Dynamic Geotechnical Characterization for the Microzonation of the Seismic Area of Catania

Antonio Cavallaro
CNR-IBAM, Catania, Italy

Michele Maugeri
University of Catania, Italy

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Antonio Cavallaro
CNR-IBAM
Catania

Michele Maugeri
Department of Civil and Environmental
Engineering, University of Catania

ABSTRACT

The present study is part of a research programme, namely "Detailed Scenarios and Actions for Seismic Prevention of Damage in the Urban Area of Catania", financed by the National Department for the Civil Protection and National Research Council – National Group for the Defence Against Earthquake (CNR – GNDT). Among the objectives of the project there are in particular the geotechnical characterisation of soils of the city of Catania and the evaluation of site effects due to local site amplification phenomena.
The investigation program was performed in seven different test areas of Catania. One of which is the "Plaja beach" sand site. The sand soil was also used to study soil-retaining wall interaction by means of the shaking table. These experiments require an accurate definition of geotechnical characterisation of soil.
To define the mechanical behaviour of Catania sand a large number of static and dynamic laboratory tests were performed on dry reconstituted specimens. The static tests includes direct shear tests performed on specimens reconstituted by pluvial deposition method with different relative density D_r.
To evaluate the equivalent shear modulus G_{eq} and damping ratio D, resonant column tests were performed by mean of Resonant Column apparatus. Particular attention was devoted to the shear modulus at very small strain ($\gamma < 10^{-3}$ %) where the soil behaviour is supposed to be elastic and at intermediate strain level (from 10^{-3} % to 0.5 %) for simulating the prefailure deformation during the shaking table tests. The behaviour of soil at intermediate strain level is relevant for the serviceability limit state according the European Codes (EC7 and EC8). Finally, two expressions to allow the complete shear modulus degradation with strain level and the inverse variation of damping ratio with normalised shear modulus respectively were proposed.

INTRODUCTION

Eastern Sicily is a high seismic hazard area. The seismicity affecting the area can be explained by post-collision processes between the African plate boundary and the Calabrian arc. These produce a peculiar tectonic setting with the regional scale structures that intersect to give rise to the Mt. Etna volcano.
The seismotectonic features of the area are illustrated by Scandone et al. (1992) and more recently by Azzaro and Barbano (2000), who propose a revised seismogenic model of southeastern Sicily. As a consequence of this tectonic setting, the seismic hazard of Catania and its suburbs is due to weak and moderate magnitude (up to M ≈ 4) events related to the seismic activity of Mt. Etna and from larger earthquakes (M = 7.0 ÷ 7.3) located to the south, generated by the regional scale tectonic structures of the Malta – Hyblean escarpment. It is along these structures that the most destructive events of the area took place, such as 1169, 1542 and 1693 earthquakes whose intensities were equal to or greater than X. Moreover, the famous 1908 earthquake, in the Messina Straits, was felt in Catania with an intensity not lower than VII.
More recently, the 1990 off-shore Augusta earthquake, in spite of its moderate magnitude (M = 5.5), caused considerable damage with an intensity of VI in Catania. It is therefore of primary interest to evaluate the seismic response of the urbanized area from moderate to strong seismic input, with particular attention to the effects that can occur on sites having topographical and/or lithological conditions favourable to large local amplifications of ground motion. The evaluation of seismic scenarios for the area of Catania has been discussed by several authors (e.g. Faccioli and Pessina, 2000) and modelling of ground motion was performed using different methodologies (Langer et al., 1999; Priolo, 1999, 2000).

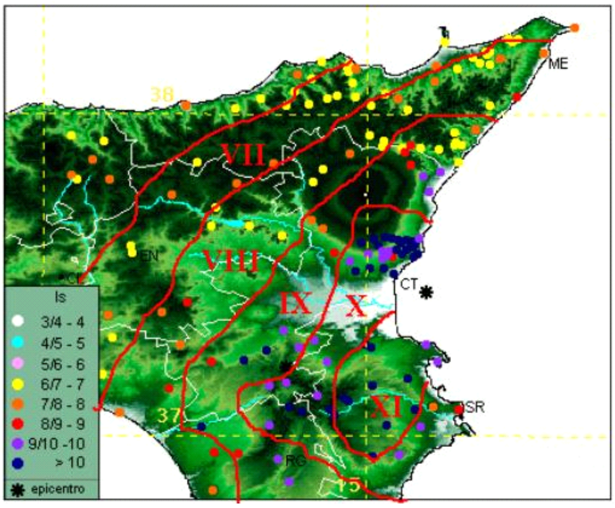

Fig. 1. Isoseismal map of the 1693 Earthquake.

The aim of this paper is to present an accurate static and dynamic geotechnical characterisation of Catania sand in order to allow the analytical modelling of the mechanical behaviour.
To realise the geotechnical characterisation static and dynamic laboratory tests were performed. By means of direct shear test were computed the shear strength parameter φ, paying attention to the relationship with relative density D_r. On the other hand, the dynamic characterisation were determined using the resonant column//torsional shear apparatus (Lo Presti et al., 1993).

GEOLOGIC SETTING

The surface geology of Catania is mostly characterized by weathered lava flows. This situation is the result of several Etnean flows that in both pre-historical and historical times covered the area. The volcanic rocks re-shaped the original morphology of the sedimentary substratum that, at present, outcrops only in small areas in the northern part of the town, whereas it predominates south of the urban area and in the alluvial plane of the Simeto river.
In order to get a reference geological information, geo-lithological map from available wells, superficial survey and data from the literature were gathered (Kieffer, 1971; Catalano et al., 1998, Monaco and Tortorici, 1999). The peculiar geo-lithological feature of the area is the complex litho-stratigraphic sequence formed by soft sediments interbedded between a clayey basement (bedrock) and upper volcanic layers composed of lava flows and pyroclastics.
The lowermost levels that characterize the area are a Lower-Middle Pleistocene succession with about a 600 m thick layer of grey-blue marly clays. These clays include thin layers of fine sands that became more frequently interbedded, gradually grading to a sandy clay formation upward. A sandy formation, several tens of meters thick, unconformable lies upon the sandy clay. The sands are rich in quartz and often include silty layers. In some localities in the surveyed area they also include tuffitic and pumice silty layers with thickness of a few metres. Intercalations of gravels and conglomeratic lens are often observed especially in the topmost, part of the sandy formation. The gravels and gravely sands constitute the higher part of the sedimentary lithology, and are composed of pebbles of polygenic origin, having a diameter ranging from a couple to about twenty centimetres. They are terraced in some cases while sometimes are etheropic with the sands.
The lava flows that overlay the urban area are generally of basaltic type, often formed by alternating massive lavas and more or less weathered scoriae levels, characterized by an extremely variable thickness of both lithologies. A detailed description of prehistoric and historic lava flows in the area of Catania is given by Sciuto Patti (1872) who performed a "geological survey" when the area was not heavily urbanized as it is at present.
Table 1 summarizes the geotechnical units defined for the area by Faccioli, (1997) and Pastore and Turello (2000).

SOIL TESTED

The investigation activity, recently linked with the

Table 1. Description of geotechnical units.

1	R – Dt	Top soil and fill (R), debris and landslides
2	M	Marine deposits
3	Alf	Fine alluvial deposits (silts and clays with subordinated sand lenses)
4	Alg	Coarse alluvial deposits (sands, gravels and pebbes)
5	X	Scoriaceous lavas, lavas in blocks, "rifusa" and volcanoclastic rocks
6	E	Fractured to slightly fractured lavas, with subordinated horizons of scoriaceous lavas, lavas in blocks, "rifusa" and volcanoclastic rocks
7	P	Pyroclastic rocks
8	SG	Yellow or brown quartzose sands and sandstone, gravels and conglomerates with pyroclastic alteration
9	ASg	Yellowish or brown clays and sandy silts, with sandy interbedding and pyroclastic alternation
10	Aa	Silty clays and grey – bluish marly clays

research programme, namely "Detailed Scenarios and Actions for Seismic Prevention of Damage in the Urban Area of Catania", financed by the National Department for the Civil Protection and National Research Council – National Group for the Defence Against Earthquake (CNR – GNDT), was performed in seven different areas of Catania:

1. the "Piana di Catania" site in the S-E zone of the city (Carrubba and Maugeri, 1988a, 1988b; Maugeri et al. 1988a, 1988b);
2. the "ENEL (National Society of Electric Energy) cabin" site in the Piana di Catania, in the S-E zone of the city (Frenna and Maugeri, 1995);
3. the "Plaja beach" site along the southern coast line of Catania (Cascone, 1996);
4. the "Tavoliere" site in the N-W zone of the city (Cavallaro et al., 1999; Castelli et al., 2000; Cavallaro et al., 2002);
5. the "Via Stellata" site in the central area (Cavallaro et al., 1999; Cavallaro et al., 2001b; Maugeri and Cavallaro, 2000);
6. the "Piazza Palestro" site in the central area (Cavallaro and Maugeri, , 2003);
7. the "San Nicola alla Rena Church" site in the central area (Cavallaro et al. 2001a).

The "Plaja beach" site along the southern coast line of Catania is characterised by fine sands with thin interbeddings of gravely sands having mean grain size between 0.24 mm (in the uppermost 10 m of soil) and 0.13 mm the water table lies around 2 m below the ground surface (Cascone, 1996).

The particle size distribution curve, obtained by means of the ASTM method for particle size analysis, was performed by a series of sieves and it is shown in Figure 2. The average particle size is D_{50} = 0.29 mm.

The uniformity coefficient, defined as the ratio of D_{60} to D_{10}, is C = 1.68 and it points out the considerable homogeneity of the particle size.

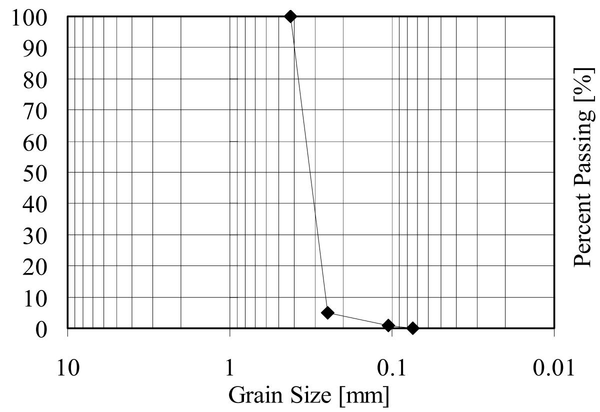

Fig. 2. Grading curve for "Plaja beach" sand.

The specific gravity of soil solid, determined with the ASTM standard test method (D 854), is G_s = 2.68.The maximum dry density was determined by pluviation. The test was performed by using a sand spreader, available at the geotechnical laboratory of the Politecnico di Torino, developed by Miura and Toki (1982) and adapted by Lo Presti (1992). The maximum dry density value is γ_{max} = 16.85 kN/m^3.

On the contrary, minimum dry density was determined according to ASTM (4254-83) method and its value is γ_{min} = 14.50 kN/m^3.

DIRECT SHEAR TESTS

The tests were performed by means of direct shear test apparatus. They were used both standard Casagrande box (6×6×2 cm) and the larger one (10×10×2 cm).

Numerous direct shear tests were performed in such a way to determine the angles of shearing resistance in function of different relative density (Figure 3).

In each test, at least three samples were used to draw the shear envelope to check for test error or sample anomalies. The specimens were reconstituted by means of the pluvial deposition procedure, developed by Lo Presti et al. (1992). This method allows obtaining fixed beforehand values of relative density, to reach a satisfying uniformity of the samples and to reduce the degree of uncertainty. The sand is put into a container, supported by a trolley sliding along one direction. On the base of this container, the sand falls through a slot. The deposition is realised getting to swing the support at constant velocity while the slot is open. It is possible to reconstitute samples with different relative density by placing the container at different height on the trolley, because relative density is correlated with the fall height of sand. After preparing the sample, a constant vertical load was applied for a term of fifteen minutes.

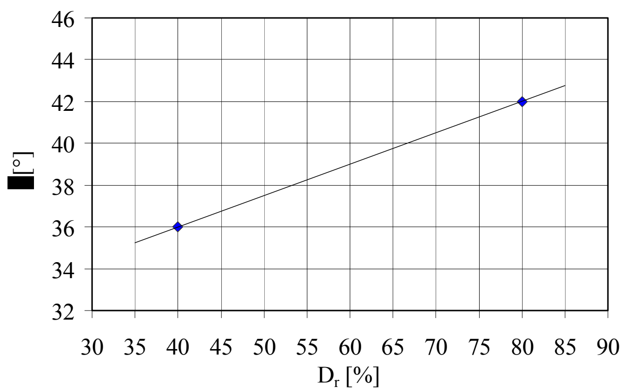

Fig. 3. Shear resistance angle vs. relative density.

During this period, both upper and lower frames are strictly connected by
means of four screws. The vertical stresses adopted (50 kPa, 100 kPa, 150 kPa) are maintained constant during the whole test time. After the rest period of fifteen minutes the screws are taken away and an electric motor produces the shear stress along the sliding surface. The advancement velocity adopted for tests on this sand is equal to 0.5 mm/min.
On the basis of the experimental results (Figure 3), it was possible to obtain the following empirical correlation between φ and D_r:

$$\varphi[°] = 0.15 \cdot D_r[\%] + 30 \quad (1)$$

RESONANT COLUMN TESTS

The equivalent shear modulus (G_{eq}) and damping ratio D were determined in the laboratory by means of a Resonant Column test (RCT) performed by means of a Resonant Column/Torsional shear apparatus.
G_{eq} 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. 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 shear stiffness at $\gamma<\gamma_t^e$ is thus the already defined G_o.
The apparatus used is a fixed-free resonant column apparatus (Hall and Richart, 1963), on solid and hollow cylindrical specimens, modified by Lo Presti et al. (1993). 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, fixed on a concrete anchor block.
The solid or hollow cylinder specimen is fixed at the bottom and its constraint at the base is due to the friction existing between the specimen and the porous sintherized bronze stone (Drnevich et al., 1978).
Torsional forces are applied at the top by means the drive system, realised 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.
The support system, in addition to permits the placement of the drive system, may possibly put the proximity transducers in and the filling in of water for saturated specimen tests.
It was realised a steel pressure cell, to permit the isotropic consolidation using an air pressure source controlled with a manual pressure regulator. The base and the top plates are connected by three vertical rods inside the cell.
In the present work hollow cylindrical specimens were reconstituted by using tapping (Drnevich et al., 1978), in order to obtain the required relative density 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 realise 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 steel pressure cell, using an air pressure source. An air cylinder (Bellofram type), fixed to the concrete anchor block and transmitted by a steel strand connected to the top, provided eventually an additional vertical load. Such a system for anisotropic confining pressure was originally developed at the University of Texas at Austin (Isenhower et al., 1987) and permits the realisation of horizontal-to-vertical effective consolidation stress ratio K always less or equal to one.
Radial strain was measured using two couples of proximity transducers located at mid-height of the specimen and by monitoring both internal and external radius displacements.
The internal diameter variation can be measured at different heights by the couple of miniature proximity transducers, movable along a steel vertical rod. Membrane thickness is assumed constant. 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.
For RCTs the damping ratio was determined using the steady-state method, during the resonance condition of the sample. The laboratory test conditions and the obtained small strain shear modulus G_o are listed in Table 2.
The dry reconstituted specimens were isotropically submitted to a confining stress to simulate the real pressure conditions. The size of hollow cylindrical specimens are Internal Diameter = 50 mm, External

Table 2. Test condition for Leighton Buzzard sand.

Test N°.	D_r [%]	e	σ'_{vc} [kPa]	K	G_o [MPa]
1	46	0.721	38	1	71
2	55	0.711	57	1	79
3	63	0.685	105	1	113
4	19	0.796	39	1	62
5	33	0.765	55	1	60
6	28	0.769	102	1	82

Diameter = 71 mm and Height = 142 mm.
The G_o values, reported in Table 2, indicate the influence of relative density and confining pressure. The results in Figure 4 showed a higher non-linearity of the sample reconstitute with relative density of 28 % rather than of 63 %.
Figure 5 shows the results of RCTs normalised by dividing the shear modulus $G(\gamma)$ for the initial value G_o at very low strain.
The experimental results of specimens were 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:

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

in which: $G(\gamma)$ = strain dependent shear modulus; γ = shear strain; α, β = soil constants.
The expression (2) allows the complete shear modulus degradation to be considered with strain level. The values of $\alpha = 9$ and $\beta = 0.815$ were obtained for Catania sand.
The damping ratio values obtained from RCT are shown in Figure 6.
The damping ratio values obtained from RCT using two

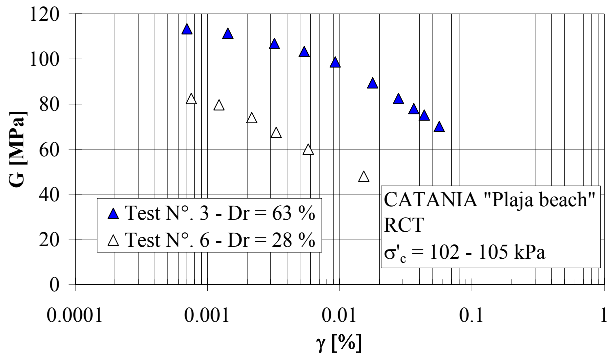

Fig. 4. G-γ curves from RCT.

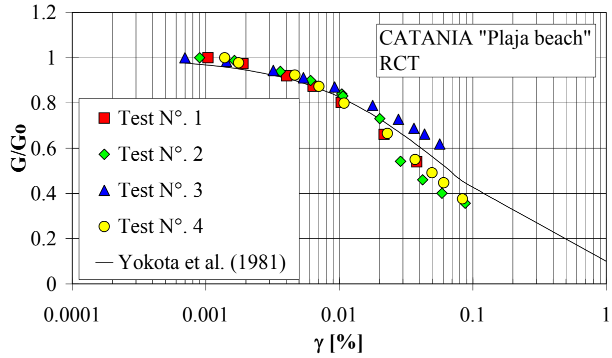

Fig. 5. G/G_o curves from RCT tests.

different relative density values are similar only for strain level of about 0.007 %. Moreover it is possible to see that the damping ratio, at very small strains, is equal to about 1.4 %. Greater values of D are obtained from relative density of 28 % for the whole investigated strain interval. 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 7 for the Catania sand:

$$D(\gamma)(\%) = \eta \cdot \exp\left[-\lambda \cdot \frac{G(\gamma)}{G_o}\right] \qquad (3)$$

in which: $D(\gamma)$ = strain dependent damping ratio; γ = shear strain; η, λ = soil constants. The values of $\eta = 80$ and $\lambda = 4$ were obtained for Catania sand.
The equation (3) assume maximum value $D_{max} = 80$ % for $G(\gamma)/G_o = 0$ and minimum value $D_{min} = 1.46$ % for $G(\gamma)/G_o = 1$. Therefore, eq. (3) can be re-written in the following normalised form:

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

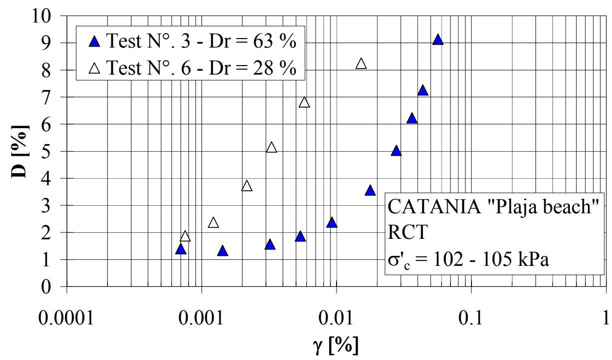

Fig. 6. Damping ratio from RCT.

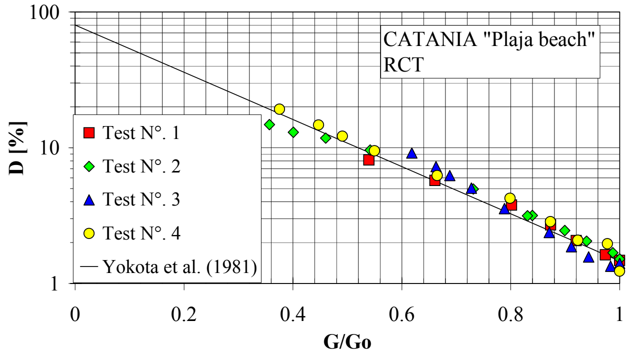

Fig. 7.D-G/G_o curves from RCT tests.

As comparison, the values of empirical parameters of equation (2) and (3) for Catania test sites are reported in Table 3.

EVALUATION OF G_O FROM EMPIRICAL CORRELATIONS

It was also possible to evaluate the small strain shear modulus by means of empirical correlation.

The empirical expression developed by Iwasaki et al. (1978), and here adopted, normalises G_o as regards the void ratio and the confining pressure:

$$G_o = 900 \cdot \frac{(2.17-e)^2}{(1+e)} \cdot p_a \cdot \left(\frac{\sigma'_{ott}}{p_a}\right)^{0.43} \quad (5)$$

where: 900 = adimensional constant; e = void ratio; p_a = reference pressure (atmospheric pressure); $\sigma'_{oct} = (\sigma'_1 + \sigma'_2 + \sigma'_3)/3$ = octahedral pressure.

G_o, σ'_{ott} and p_a are expressed in the same unit.

The results are reported in Table 4 and then compared with the RCTs values.

Higher values of G_o were observed for the equation of Iwasaki et al. (1978). This behaviour can be explained by considering that the Iwasaki et al. (1978) equation was developed from cyclic loading torsional shear results.

Table 3. Soil constants for Catania area.

Site	α	β	η	λ
1. Piana di Catania	7.15	1.223	19.87	2.16
2. ENEL box	-	-	-	-
3. Plaja beach	9	0.815	80	4
4. Tavoliere	-	-	-	-
5. Via Stellata	11	1.119	31	1.921
6. Piazza Palestro	6.9	1	23	2.21
7. San Nicola alla Rena Church	7.5	0.897	90	4.5

Table 4. G_o from Iwasaki et al. (1978) equation.

Test N°.	Dr [%]	e	σ'_{vc} [kPa]	K	G_o (Iwasaki, 1978) [MPa]	G_o from tests [MPa]
1	46	0.721	38	1	102	71
2	55	0.711	57	1	124	79
3	63	0.685	105	1	169	113
4	19	0.796	39	1	89	62
5	33	0.765	55	1	110	60
6	28	0.769	102	1	142	82

Moreover the normalised experimental results have been compared with the empirical correlation proposed by Jamiolkowski et al. (1991), that is valid for average pressure of consolidation σ'_m = 100 kPa:

$$G_o = 60 \cdot \frac{1}{e^{1.3}} \quad (6)$$

with G_o expressed in MPa.

G_o evaluated by laboratory tests has been normalised to the average pressure of consolidation of 100 kPa by means the expression:

$$G_{o,norm} = G_o \cdot \left(\frac{100}{\sigma'_m}\right)^{0.62} \quad (7)$$

where: σ'_m is the average pressure of consolidation.

In Table 5 the G_o values obtained by eq. (6) and the $G_{o,norm}$ (eq. 7) values are showed.

The comparison between experimental values and empirical correlation has a good agreement. It is worthwhile to point out that the considered equation underestimate G_o.

CONCLUSIONS

In this paper a geotechnical characterisation of Catania sand in static and dynamic field has been presented.

Table 5. G_o from Jamiolkowski et al. (1994) equation.

Test N°.	Dr [%]	e	σ'_{vc} [kPa]	K	G_o Jamiolkowski, (1991) [MPa]	$G_{o\ norm}$ [MPa]
1	46	0.721	38	1	92	129
2	55	0.711	57	1	93	112
3	63	0.685	105	1	98	110
4	19	0.796	39	1	81	111
5	33	0.765	55	1	85	87
6	28	0.769	102	1	84	81

On the basis of pluvial deposition procedure and direct shear tests results empirical correlation between φ and D_r is proposed.
Available data enabled one to define the small strain shear modulus trend in relation to the void ratio values. RCTs are also used to describe the G and D variation with strain level.
On the basis of the experimental results obtained, it is possible to draw the following conclusions:

- at small strain G_o is depending on soil relative density and confining pressure;
- at small strain G_o values evaluated by empirical equations are higher than those evaluated by RCTs ;
- higher non-linearity was showed for samples reconstitute at small relative density;
- at small strain damping ratio is not less than one;
- damping ratio values determined from RCT for relative density of 28 % are greater than those obtained for D_r = 63 %.

The initial shear modulus and soil non-linearity in terms of shear modulus and damping ratio are required for the evaluation of site effects due to local site amplification phenomena. The dynamic Catania sand soil characterisation in also to required to perform shaking table tests on soil-retaining wall and soil-foundation interaction

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