grey vacuoles (to 2.80 - 7.80 m depth), a layer of compact basaltic rock with included light to dark fractures (to 7.80 - 23.40 m depth), a layer of yellow - brown tufites with medium-fine grain size ochre to grey clay slightly silty

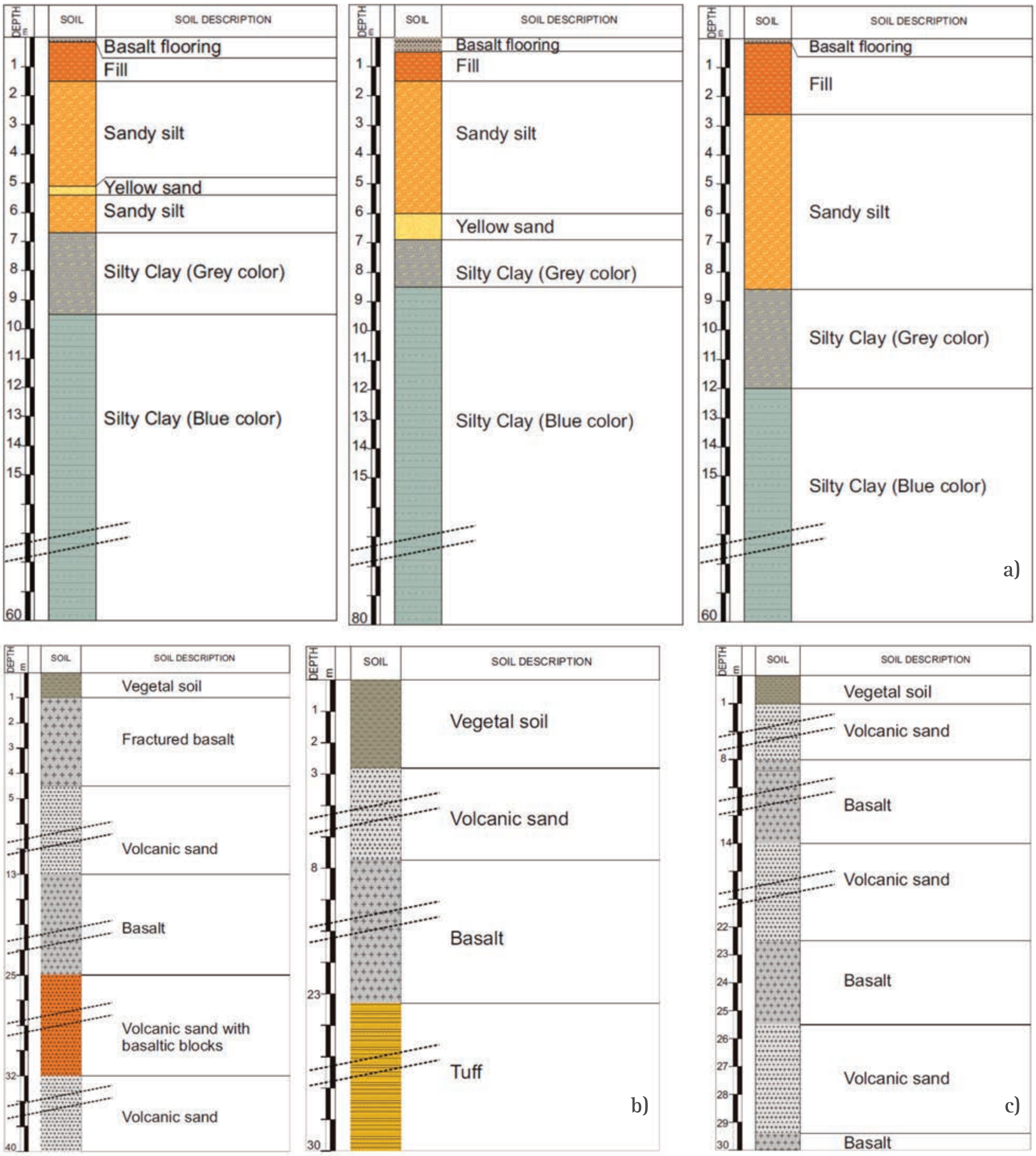


FIGURE 3. Soil profiles of: a) S1, S2, S3, on INGV; b) S1, S2 on IC NS; c) S1 on CD MTC.

(to 6.90 - 8.50 m depth).

The “Madre Teresa di Calcutta School” (CD MTC) area mainly consists:

S1: a layer of topsoil (to 0.00 - 1.00 m depth), a layer of sand and dark grey volcanic breach (to 1.00 - 8.00 m depth), a layer of compact basaltic rock with included light grey to dark grey fractures (to 8.00 - 14.00 m depth), a layer of sand and dark grey volcanic breach (to 14.00 - 22.50 m depth), a layer of compact basaltic rock with included light grey to dark grey fractures (to 22.50 - 25.00 m depth), a layer of sand and dark grey volcanic breach (to 25.00 - 29.30 m depth), a layer of compact basaltic rock with included light grey to dark grey fractures (to 29.30 - 30.00 m depth).

Using information made available from in situ boreholes, soil profiles of the ground beneath the Catania test sites could be designed (Figure 3). Trying to summarize the borehole results it is possible to define four soil classes, namely: basaltic rock, sand, volcanic breach and silty clay.

Based on the laboratory tests typical range of physical characteristics, index properties and strength parameters of the deposits mainly encountered in these areas are reported in Table 1, 2, 3.

On the basis of SDMT the INGV deposits mainly consist of over-consolidated sandy silt slightly clayey and clay slightly silty soil.

The value of the natural moisture content wn prevalently

Site	H [m]	γ kN/m³	$W_{n\ (\%)}$	G_s	e	n	S_r (%)	DST		CU$_x$T				UUT$_x$T
								c' (kPa)	φ' (°)	c_u (kPa)	$φ_u$ (°)	c' (kPa)	φ' (°)	c_u (kPa)
S1C1	4.00 - 4.50	20.01	16.99	2.74	0.57	0.36	81.60	11	29	-	-	-	-	-
S1C2	9.00 - 9.50	19.71	26.21	2.76	0.74	0.42	98.45	38	16	55	12	32	17	-
S1C3	34.00 - 34.50	19.61	22.65	2.76	0.69	0.41	90.15	51	20	-	-	-	-	226
S2C1	5.00 - 5.40	18.24	15.78	2.76	0.72	0.42	60.59	14	26	-	-	-	-	-
S2C2	7.20 - 7.70	19.22	24.45	2.79	0.77	0.44	88.41	28	22	104	13	69	19	-
S3C3	26.50 - 27.00	19.12	26.35	2.72	0.76	0.43	93.97	50	20	-	-	-	-	106

TABLE 1. Mechanical characteristics for INGV of Catania areas. Where: c' = Cohesion and φ' = Angle of Shear Resistance; Direct Shear Test (DST), CU Triaxial Tests (CUT$_X$T), UU Triaxial Tests (UUT$_X$T).

Site	H [m]	γ kN/m³	$W_{n\ (\%)}$	G_s	e	n	S_r (%)	DST		CU$_x$T				UUT$_x$T
								c' (kPa)	φ' (°)	c_u (kPa)	$φ_u$ (°)	c' (kPa)	φ' (°)	c_u (kPa)
S1C2	7.00 - 7.50	16.57	8.69	2.74	0.77	0.43	31.12	20	37	-	-	-	-	-
S1C3	11.50 - 12.00	16.48	12.36	2.82	0.89	0.47	39.17	30	37	-	-	-	-	-
S1C1	5.00 - 5.50	16.87	3.76	2.74	0.65	0.39	15.78	18	39	-	-	-	-	-

TABLE 2. Mechanical characteristics for IC NS of Catania areas. Where: c' = Cohesion and φ' = Angle of Shear Resistance; Direct Shear Test (DST), CU Triaxial Tests (CUT$_X$T), UU Triaxial Tests (UUT$_X$T).

Site	H [m]	γ kN/m³	$W_{n\ (\%)}$	G_s	e	n	S_r (%)	DST		CU$_x$T				UUT$_x$T
								c' (kPa)	φ' (°)	c_u (kPa)	$φ_u$ (°)	c' (kPa)	φ' (°)	c_u (kPa)
S1C1	3.00 - 3.50	16.18	6.50	2.71	0.75	0.43	23.46	20	44	-	-	-	-	-
S1C2	6.00 - 7.00	16.77	4.32	2.72	0.66	0.40	17.87	11	38	-	-	-	-	-
S1C4	15.00 - 16.00	16.97	1.82	2.75	0.62	0.38	8.08	0	10	-	-	-	-	-

TABLE 3. Mechanical characteristics for CD MTC of Catania areas. Where: c' = Cohesion and φ' = Angle of Shear Resistance; Direct Shear Test (DST), CU Triaxial Tests (CUT$_X$T), UU Triaxial Tests (UUT$_X$T).

ranges from between 16 - 26 % for INGV, 4 - 12 % for IC NS and 2 - 6 % for CD MTC. Characteristic values for G_s (specific gravity) ranged between 2.72 and 2.79 for INGV, 2.74 - 2.82 for IC NS and 2.71 - 2.75 for CD MTC.

Figure 4 shows index properties of INGV, IC NS and CD MTC areas. The water level is of 3.50 m from the ground surface for INGV, 0 m for IC NS and CD MTC areas. As regards strength parameters of the deposits mainly (Tables 1, 2, 3) encountered in this area c' from DST ranged between 11 kPa and 51 kPa for INGV, 18 kPa and 30 kPa for IC NS and 0 and 20 kPa for CD MTC while φ' from DST ranged between 16° and 29° for INGV, 37° and 39° for IC NS and 10° and 20° for CD MTC. The laboratory results of unconfined compression tests performed on sample retrieved on IC NS and CD MTC areas are reported in Table 4 together the dynamic results of nondestructively Ultrasonic Tester Tests (UTT).

Site	Borehole	H(m)	γ kN/m³	R_c (MPa)	V_p (m/s)	V_s	υ	G (MPa)	E (MPa)
IC NS	SICL1	1.10 - 1.50	25.62	97.24	-	-	-	-	-
IC NS	SICL4	16.00 - 17.00	27.59	132.93	2812	1773	0.17	8779	20544
IC NS	SICL2	5.60 - 6.00	27.51	135.77	3427	2076	0.21	12000	29041
CD MTC	SICL3	1.00 - 11.50	26.26	146.08	2621	1668	0.16	7393	17152

TABLE 4. Test Results of nondestructively ultrasonic tester tests (UTT). Where: R_c = Compressive Strength.

4. SHEAR MODULUS BY IN SITU TESTS

It was also possible to evaluate the small strain shear modulus in the investigated Catania test sites by means of the results deriving from the following seismic tests based on Down Hole (DH) and Cross Hole method (CH).

In Figure 5, the shear and compression wave velocities against depth have been reported. In Figure 6 the dynamic Poisson ratio variation with depth, obtained from Down Hole (DH) and Cross Hole (CH) tests, is plotted to show site characteristics. It is clear that the values oscillate around 0.36 - 0.45 for CH and 0.45 - 0.49 for DH.

In Figure 7 the coefficient of earth pressure at rest K_0 variation with depth, obtained from a Down Hole (DH) and Cross Hole tests, is plotted to show site characteristics. It is clear that apart from the top 5 m, the values oscillates around 0.60 - 0.75 from CH and 0.90

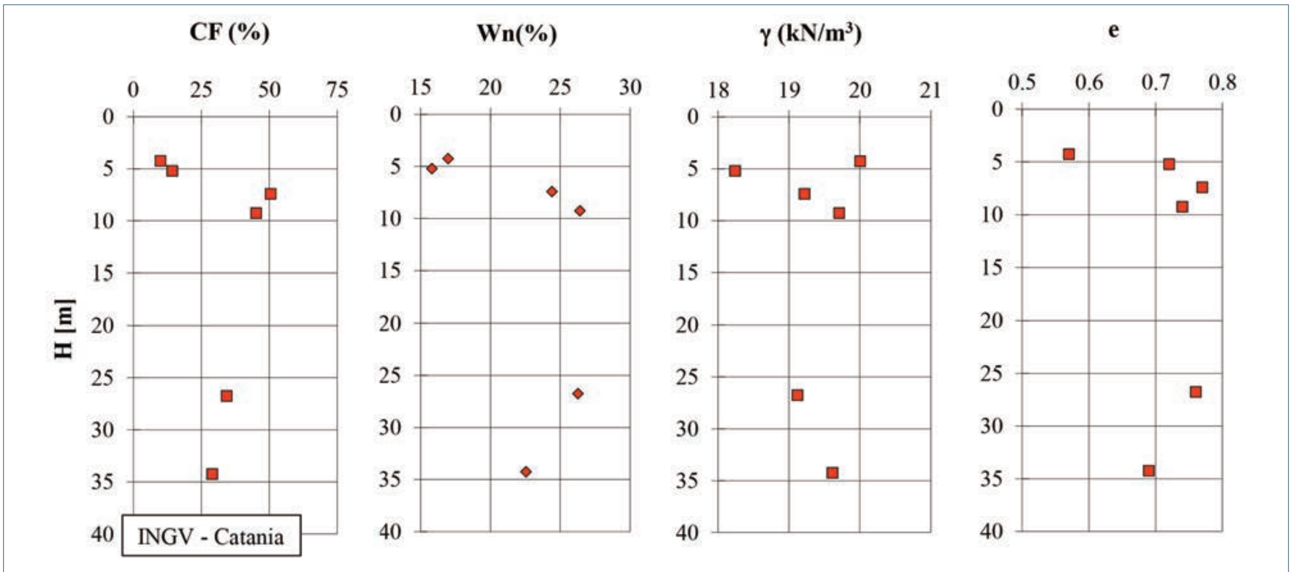


FIGURE 4. Index properties of INGV, IC NS and CD MTC areas.

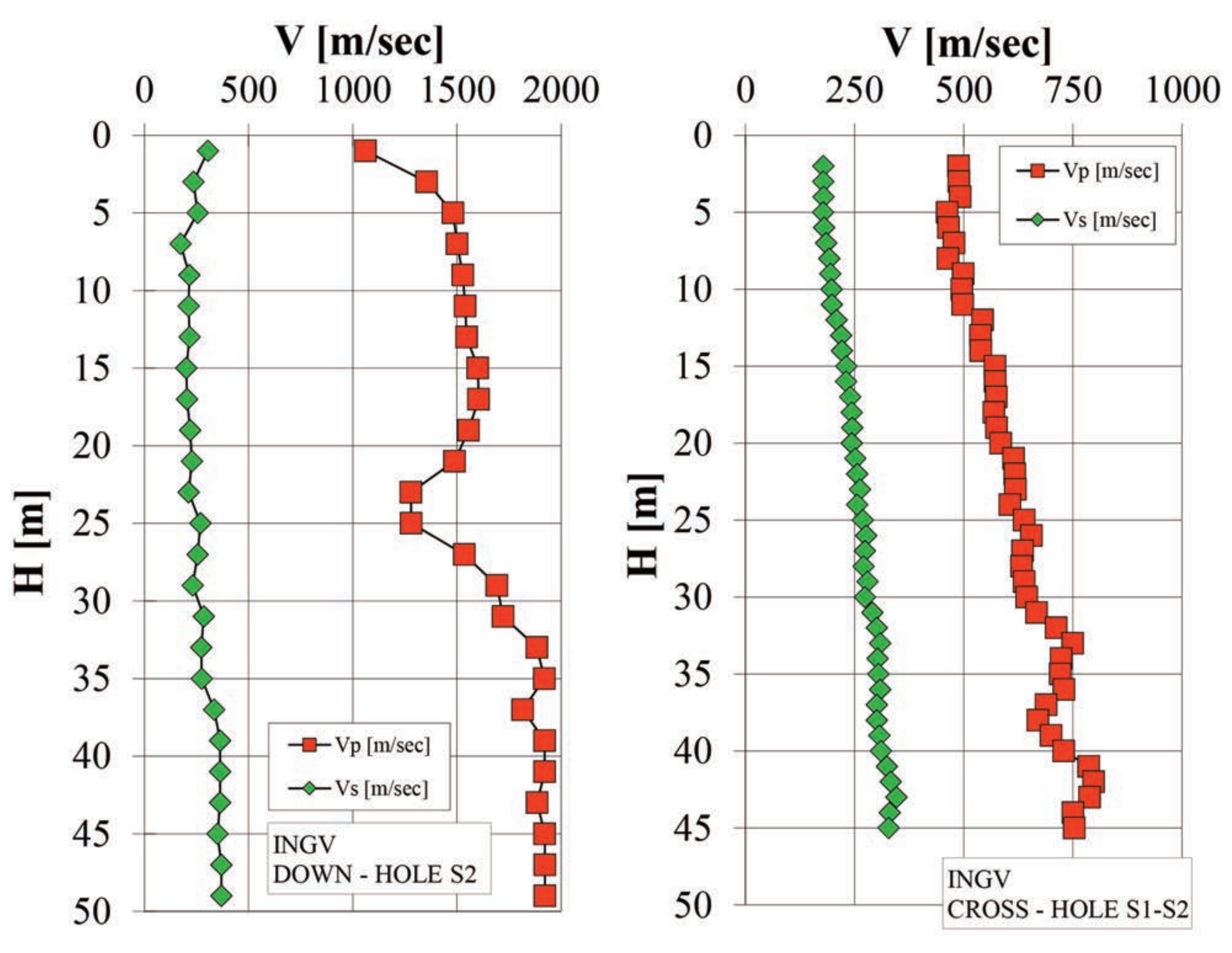


FIGURE 5. V_s and V_p from Down Hole and Cross Hole tests in INGV area.

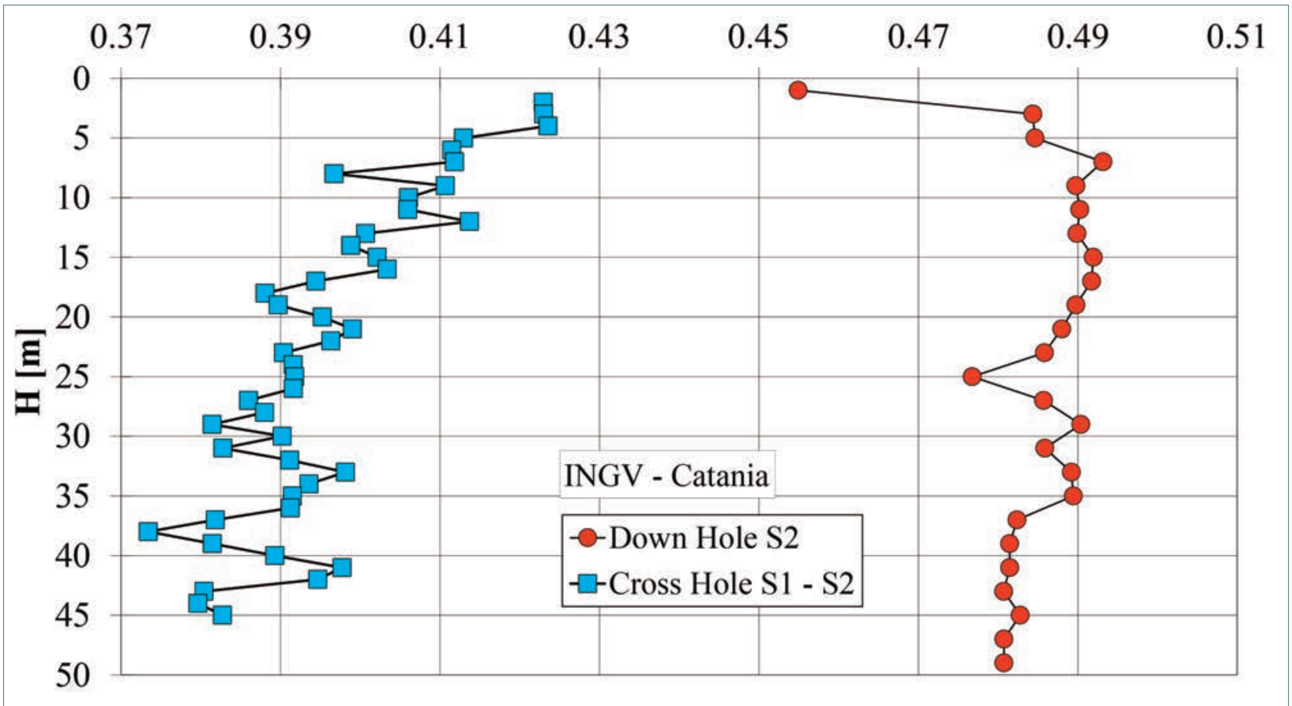


FIGURE 6. Poisson ratio from Down Hole and Cross Hole tests.

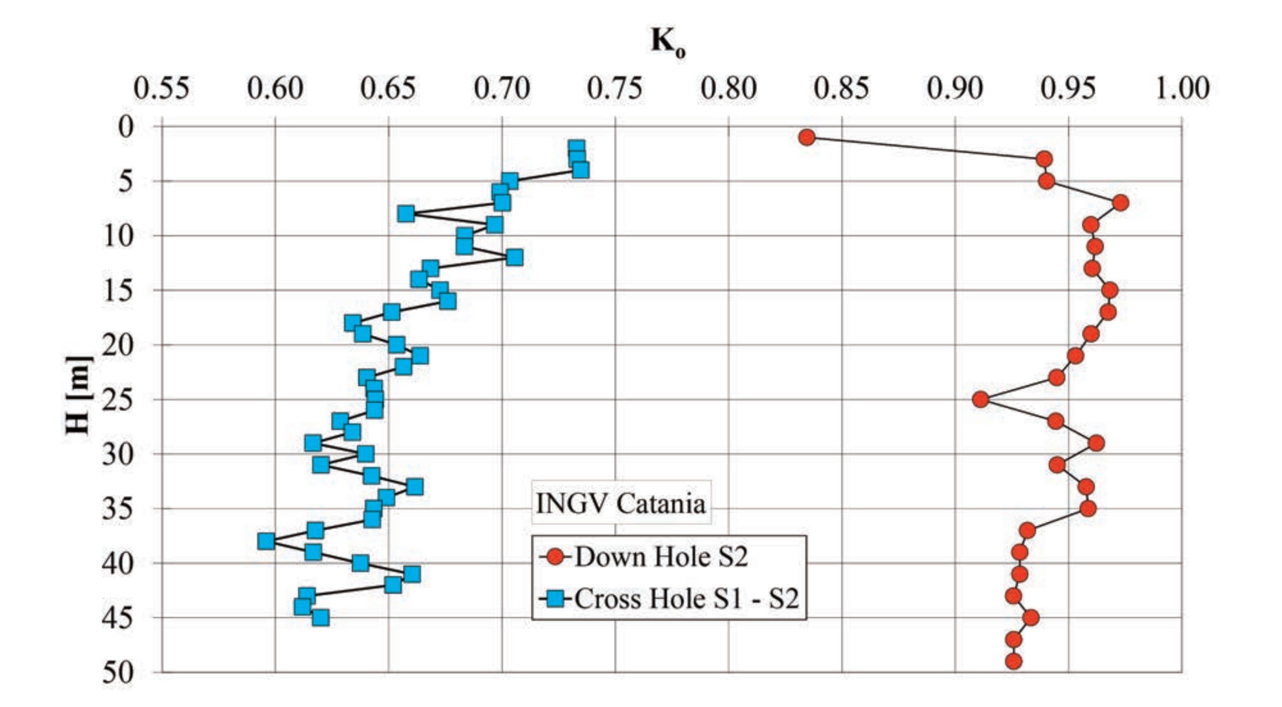


FIGURE 7. The coefficient of earth pressure at rest K_o from Down Hole and Cross Hole tests.

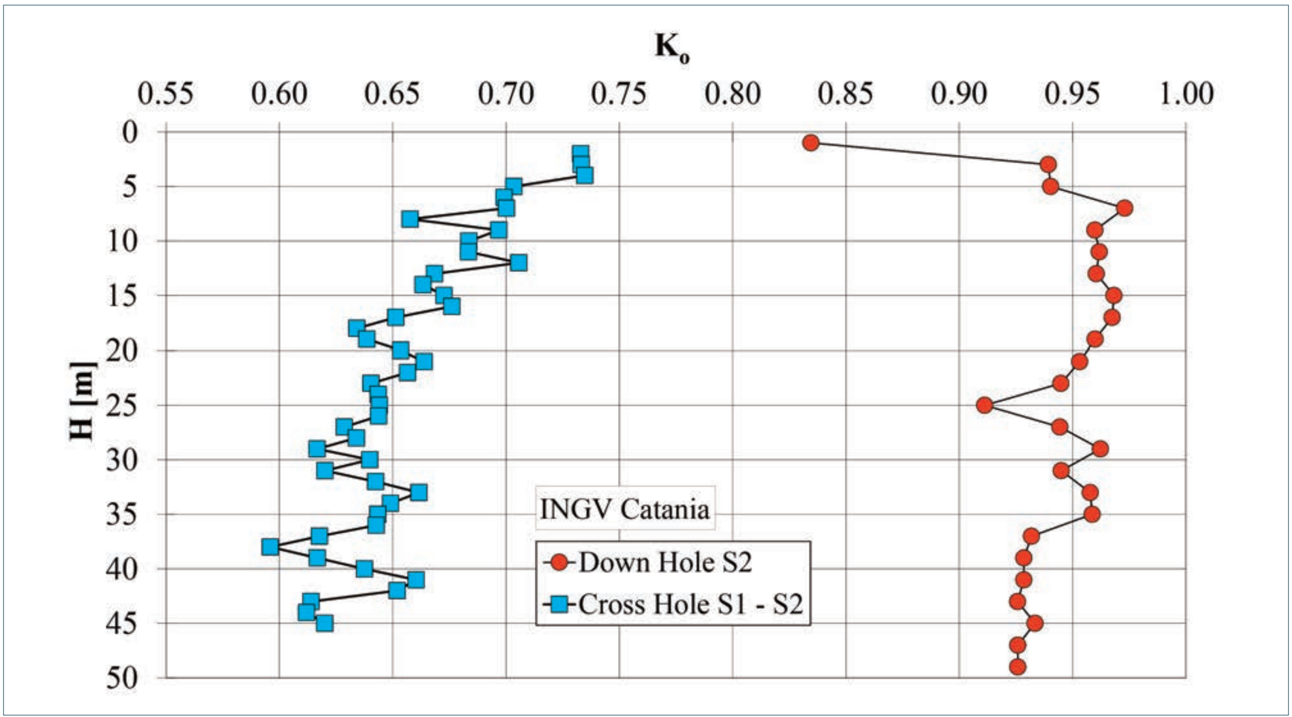


FIGURE 8. G_o from Down Hole and Cross Hole tests.

- 0.95 from DH.

A comparison between G_o values obtained from in situ test performed on the area under consideration is shown in Figure 8. The Down Hole and Cross Hole tests performed in INGV area showed G_o values increasing with depth. Very high values of G_o are obtained for depths greater than 30 m. According to these data, it is possible to assume that G_o values oscillate around 50 - 250 MPa.

The SDMT [Marchetti 1980; 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 [Castelli et al., 2016b; Cavallaro, 1999c; Cavallaro et al., 2012, 2015]. This apparatus was also used in offshore condition by Cavallaro et al. [2013b, 2013c].

V_s may be converted into the initial shear modulus G_o by the well-known relationships:

$$G_0 = \rho V_s^2 \quad (1)$$

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; Castelli et al., 2016c]. A summary of SDMT parameters are shown in Figure 9 where:

- I_d: Material Index; gives information on soil type (sand, silt, clay);
- φ': Angle of Shear Resistance;
- M: Vertical Drained Constrained Modulus;
- C_u: Undrained Shear Strength;
- K_d: Horizontal Stress Index; the profile of K_d is similar in shape to the profile of the overconsolidation ratio OCR. Kd = 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.

a) Jamiolkowski et al. [1995]

$$G_o = \frac{600 \cdot \sigma_m'^{0.5} p_a^{0.5}}{e^{1.3}} \quad (2)$$

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 pa are expressed in the same unit.

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

b) Ohta and Goto [1978]

$$V_s = 69 \cdot N_{60}^{0.17} \cdot Z^{0.2} \cdot F_A \cdot F_G \quad (3)$$

where: V_s = shear wave velocity (m/s), N_{60} = number of blow/feet from SPT with an Energy Ratio of 60%, Z = depth (m), F_G = geological factor (clays=1.000, sands=1.086), F_A = age factor (Holocene = 1.000, Pleistocene = 1.303).

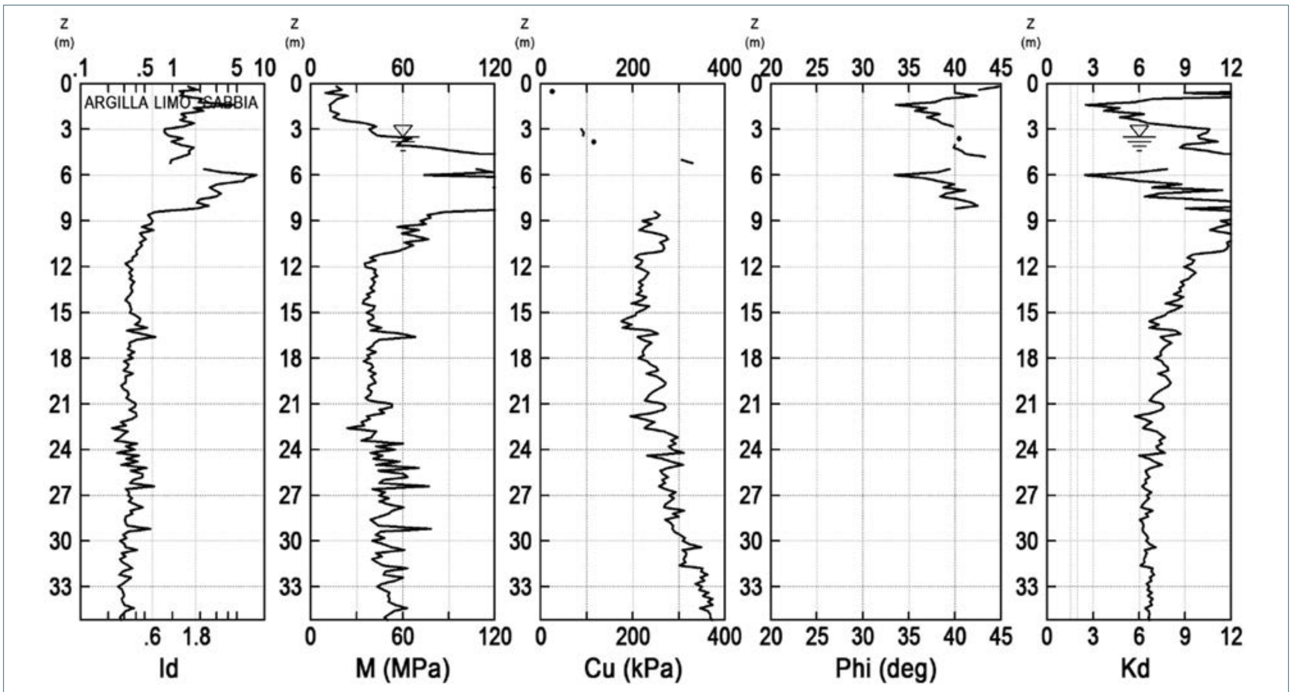


FIGURE 9. Results of the SDMTs in terms of geotechnical parameters for INGV area.

Figure 10 shows results of the SDMTs performed in the test sites in terms of shear wave velocity profiles.

It was also possible to evaluate the small strain shear modulus G_o in the Catania test sites by means of the following empirical correlations available in literature based on laboratory test results, Standard Penetration Tests (SPT) or seismic Marchetti dilatometer tests results:

c) Hryciw [1990]

$$G_o = \frac{530}{\left(\sigma_v'/p_a\right)^{0.25}} \frac{\gamma_D/\gamma_w - 1}{2.7 - \gamma_D/\gamma_w} K_o^{0.25} \cdot \left(\sigma_v' \cdot p_a\right)^{0.5} \quad (4)$$

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

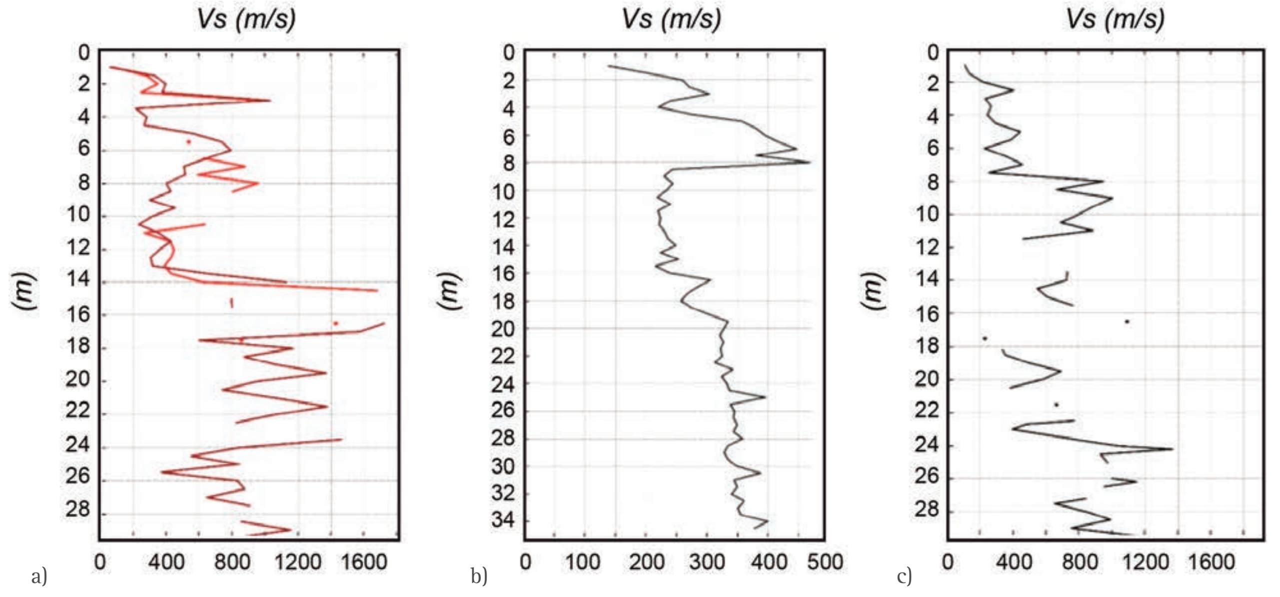


FIGURE 10. Shear wave velocity profiles obtained from SDMT for CD NS a), INGV b) and CD MTC c) areas.

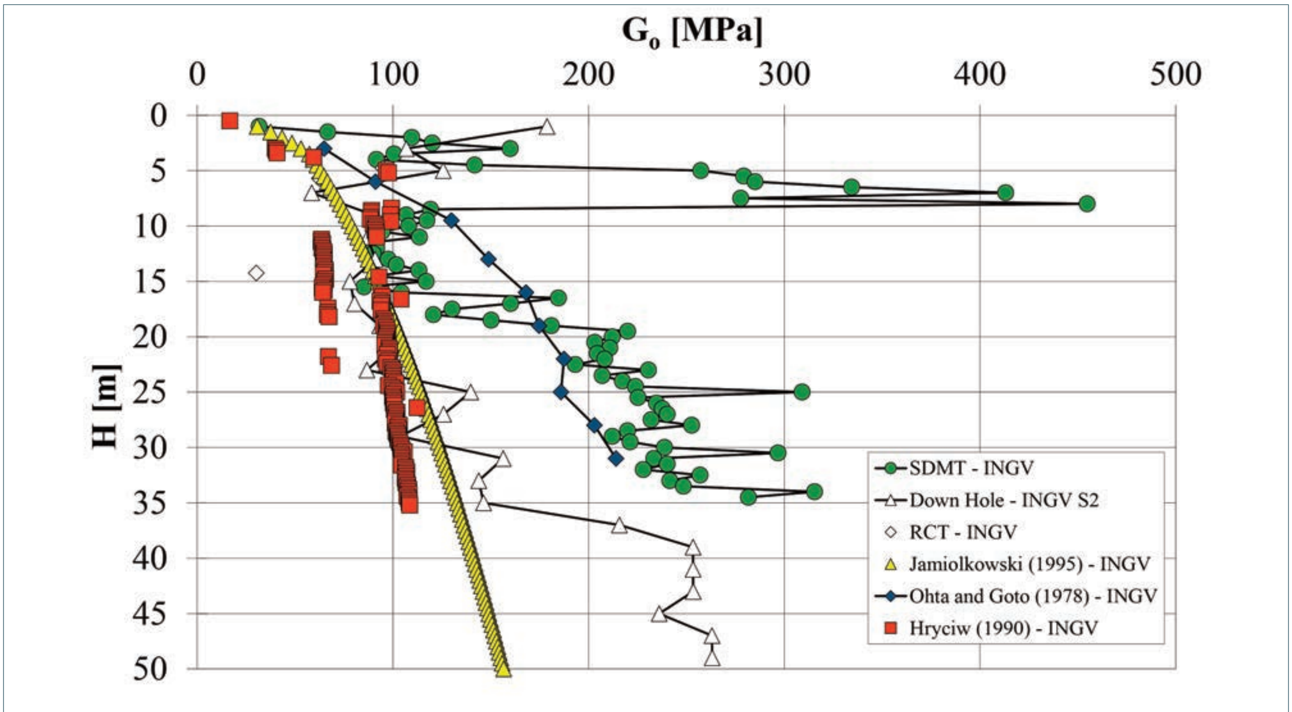


FIGURE 11. G_o values obtained by SDMT, by D-H and by empirical correlations for INGV site.

pressure at rest, as inferred from SDMT results according to Marchetti [1980].

Figure 11 shows the Go values obtained by SDMT and those obtained by means of the empirical correlations. On the whole, Equations (2) and (4) seems to provide the most accurate trend of G_o with depth, as can be seen in Figure 11. A good agreement exists between empirical correlations and SDMT. However, as can be seen in Figure 11, the method by Hryciw [1990] was not capable of detecting the SDMT results for sandy soil as reported in Figure 11. Figure 11 shows also the value of Go 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 %. At the depth of about 7 m high values of G_o are registered by

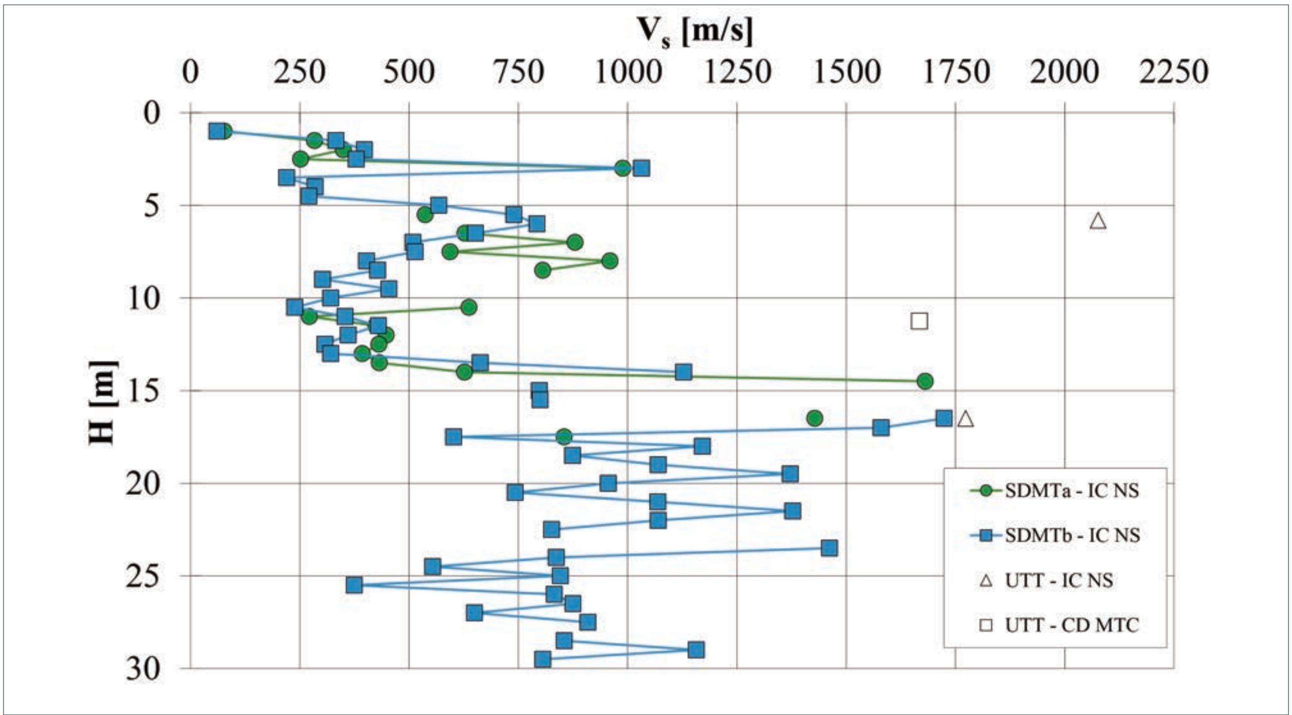


FIGURE 12. V_s from SDMT, UTT and by empirical correlation for IC NS and CD MTC sites.

SDMT probably due to the presence of a layer of grey - blue clay slightly silty with included decimeter dark black sand lenses. High values of G_o were obtained for levels higher than 25 m depth.

In Figure 12 it is proposed a comparison between the values of V_s obtained from SDMT and Ultrasonic Tester Tests UTT. Up to a depth of 15 m higher V_s values are obtained in the laboratory by nondestructively ultrasonic tester tests (UTT) rather than those obtained in situ from SDMT tests.

5. SHEAR MODULUS AND DAMPING RATIO BY LABORATORY TESTS

Shear modulus G and damping ratio D of Catania tests sites deposits were obtained in the laboratory by Resonant Column Tests (RCT) and by Cyclic Loading Torsional Shear Tests (CLTST) performed by means of a Resonant Column/Cyclic Loading Torsional Shear Apparatus [Cascante et al., 1998] (Figure 13).

A Resonant Column test consists in exciting one end of a confined solid or hollow cylindrical soil specimen. The specimen is fixed at the bottom (fixed-free test) and it is excited in torsion or flexure at the top by means of an electromagnetic drive system. Once the fundamental resonant frequency is established from measuring the motion of the free end, the velocity of the propagating wave and the degree of material damping are derived. The shear modulus is then obtained from the derived velocity V_s (in case of torsion) and the density ρ of the sample [Cavallaro et al., 1999a; Maugeri and Cavallaro, 1999].

The equivalent shear modulus Geq is the unload-reload shear modulus that is evaluated from RCT in function of velocity Vs and density ρ of the sample, while G_o is the maximum value or also "plateau" value as observed in the G-log(γ) plot; G is the secant modulus [Castelli et al., 2016c; Cavallaro, 2016; Lo Presti et al., 1999a].

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 [Capilleri et al., 2014; Lo Presti et al., 1999b].

For CLTSTs the damping ratio (D) was calculated as the ratio between the area enclosed by the unloading-reloading loop and represents the total energy loss during the cycle and W is the elastic stored energy. For RCTs the damping ratio was determined using the steady-state method during the resonance condition of the sample.

The apparatus used is a fixed-free resonant column apparatus [Hall and Richart, 1963]. It enables the specimen consolidation under both isotropic and anisotropic stresses. It is composed of a drive system, a support system, and a base plate. The solid or hollow cylinder specimen is fixed at the bottom and its constraint at the base

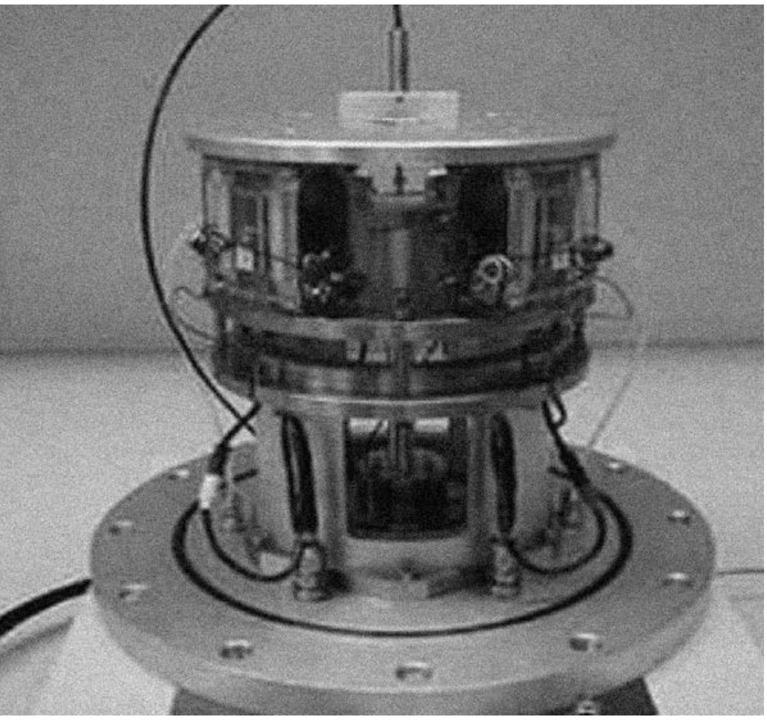


FIGURE 13. Resonant Column/Cyclic Loading Torsional Shear Apparatus.

is due to the friction existing between the specimen and the porous synthesized bronze stone [Drnevich et al., 1978]. Torsional forces are applied at the top by means the drive system, realized in aluminium. It is an electrical motor constituted of four magnets connected with the top of the sample and eight coils placed on the inox steel annular base, which is strictly linked to the support system. The weight of the motor is counterbalanced by a spring. A programmable function generator (PGF) excites the electrical motor of Stokes.

Solid cylindrical specimens were built by using tapping [Drnevich et al., 1978], in order to obtain the required relative and a good uniformity during the deposition. The mold is assembled and a little depression is applied to let the membrane adhere to the inside surfaces. The material is placed in the mold using a funnel-pouring device. The soil is placed as loosely as possible in the mold by leaving the soil from the spout in a steady stream, holding the pouring device upright and vertical, and maintaining constant the fall height. It is possible to obtain different values of relative density changing the height of deposition. In order to realize high values of relative density it could be necessary to beat delicately the mold surface during the deposition. Each sample was reconstituted with fresh sand. Each specimen was subjected to an isotropic load achieved in a plexiglas pressure cell, using an air pressure source. The axial strain was measured by using a high-resolution proximity transducer, which monitors the aluminium top-cap displacement. Shear strain was measured by monitoring the top rotation with a couple of high-resolution proximity transducers.

During a resonant column test, the proximity transducers are not able to appraise the value of the targets displacements, because of the high frequency of the oscillations. Then rotation on the top of the specimen is measured by means of an accelerometer. The laboratory test conditions and the obtained small strain shear modulus Go are listed in Table 5. The undisturbed specimens were isotropically reconsolidated to the best estimate of the in situ mean effective stress. The same specimen was first subject to RCT, then to CLTST after a rest period of 24 hrs with opened drainage. CLTST were performed under stress control condition by applying a torque, with triangular time history, at a frequency of 0.1 Hz. The size of solid cylindrical specimens are Radius = 25 mm and Height = 100 mm. The G_o values [G_o (1) and G_o (2)], reported in Table 5, indicate moderate influence of strain rate even at very small strain where the soil behaviour is supposed to be elastic.

Borehole	H (m)	σ'_{vc} (kPa)	e	CLTST RCT	G_o (1) (MPa)	G_o (2) (MPa)	G_o (3) (MPA)	γ_{max}(%)
S1C1	4.75	75	0.57	U	95	-	126	0.098
S3C1	5.70	90	0.76	U	62	46	58	0.114
S2C3	14.25	170	0.76	U	30	28	78	0.501
S2C5	72.25	475	0.75	U	47	-	-	0.361

TABLE 5. Test condition for INGV area specimens. Where: U = Undrained. G_o (1) from RCT, G_o (2) from CLTST after 24 hrs, G_o (3) from Down-Hole.

In order to appreciate the rate effect on G_o, it is worthwhile to remember that the equivalent shear strain rate ($\dot{\gamma} = 240 \cdot f \cdot \gamma$ [%/s]) experienced by the specimens during RCT can be three orders of magnitude greater than those adopted during CLTST. The effects of the rate and loading conditions become less relevant with an increase of the shear strain level, as can be seen in Figure

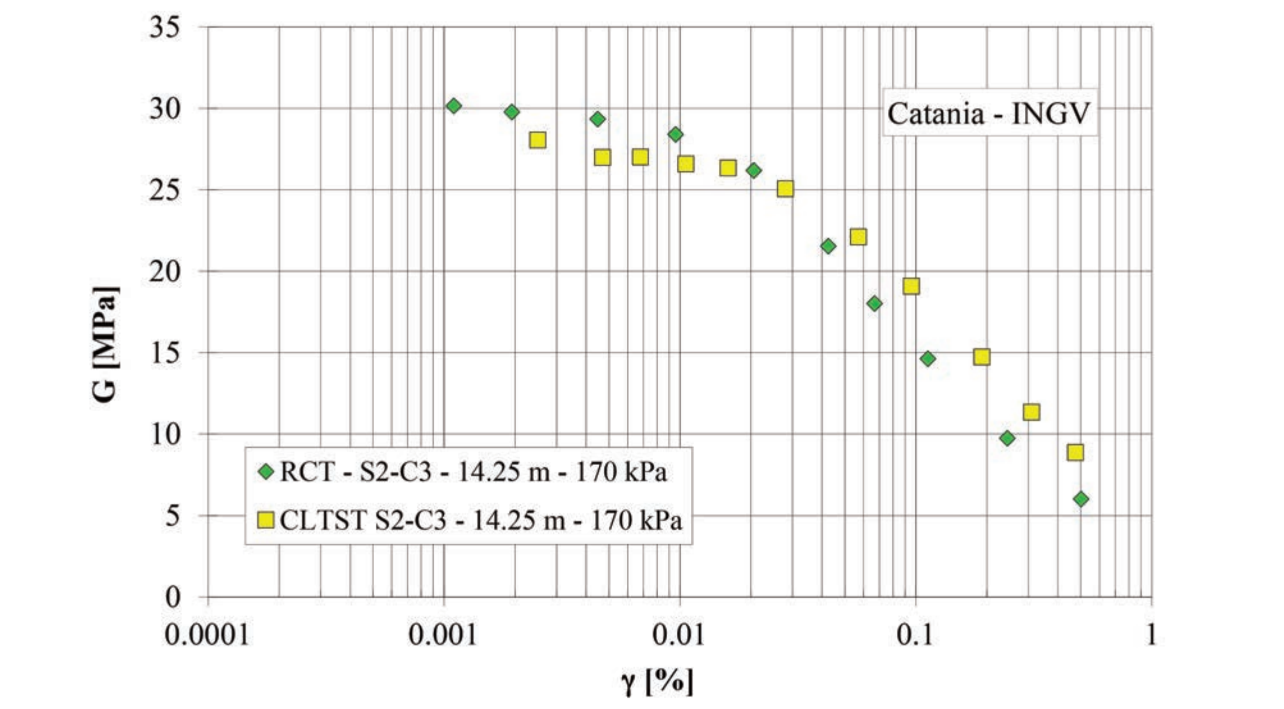


FIGURE 14. G-γ curves from RCT and CLTST tests.

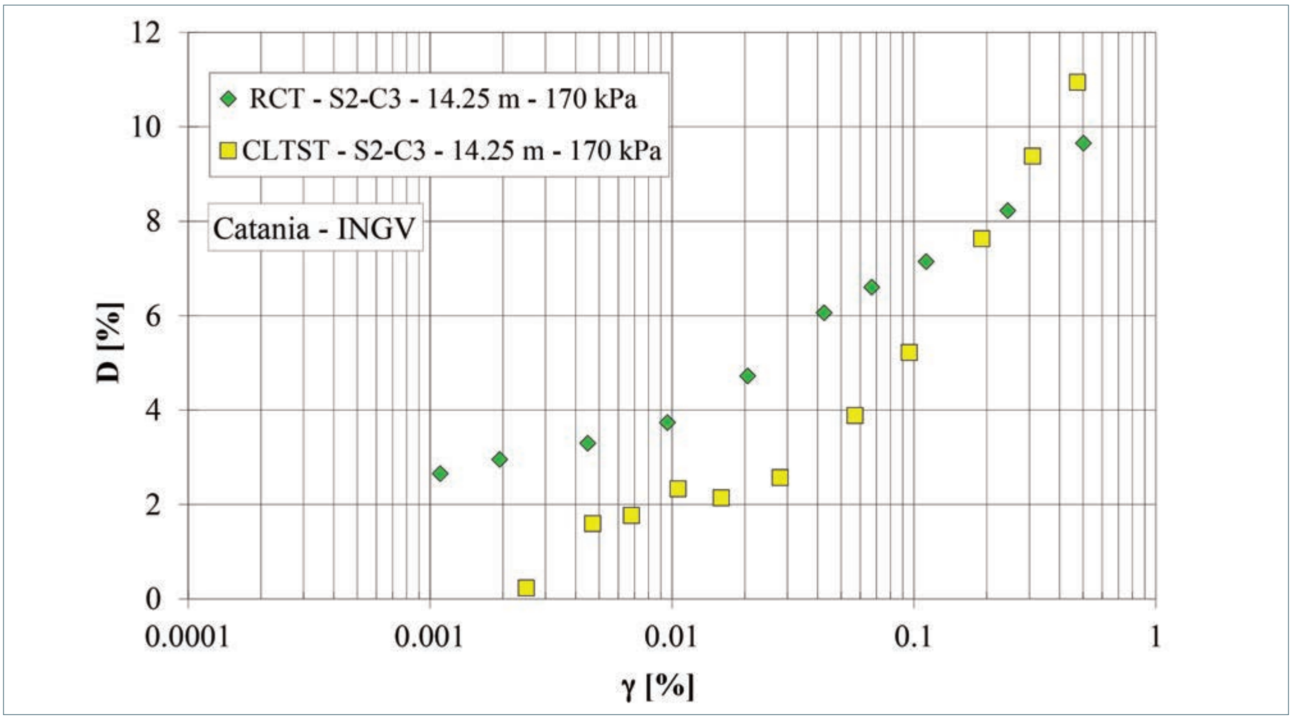


FIGURE 15. D-γ curves from RCT and CLTST tests.

14 where the G-γ curves obtained from CLTST and RCT are compared. It is possible to notice that the lowest decay of G with γ is observed in CLTST, while the maximum decay occurs during RCT. Finally higher values of the initial shear modulus [G_0 (3)] have been obtained from Down - Hole tests. In general (Figure 15) higher values of D are obtained by RCT than CLTST. The damping ratio values obtained from RCT by steady-state method increases with the strain level, higher values of D have been obtained from strain level higher than 0.02 %. Greater values of D are obtained from RCT for strain level higher than 0.2 %. The experimental results were

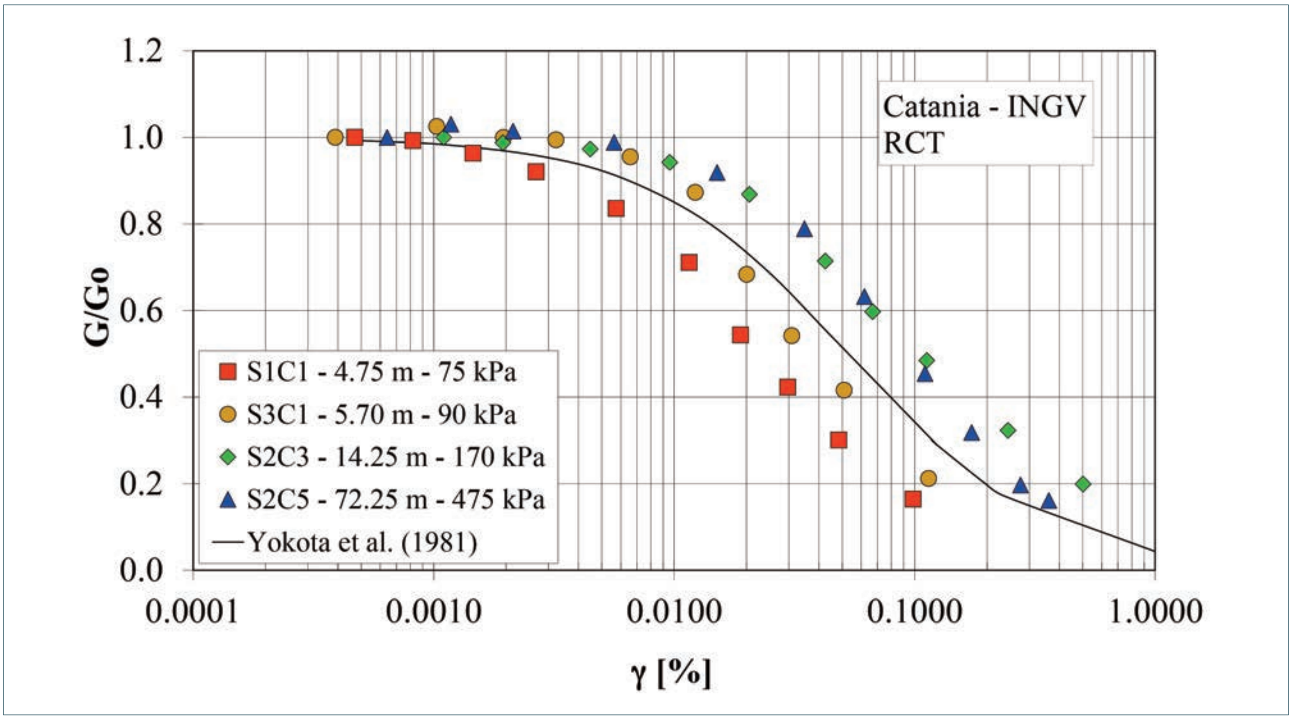


FIGURE 16. G/G_o - γ curves from RCT tests.

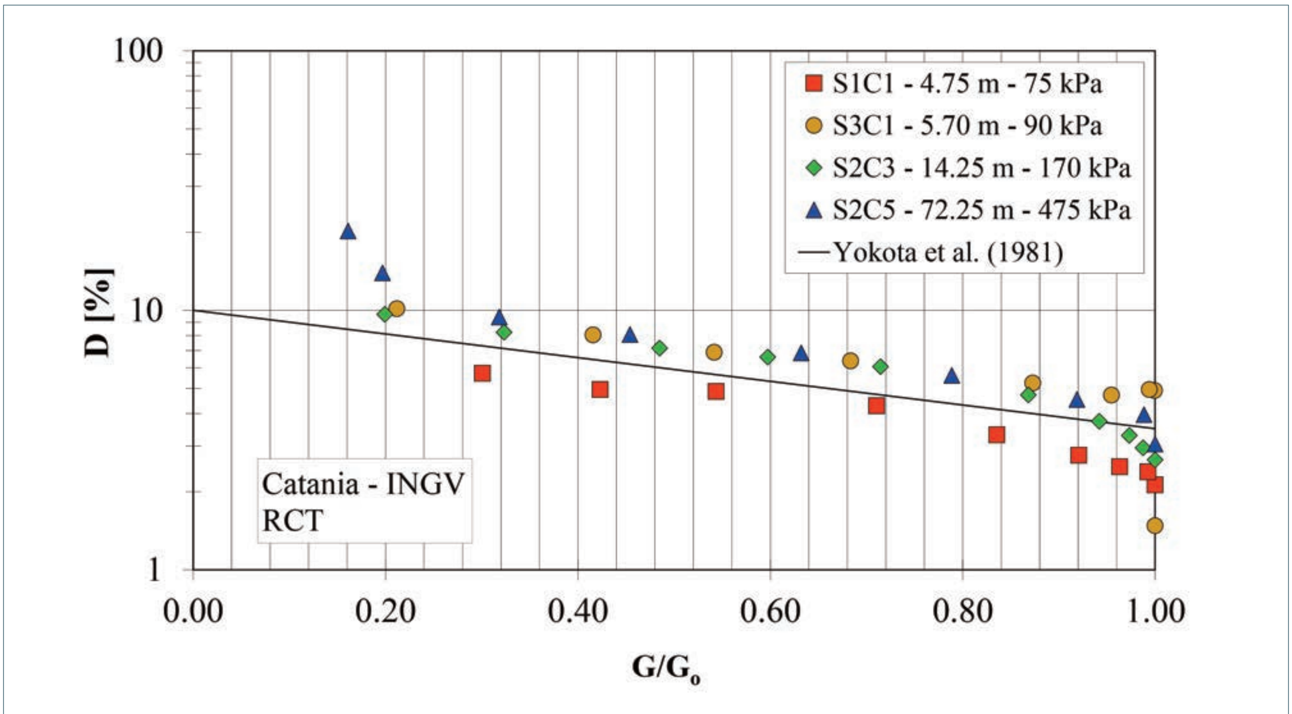


FIGURE 17. D/G_o curves from RCT tests.

used to determine the empirical parameters of the eq. proposed by Yokota et al. [1981] to describe the shear modulus decay with shear strain level (Figure 16):

$$\frac{G(\gamma)}{G_0} = \frac{1}{1+\alpha\gamma\,(\%)^{\beta}} \tag{5}$$

in which: $G(\gamma)$ = strain dependent shear modulus; γ = shear strain; α, β = soil constants. The expression (1) allows the complete shear modulus degradation to be considered with strain level. The values of α = 22 and β = 1.05 were obtained for INGV area.

As suggested by Yokota et al. [1981], the inverse variation of damping ratio with respect to the normalised shear modulus has an exponential form as that reported in Figure 17 for the INGV area:

$$D(\gamma)(\%) = \eta \cdot \exp\left[-\lambda \cdot \frac{G(\gamma)}{G_0}\right] \tag{6}$$

in which: D(γ) = strain dependent damping ratio; γ = shear strain; η, λ = soil constants. The values of η = 10 and λ = 1.05 were obtained for INGV area.

The Equation (5) assume maximum value Dmax = 10 % for G(γ)/Go = 0 and minimum value Dmin = 3.50 % for G(γ)/Go = 1. Therefore, Equation (5) can be rewritten in the following normalised form:

$$\frac{D(\gamma)}{D(\gamma)_{max}} = \exp\left[-\lambda \cdot \frac{G(\gamma)}{G_0}\right] \tag{7}$$

6. CONCLUSIONS

The paper represents a report about static and dynamic properties of soils in the city of Catania. A great availability of borehole data, geophysical surveys and laboratory tests have been carried out from various campaigns of geological surveys. In order to study the dynamic characteristics of soils in three Catania test sites, 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.

Therefore a site characterisation of "National Institute of Geophysics and Volcanology" (INGV), "Nazario Sauro building School" (IC NS) and "Madre Teresa di Calcutta School" (CD MTC) areas for seismic response analysis was presented. Using information made available from in situ boreholes, soil profiles beneath the Catania test sites have been proposed. Trying to summarize the borehole results it is possible to define four soil classes, namely: basaltic rock, sand, volcanic breach and silty clay.

Available data permitted to define the small strain shear modulus Go profile variation with depth. On the basis of the obtained results it is possible to draw the following conclusions:

- the influence of strain rate at very small strain is so negligible;
- a degradation phenomenon occurs during RCT;
- damping ratio values obtained by RCT are greater than those obtained by CLTST;
- higher values of G_o were obtained by Down-Hole tests;
- different G_o values are obtained by SDMT than Down Hole and empirical correlations.

On the basis of in situ test results, it is possible to stress that the small strain shear modulus measured in the laboratory is smaller than that obtained in situ by means of DH tests; this is probably due to a disturbance phenomenon occurred during sampling.

Moreover three empirical correlations available in literature based on laboratory test results, Standard Penetration Tests (SPT) and Seismic Dilatometer Marchetti Tests (SDMT) results were proposed. On the whole, equations proposed by Jamiolkowski et al. [1995] and by Hryciw [1990] seem to provide the most accurate trend of Go with depth.

Finally two empirical expressions have been proposed to describe the complete shear modulus degradation with strain level and the inverse variation of damping ratio with respect to the normalised shear modulus.

Moreover, analysing the shear wave velocity profiles as well as the profiles of the horizontal stress index Kd of the test sites "National Institute of Geophysics and Volcanology" (INGV) and the school "Madre Teresa di Calcutta School" (CD MTC), it is possible to observe that:

- higher values of shear wave velocity Vs in the (CD MTC) site have been obtained by tests in the upper 30 m of soil, so that slight soil amplification phenomena can occur;
- lower values (<400 m/s) of shear wave velocity Vs in the (INGV) site have been obtained by tests in the upper 30 m of soil, so that considerable soil amplification phenomena can occur.

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