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A geotechnical study for the historical heritage preservation of the City of Noto (Italy)

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ABSTRACT: Eastern Sicily is extremely rich with artistic and monumental heritage, but at the same time it is the most seismically active area of Italy. In particular, the city of Noto, now considered the capital of baroque in Sicily, was destroyed by the 1693 Earthquake and rebuilt in another site, as many other cities. The seismic microzonation is now being studied for this area. The following in situ investigations were carried out in order to determine the soil profile and the geotechnical characteristics of the site under consideration, with special attention for the variation of shear modulus and damping with depth: Geological boring, Down Hole (DH) tests, Dilatometer tests (DMT), Cone penetration tests (CPT) and Standard penetration tests (SPT). Moreover, the following laboratory investigations were carried out on undisturbed samples: Resonant column tests (RCT), Cyclic loading torsional shear tests (CLTST), Cyclic loading triaxial tests (CLTxT), Oedometer tests and Direct shear tests. This work aims to be the starting point for a correct approach to the problems concerning the safeguarding of the artistic and monumental heritage.

1 INTRODUCTION

The old city of Noto, few kilometres in the upper part of the city of Noto, was destroyed by the 11th January 1693 earthquake and both the build-up areas had heavy damages in occasion of the 7th January 1727 earthquake. The 13th December 1990 earthquake damaged several 18th century constructions and drew attention to the need for safeguarding its artistic monumental heritage, maximum expression of Sicilian baroque (Cavallaro et al. 2003a).

In order to study the dynamic characteristics of soils in Noto municipal area, laboratory and in situ investigations have been carried out to obtain soil profiles with special attention to the variation of the Young Modulus (E) shear modulus (G) and damping ratio (D) with depth. This paper tries to summarise this information in a comprehensive way in order to provide a representative geotechnical model of ground condition of the different zones where important monuments are located. This enabled the evaluation of site effects to define the earthquake design actions and then the rational restoration and strengthening of some monuments, before their collapse, with the exception of Noto Cathedral, which was restored after its partial collapse, caused by the 1990 Sicilian earthquake.

2 HISTORICAL BACKGROUND AND SEISMICITY OF AREA

The area around Noto was populated by a Bronze Age people between 2000–1500 BC. The famous archaeologist Paolo Orsi, who explored and studied the site, gave the name “Casteluccio Culture” to the site and its inhabitants. The major part of the finds are now on display at Syracuse Archaeological Museum. There are a few ruins of a prehistoric village and a primitive necropolis. The history of

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Noto prior to the 1693 quake belongs to the old town, now called "Noto Antica" and known in antiquity as "Netum." What remains of the old town is located some 13 kilometers away from the present town of Noto. The legend tells that Noto Antica was founded by a King of the Siculi named Ducetius in about 500 BC. Scholars dated the earliest ruins to about 800 BC. With the Greek colonization of Syracuse, Netum came into contact with the advanced Hellenistic Culture and was eventually absorbed by it. Noto Antica achieved a certain level of importance during the Arab period when it became the administrative center of Noto Valley, one of the three provinces that the Arab governors had subdivided Sicily into. The town was one of the last bulwarks of Saracen resistance to the Norman takeover, not surrendering to Count Roger de Hauteville until 1091.

Southeastern Sicily experiences relatively unfrequent but strong earthquakes: in three cases during this millennium and as concerns the previous times, in an unknown but obviously conspicuous number of ~~the~~ other cases. In the past centuries, Sicily was struck by strong earthquakes whose characteristics derive from the geodynamic feature of the Western Mediterranean Sea.

Figure 1. The Saint Nicola Cathedral and a detail of the interior.

As concerns the earthquakes in the current millennium, we have many coeval sources testifying their effects but unfortunately paying little attention to the environmental consequences. Much of this reference material, physically dispersed through a myriad of public and private institutions, has been recently made available (Boschi et al. 1995, 1997).

A detailed list of the earthquakes which struck this area has been given by C.N.R. (1985a). A study of the most intense earthquakes which damaged the city of Noto has been made by C.N.R. (1985b). A brief description of the most significant earthquakes can be summarized as following reported.

Catania earthquake on February 4th 1169 is one of the oldest shocks of great magnitude with available detailed studies. The earthquake took place in the Southern part of Sicily where seismicity is characterized by very strong energy releases usually occurring after long quiet periods. The shock caused heavy damages (Pertz 1866; Siragusa 1897). The epicentral area was located near the city of Catania where the intensity seems to have reached the XI degree in the MCS scale (Agnello 1997; Lombardo 1985; Postpischl 1985;. In Noto area, the earthquake intensity reached the X degree. It caused many victims and destroyed many buildings.

On December 10th 1542 another earthquake struck the city of Noto, however it seemed to be one of the weakest that have historically occurred in Noto area (Ha-Kohen, XVI century). The epicenter was located near the city of Sortino, which is about 30 km far from Noto. In the epicentral area, the intensity was about IX degree while in Noto it reached the VII degree (Barbano 1985a).

The "Val di Noto" earthquake of 11th January 1693 is considered one of the most powerful earthquakes in Italy. It is thought that more than 1500 aftershocks occurred for about two years more (Barbano 1985b). This earthquake was the most destructive of all time reaching the intensity of 11° degree of MCS scale. It struck a vast territory of southeastern Sicily and caused the partial, and in many cases the total, destruction of 57 cities in the area: Catania with 19000 inhabitants, Modica (18000), Siracusa (15000), Acireale (13000), Caltagirone (12000), Noto (12000), Vizzini (11000), Lentini (10000), and Ragusa (10000). There were around 60000 victims (Agnello 1931; Anonimo 1693; Boccone 1697; Bottone 1718). Its epicenter was located near the city of Lentini, which is 45 km far from Noto; the effects were quiet strong even in the South of Italy and on the African coasts.

On 13th December 1990, another earthquake struck Noto (De Rubeis et al. 1991; Rovelli et al. 1991). Anyway, the intensity was not too strong and reached, in the epicentral area, the VII degree. The magnitude was about $M = 5.4$. Due to the low intensity, this time the damage interested only several old buildings and ancient monuments and was mostly limited to cornice falls and masonry fractures.

Figure 2. “Tina Di Lorenzo” Theatre and a detail of the interior.

After the 11th January 1693 earthquake Noto was re-built in a new site. The greater towns destroyed by the 1693 earthquake, with the only exception of Modica and Ragusa, were “demaniali” cities, like Noto, subjected directly to the royal power. Many inhabited areas were feuds of the powerful aristocratic Sicilians families instead.

In 1693, Sicily was part of the Spanish kingdom and it was administered by a “vicerè” (pro-rex) who at the moment of the disaster was the Duke De Uzeda. He named Giuseppe Lanza, Duke of Camastra, as his General Vicar, military of career and expert of architecture.

The Vicar with his competence and with the collaboration of the artillery colonel and military architect Carlos de Grunemberg provided for the first helps and mailed the plans of reconstruction of the “demaniali” cities. In Noto, the reconstruction began under the Spanish domination and achieved most substantial results under the Bourbon kingdom who ruled Sicily from 1735 until Garibaldi enterprise.

The reconstruction hocked intellectual and economic resources for 50 years and thanks to the successful combination of cultured owners and high technical ability (to be remembered the exceptional “lapidum incisores”) it constitutes one of the greatest examples of urban planning of every era. In numerous cases the reconstruction was made in a different site because, as military demands had changed, fortification of the inhabited area was no longer necessary. The urbanistic “culture” of the managing class of that time was theoretical and the most known models were those of the cities with geometric design (Carlentini 1551; La Valletta 1566, Plamonova 1593).

In Noto, thanks to the meeting among “fra” Angelo Italia, a Jesuit architect, local experts and Spanish engineers, an extraordinary plan was realized by merging the rigor of the geometric grate with the articulation of the three principal squares (the S. Francesco square, the Cattedrale square and XXIV Maggio square). The light transversal slope determines varying glimpses that make mutable the urban landscale (one of the characteristics of the figurative baroque art in urbanistic field). The result is made precious by the quality and the greatness of the buildings in many cases designed by famous architects like Gagliardi, Labisi and Sinatra. Not of secondary importance was the contribution of the Noto's calcarenite unique for its color.

Noto became a model of the baroque city (Figures 1, 2), more than other centers like Catania, Caltagirone and Acireale, rich of artistic heritage and baroque architecture. Noto has been identified for a style that is one the greatest demonstrations of the artistic creativeness of all times.

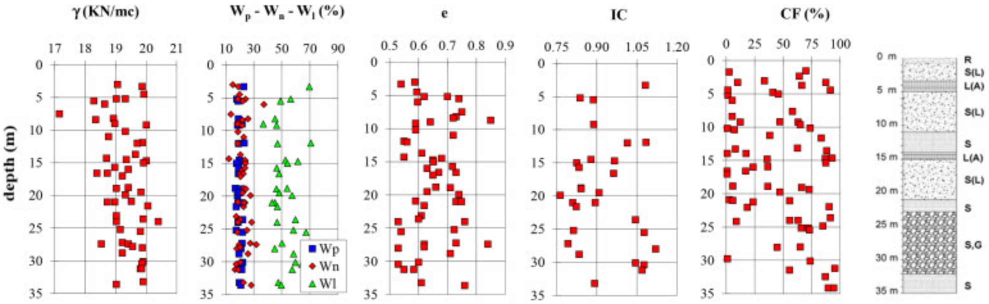

Figure 3. Index properties of Noto soil; where R: Landfill; S(L): Silty Sand; L(A): Clayey silt; S: Sand; S,G: Sand and Gravel.

3 STATIC AND DYNAMIC CHARACTERISTICS OF THE SOIL

The Pliocene Noto deposits mainly consist of a medium stiff, over-consolidated lightly cemented silty-clayey-sand (Castelli et al. 2016a). The pre-consolidation pressure σ'_p and the over-consolidation ratio $OCR = \sigma'_p/\sigma'_{vo}$ were evaluated from the 24 h compression curves of incremental loading (IL) Oedometer tests. Moreover, 9 flat dilatometer tests (DMT) were performed to assess OCR and the coefficient of earth pressure at rest K_o following the procedure suggested by Marchetti (1980), Cavallaro et al. (2012a, 2012b; and Castelli et al. (2016a, 2016b). The values of basic soil properties are showed in Figure 3. Resonant Column (RCT) and Cyclic Loading Torsional Shear (CLTST) tests have been performed by using the same apparatus (Cavallaro & Maugeri 2005; Capilleri et al. 2014; 2016a, 2018) to evaluate the shear modulus G and damping ratio D of the municipal area of Noto soil. The laboratory test conditions are listed in Table 1.

Table 1. Test condition for Noto soil specimens.

Test	Sample	H [m]	σ'_{vc} [kPa]	σ'_{hc} [kPa]	γ [kN/m^3]	e	PI	G_o (1) [MPa]	G_o (2) [MPa]	E_o [MPa]	Specimen
1	S16CI1	4.50	144	144	19.32	1.236	–	86	122	–	S
2	S15CI1	7.60	145	145	17.16	0.777	–	153	185	–	S
6	S15CI2	10.00	225	195	19.47	0.817	41	–	–	195	S
3	S15CI2	10.00	190	163	19.69	0.740	41	40	49		H
4	S16CI2	17.50	336	336	19.22	0.747	–	337	465	–	S
5	S16CI2	17.50	380	380	19.22	1.238	–	207	244	–	S

where: U = Undrained. G_o (1) from CLTST, G_o (2) from RCT. S = Solid cylindrical specimen. H = Hollow cylindrical specimen.

The samples have the following geological characteristics: S16CI1 – Brown stiff clayey silt, with traces of minute calcareous elements; S15CI1 and S15CI2 – Brown to white-grey silty sand; S16CI2 – Brown silty sand with traces of minute rounded calcareous elements.

The undisturbed specimens were isotropically reconsolidated to the best estimate of the in situ mean effective stress.

The same specimens were first subjected to CLTST (Cyclic Loading Torsional Shear Test), then to RCT (Resonant Column Test) after a rest period of 24 hrs with opened drainage. CLTST were performed under stress control condition by applying a torque variable over time 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 while the size of hollow cylindrical specimens are External Radius = 25 mm, Internal Radius = 25 mm and Height = 100 mm.

One specimen was tested in the triaxial apparatus equipped with local strain gauges (Cavallaro & Maugeri 2004; Castelli et al. 2019; Lo Presti et al. 1999). The size of solid cylindrical specimens are Radius = 35 mm and Height = 140 mm.

The specimen underwent dry setting: Dry filter papers and dry porous stones were used during specimen setting. The bottom drainage line was filled with water up to 1 cm below the porous stone. The top drainage line was left empty. After the specimen had been set up and the pressure cell had been sealed, the system saturation was achieved in two steps. Flushing deaired water with a head of 50 cm was applied to the specimen, from the bottom to top, for at least 24 h. During this stage, the loading ram was blocked so that the vertical stress automatically increased to counteract the tendency of the specimen to swell. The horizontal stress was controlled by means of a PC in order to prevent any radial displacement with a tolerance of ±0.5 μm. The radial displacement was monitored by means of a pair of proximity transducers. Back pressurization was carried out in order to dissolve any air bubbles that might still be trapped in the lines and in the space between the specimen and the membrane. This stage was terminated when the B parameter was equal to or larger than 0.95. Back-pressurization was carried out increasing the total isotropic stress by steps of 50 kPa in undrained conditions. The corresponding pore pressure increase was recorded in order to check Skempton's B parameter. Thereafter, the back pressure was increased by 50 kPa and the drainage was opened. The next step was applied after at least 2 h in order to achieve an acceptable pressure equalization. As far as the wet setting procedure is concerned, the specimen only underwent back-pressurization in order to achieve an acceptable degree of saturation. The effective isotropic stress applied to the specimen during this process ranged from 15 to 30 kPa.

After the dry setting, this specimen was reconsolidated to the in situ geostatic stresses (PC-controlled K_o condition). In particular, the axial stress was increased up to a target value ($\sigma'_{vc} = \sigma'_{vo}$) by moving up the loading ram with a strain rate of about 0.01 %/ min. In the meantime- the radial stress was increased in order to keep the lateral displacement equal to zero within a tolerance of a 0.5 pm. The above described process was controlled by means of a PC. After the achievement of the target axial stress, the test was paused to dissipate any possible excess of pore pressure and a certain amount of creep deformation. The test was paused until the creep rate became smaller than 0.05 [%/day] following the suggestions given by Jardine et al. (1991). This condition was obtained alter about 24 h. During this period, the vertical stress was kept constant while the horizontal stress was automatically adjusted in order to have a zero radial strain. Consolidation test were performed with a strain rate of 0.001 %/min.

After the consolidation stage, the specimen was subjected to Cyclic Loading Triaxial test (CLTxT), at constant strain rate. Six different strain levels of progressive amplitude were imposed to the specimen (Step 1: $\varepsilon_{sa} = 0.00087$ %; Step 2: $\varepsilon_{sa} = 0.00526$ %; Step 3: $\varepsilon_{sa} = 0.01397$ %; Step 4: $\varepsilon_{sa} = 0.03672$ %; Step 5: $\varepsilon_{sa} = 0.07871$ %; Step 6: $\varepsilon_{sa} = 0.26596$ %). For each strain level, 30 cycles were applied. The maximum applied axial strain (single amplitude) was about 0.3 %. The same specimen was subjected, after a rest period of 24 hrs with open drainage, to Monotonic Loading Triaxial test (MLTxT). The obtained small strain Young modulus E_o is reported in Table 1. The small strain Young's modulus E_o was determined from the initial slope of the stress-strain curve at strains of less than 0.001%.

Normalized shear modulus G/G_o and damping (D) obtained from RCT and CLTST are shown in Figure 4. The same shear modulus decay is obtained from both type of tests but the damping ratio values provided by CLTST are smaller than those measured in RCT. For 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. The damping ratio values obtained

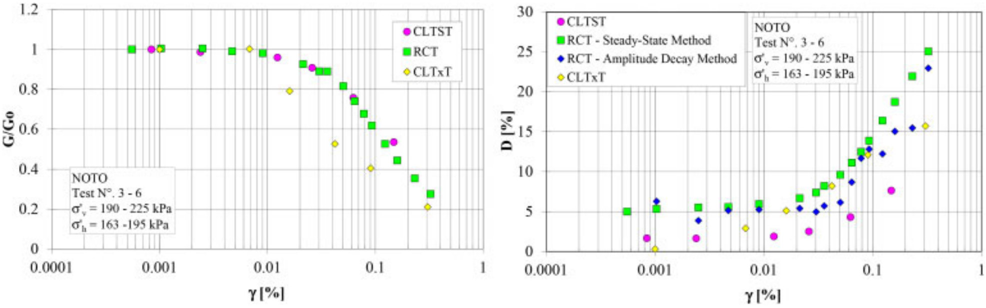

Figure 4. $G/G_o - \gamma$ and damping ratio curves from CLTST, RCT and CLTxT.

from RCT using two different procedures are similar even if higher values of D have been obtained from steady-state method. It is possible to see that the damping ratio from CLTST, at very small strains, is equal to about 1 %. Greater values of D are obtained from RCT for the completely investigated strain interval.

In Figure 4 we compare the results from CLTxT. It is possible to notice that CLTxT results show a greater non-linearity while the damping ratio values from CLTxT and those from CLTST are comparable for stress level less than 0.01 %. It should be remembered that CLTxT have been performed at constant strain rate equal to 0.01 %/min. Yet the different deformation mechanism (different stress-path) could be responsible for the observed differences.

In Figure 5 is shown the effect of N on stiffness and damping ratio (D), which represents a typical test results. Figure 5 shows, for different strain levels, the decrease of E and the increase of D with N.

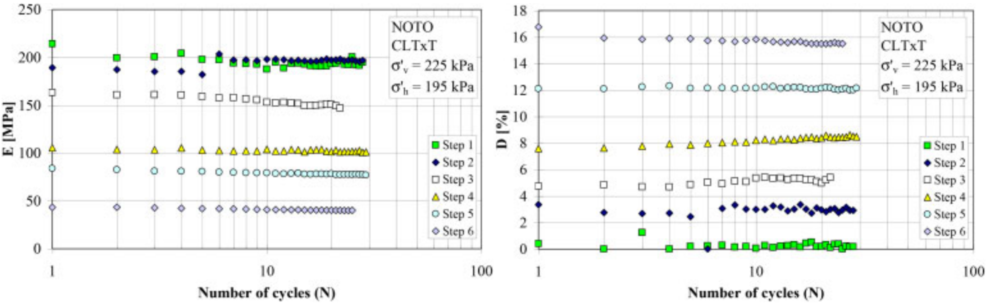

Figure 5. Dependence of unloading-reloading stiffness and damping on number of cycles (N).

The effect is quite negligible for strain amplitude of less than 0.1 % and become relevant beyond such a limit (Cavallaro et al. 1999a, 1999b).

This trend is the effect of soil degradation and only for step 1 ($\varepsilon_{sa} = 0.00087$ %) it is possible to observe a decrease of D. The Authors were inclined to believe that such behaviour could be a consequence of very low strain rates. Therefore a consequence of creep deformations. Moreover, even at more usual frequency (0.1 Hz) Cavallaro et al. (2003b) observed a similar behaviour in the case of lightly overconsolidated clay.

The small strain shear modulus G_o can be evaluated in situ by Down Hole tests using the relationships: $G_o = \rho V_s^2$ (where: ρ = mass density) based on theory of elasticity. Marchetti (1997) proposes a dynamic evolution of the dilatometer (SDMT) which unfortunately was not used at the Noto site (Cavallaro et al. 2012a, 2012b; Castelli et al. 2016c; Cavallaro & Grasso 2021)

An attempt was made to evaluate the small strain shear modulus by means of the following empirical correlations based on penetration tests results, CPT, SPT and DMT (Marchetti 1980) or laboratory results available in literature (Figures 6 and 7).

- Imai and Tomaichi (1990):

$$G_o = 28 \cdot (q_c)^{0.611} \tag{1}$$

for any soil.

- Mayne and Rix (1993):

$$G_o = \frac{406 \cdot q_c^{0.696}}{e^{1.13}} \tag{2}$$

for clayey strata;
where: G_o and q_c are both expressed in [kPa] and e is the void ratio. Equation (2) is applicable to clay deposits only.

- Simonini and Cola (2000):

$$G_o = 49.2 \cdot (q_t)^{0.51} \tag{3}$$

It is also possible to evaluate the small strain shear modulus using the relation $G_o = \rho \cdot V_s$ by the following equations proposed by Ohta and Goto (1978) and Yoshida and Motonori (1988) for the shear waves velocity V_s:

- Ohta and Goto (1978):

$$V_s = 69 \cdot N_{60}^{0.17} \cdot Z^{0.2} \cdot F_A \cdot F_G \tag{4}$$

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)

- Yoshida and Motonori (1988):

$$V_s = \beta \cdot (N_{SPT})^{0.25} \cdot \sigma_{vo}^{\prime 0.14} \tag{5}$$

where: V_s = shear wave velocity (m/s), NSPT = number of blows from SPT, σ'_{vo} = vertical pressure, β = geological factor (any soil = 55, fine sand = 49).

- Hryciw (1990):

$$G_o = \frac{530}{(\sigma'_v/p_a)^{0.25}} \frac{\gamma_D/\gamma_w - 1}{2.7 - \gamma_D/\gamma_w} K_o^{0.25} \cdot (\sigma'_v \cdot p_a)^{0.5} \tag{6}$$

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 DMT results according to Marchetti (1980).

- Jamiolkowski et al. (1995):

$$G_o = \frac{600 \cdot \sigma_m^{\prime 0.5} p_a^{0.5}}{e^{1.3}} \tag{7}$$

The Jamiolkowski et al. (1995) method was applied considering a given profile of void ratio.

The values for parameters, which appear in equation (7), are equal to the average values resulting from laboratory tests performed on quaternary Italian clays and reconstituted sands.

Equation (7) incorporates a term, which expresses the void ratio; the coefficient of earth pressure at rest only appear in equation (6). However only equation (6) tries to obtain all the input data from the DMT results.

As regard Noto soil, the G_o values obtained with the methods above indicated for CPT and SPT are plotted against depth in Figure 6.

The results obtained show a greater similarity between the G_o results obtained by the empirical correlations proposed for SPT, which, moreover, are quite close together. More dispersed and higher are the G_o values obtained through the correlation equations proposed for CPT.

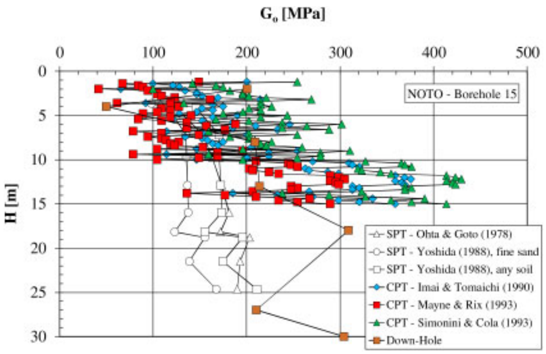

Figure 6. Small strain shear modulus G_o by empirical correlations based on CPT and SPT.

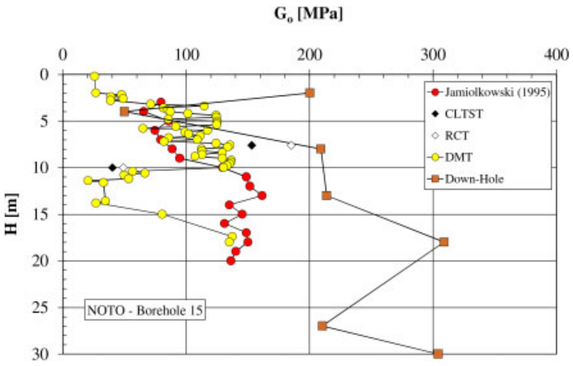

Figure 7. G_o from Down Hole, empirical correlation and RCT.

The lowest values of the shear modulus are obtained by the equation proposed by Mayne and Rix (1993). Only by the Down Hole test it is possible to identify the rapid of G_o at a depth of about 16 m in correspondence with some layer characterized by higher mechanical characteristics that SPT cannot identify.

The N_{60} values, experimentally determined during SPT, did an unimportant variation in the transition zone at depth of about 16 m, where the characteristics of the soil change from clayey silt to silty sand and then to sand with gravel.

Standard Penetration Tests were performed at intervals from 1.5 to 3.0 m. The quite large interval used could explain why the thin sand layers were not detected. Consequently, the obtained G_o values, in the transition zone, resulted to be quite low.

Unfortunately, the depth investigated by DMT is not able to intercept the most consistent layers of sand and sand with gravel. Even if, the method by Hryciw (1990) is distant from the trend of the results obtained from the Down Hole tests as can be seen in Figure 7

From a comparison between Figure 6 and Figure 7 all the considered methods show very different G_o values of the Pliocene Noto soil. On the whole, Down Hole seems to provide the most accurate trend of G_o with depth even if the available data are unable to investigate the behavior of the soil for depths greater than 30 m. The method by Jamiolkowski et al. (1995) was applied considering a given profile of void ratio but while guaranteeing continuity of results, it fails to intercept the most consistent layers of sand and sand with gravel.

In Figure 7 the RCT results are also reported. The data obtained also show as the dynamic laboratory tests are able to interpret the G_o trend obtained from the Down Hole test only at the depth of 7.5 m.

4 CONCLUDING REMARKS

A site characterization for a correct approach to the problems concerning the safeguarding of the artistic and monumental heritage has been presented in this paper. On the basis of the data shown it is possible to draw the following conclusions:

- when $\gamma \geq \gamma_t^v$, degradation phenomena occur; the normalized shear modulus obtained from CLTxT results show a greater non-linearity
- damping ratio values determined from RCT are greater than those obtained from CLTST while the damping ratio values from CLTxT and those from CLTST are comparable for stress level less than 0.01 %;
- the observed differences between RCT, CLTST and CLTxT results are probably due to rate and/or frequency effects and different deformation mechanism (different stress-path).
- empirical correlations between the small strain shear modulus and penetration test results were used to infer G_0 from SPT, CPT, DMT and Down Hole. This comparison clearly indicates that a certain relationship exists between G_0 and the penetration test results, which would encourage to establish empirical correlations for a specific site. This approach makes it possible to consider the spatial variability of soil properties in a very cost effective way.
- the values of G_0 were compared to those measured with DMT and DH tests. This comparison indicates that some agreement exists between empirical correlations by DMT and DH test.
- relationships like those proposed by Jamiolkowski et al. (1995) seem to be capable of predicting G_0 profile with depth only in the initial strata. The accuracy of these relationships could obviously be improved if the parameters, which appear in the equations, were experimentally determined in the laboratory for a specific site.
- probably only Down Hole test is able to correctly investigate the various layers of soil, identifying even the smallest variations in the mechanical characteristics.

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