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In Situ and Laboratory Tests for Site Response Analysis in the Ancient City of Noto (Italy)

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***Abstract* – The city of Noto belongs to a seismic area located on the eastern zone of Sicily (Italy). The following in situ investigations were carried out in order to determine the soil geotechnical characteristics: Down Hole (DH) tests, Dilatometer tests (DMT), Multichannel Analysis of Surface Waves (MASW) and geotechnical borings. Moreover the following investigations in the laboratory were carried out on undisturbed samples: Resonant Column, monotonic compression loading Triaxial tests and Direct shear tests. Finally synthetic seismograms have been drawn at the bedrock with the aim to perform the ground response analysis at the surface, in terms of time history and response spectra, by a linear-equivalent model.**

I. INTRODUCTION

The city of Noto, located in the South-Eastern Sicily, was affected in the past by several destroying earthquakes of about magnitude greater than 7.0. The area, belongs to the Ibleo-Maltese escarpment, is placed near the contact between the African and the Euro-Asiatic plates, and it is therefore a seismogenic area. According to the frequency and the importance of the seismic effects suffered in past times, Eastern Sicily must be considered one of the most high seismic risk areas in Italy. The area is densely populated territory; a huge patrimony of historical and monumental buildings is placed in the area.

In situ and laboratory investigations have been carried out in order to determine the soil dynamic characteristics in the Noto tests sites.

In the tests sites some boreholes have been performed and undisturbed samples were retrieved. In the boreholes a Down-Hole geophysical survey and MASW tests were performed. On the undisturbed samples static soil tests and dynamic soil tests were performed (Resonant Column Tests).

Finally, accelerograms and synthetic seismograms of scenario earthquakes have been used to evaluate the local site response analysis at the surface. The ground response analysis at the surface, in terms of time histories and response spectra, has been obtained by a 1-D linear-equivalent model.

II. SEISMICITY AND GEOLOGICAL CHARACTERISTICS OF THE AREA

Over the last 9 centuries the strongest earthquake, with epicentral intensity falling within the interval VIII and XI MCS, are only 8, and the last of these with epicentral intensity of VIII MCS, dates back to 11 January 1946 ([1], [2]). Afterwards, the strongest earthquake, about 140 years later, is the Sicilian Earthquake of December 13, 1990, with the epicentre close to Augusta and maximum intensity of VII - VIII MCS.

The old city of Noto, few kilometers in the upper part of the city of Noto, was destroyed by the Val di Noto earthquake of January 11, 1693; the build-up areas suffered also heavy damages in occasion of the January 7 , 1727 earthquake. The December 13, 1990 earthquake damaged several eighteenth century constructions in Noto and called the attention on need of safeguarding the artistic monumental patrimony of this city, maximum expression of Sicilian baroque ([3], [4], [5], [6]).

In physiographic terms, SE. Sicily consists basically of a plateau - the Hyblean Mountains - dissected by canyons and bounded towards north and west by loawer, smoothly undulated to flat lands [7]. The area, as defined here, extends over 4300 km^2, and has a population of about 800,000 (Figure 1). The epicentres of the historical scenario strong earthquakes which heavy damaged the cities of Noto, Augusta and Siracusa are reported in Figure 2 [8]. The strongest are those of 1169, 1542, 1693, 1848 and 1990.

In the Hyblean Mts., limestone, marlstone, calcarenite and intermediate rock types, mostly well lithified, are predominant.

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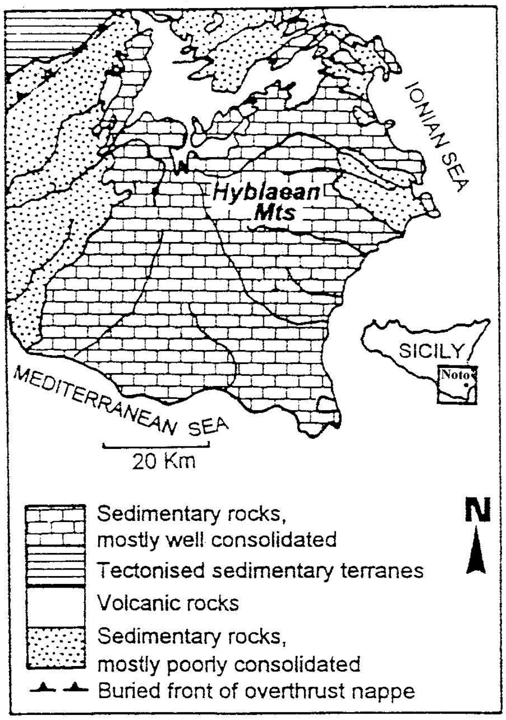

Figure 1. Location of Noto (Sicily) and geology of the area, after [7].

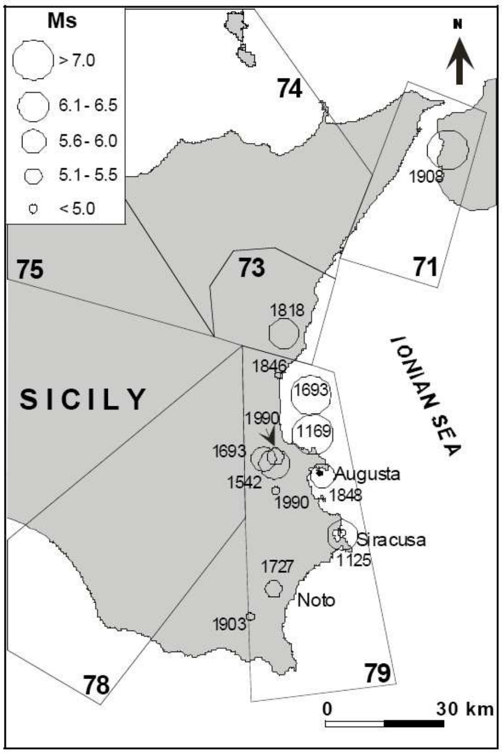

Figure 2. Location of the epicentres of the historical scenario strong earthquakes which heavy damaged the cities of Noto, Augusta and Siracusa, after [8].

Clay or clay-rich layers are locally interbedded with volcanic rocks in a significant part of the N-E sector, as well as in the peninsula at the S-E Hills and plains north and west of the Hyblean mounts. Are also underlain by sedimentary rocks, mostly sand and sandstone with minor amounts of both coarser and finer materials; however, here the degree of consolidation is lower. Importantly attitude of strata is sub-horizontal throughout the area illustrated above [9]. For all these reasons, the geology of this Region is considerably uniform. A comprehensive study on ancient earthquake-triggered landsliding in S-E Sicily was proposed by [7].

The city of Noto is located in the "*Val di Meti*" and is characterized, from a geological point of view, by lands owned to the Trubi Formation (Lower-middle Pliocene) overcoming the Tellaro Formation that consists of carbonate shelf deposits and representing the geological substratum.

The site investigation was performed within the municipal area of Noto and reached a maximum depth of 51 m.

III. BASIC SOIL PROPERTIES

Laboratory tests have been performed on undisturbed samples retrieved by means of an 86 mm Shelby tube sampler. The Pliocene Noto deposits of Trubi Formation mainly consist of a medium stiff, over-consolidated lightly cemented silty-clayey-sand [10], [11].

The pre-consolidation pressure σ'_p and the over-consolidation ratio OCR = σ'_p / σ'_{vo} were evaluated from the 24h compression curves of incremental loading (IL) oedometer tests. Moreover, 9 Marchetti's flat dilatometer tests (DMT) were used to assess OCR and the coefficient of earth pressure at rest K_o following the procedure suggested by [12].

For depths of about 15 m, DMT results show an OCR from 1 to 4.5 ($K_o = 0.5 \div 1.0$).

The OCR values inferred from oedometer tests (OCR from 1 to 3) are lower than those obtained from in situ tests. One possible explanation of these differences could be that lower values of the pre-consolidation pressure σ'_p are obtained in the laboratory because of sample disturbance.

The value of the natural moisture content wn prevalently range from between 12 - 37 %. Characteristic values for the Atterberg limits are: w_l = 37 - 69 % and w_p = 17 - 22 %, with a plasticity index of PI = 15 - 47 %. The obtained data indicate a low degree of homogeneity with depth of the deposits [10], [11].

IV. STIFFNESS AND DAMPING RATIO

Shear modulus G and damping ratio D of Noto soil were obtained in the laboratory from resonant column tests (RCT). These tests were performed on Shelby tube specimens retrieved from Noto site. The Resonant Column/Torsional shear apparatus were used for this purpose [10], [11].

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. 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 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 [13].

Five Resonant Column (RCT) tests have been per-formed by using the same apparatus to evaluate the shear modulus G and damping ratio D of the municipal area of Noto soil.

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

Table 1. Test condition for Noto soil specimens.

Test No.	H [m]	σ'_{vc} [kPa]	σ'_{hc} [kPa]	γ [kN/m^3]	e	PI	G_o [MPa]	RCT
1	4.50	144	144	15.97	1.236	-	122	U - S
2	7.60	145	145	18.81	0.777	-	185	U - S
3	10.00	190	163	19.69	0.740	41	49	U - H
4	17.50	336	336	19.13	0.747	-	465	U - S
5	17.50	380	380	16.40	1.238	-	244	U - S
6	10.00	225	195	19.47	0.817	41	-	U - S

where: U = Undrained. S = Solid cylindrical specimen. H = Hollow cylindrical specimen.

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

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.

Figure 3 shows the results of RCTs normalised by dividing the shear modulus G(γ) for the initial value G_o at very low strain.

The experimental results of specimens were used to determine the empirical parameters of the equation proposed by [14] to describe the shear modulus decay with shear strain level:

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

The expression (1) allows the complete shear modulus degradation to be considered with strain level. The values of α = 115 and β = 1.206 were obtained for the city of Noto.

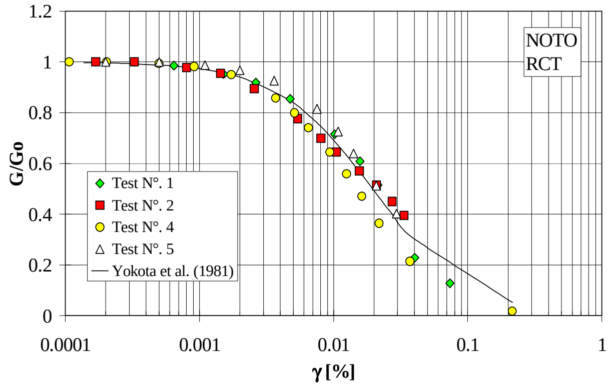

Figure 3. G/G_o-γ curves from RCT.

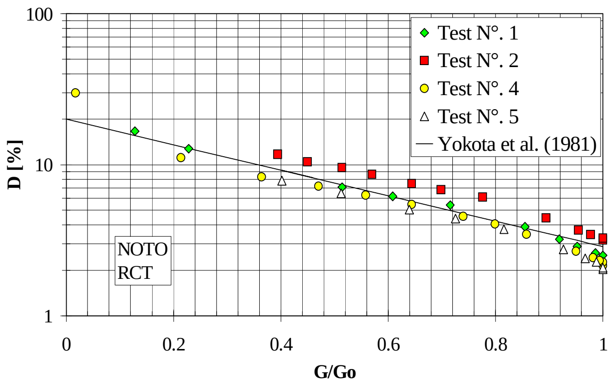

Figure 4. D-G/G_o curves from RCT.

As suggested by [14], the inverse variation of damping ratio in respect to the normalized shear modulus has an exponential form, like that reported in Figure 4:

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

in which: D(γ) = strain dependent damping ratio; γ = shear strain and η, λ = soil constants. The values of η = 20 and λ = 1.941 were obtained for the city of Noto. For the city of Noto equation (2) assumes the maximum value D_{max} = 20 % for G(γ)/G_o = 0 and a minimum value D_{min} = 2.87 % for G(γ)/G_o = 1 .

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

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

V. SHEAR MODULUS FROM IN SITU TESTS

Dynamic in situ tests were performed on Noto area. In Figure 5 the Poisson ratio variation with depth, obtained from a Down Hole (D-H) test, is plotted to show site characteristics. It is seen that from the top 16 m, the values oscillates around 0.36.

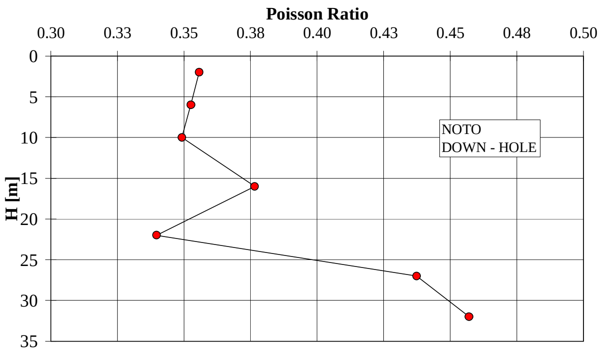

Figure 5. Poisson ratio from in situ tests.

Moreover seismic stratigraphic models were obtained in some of Noto sites by inversion of surface wave dispersion curve of Rayleigh artificially generated with a striking mass of 20 kg and with the use of a small cannon projectile gunpowder (4 - 6 g of explosives). They were used geophones of 4.5 Hz and 1 Hz, for greater distances [15].

The measures were analyzed by FTAN technique (Frequency Time ANalysis). The FTAN method ([16], [17]) is based on the analysis of the two-dimensional time-frequency signal and allows the separation of individual modes propagation starting from the complete signal. Thanks to the introduction of an additional filtering "floating point filtering" it is more easy the selection of the signal. The analysis is two-dimensional since the dispersion curve is a function of two variables: time and frequency. It is possible to localize a signal in terms of dispersion curves of more ways representing the spectral amplitudes snapshots in function on the time and speed group. For the inversion the Hedgehog nonlinear method is used ([18], [19]). The results obtained by FTAN technique are showed in Figure 6 for Site 1 performed on Tellaro Formation and for Site 2 and Site 3 performed on Trubi Formation.

It was also possible to evaluate the small strain shear modulus in the Noto area by means of the following empirical correlation based on dilatometer tests (DMT) results available in literature by [20]:

$$G_o = \frac{530}{(\sigma'_v/p_a)^{0.25}} \frac{\gamma_D/\gamma_w - 1}{2.7 - \gamma_D/\gamma_w} K_o^{0.25} \cdot (\sigma'_v \cdot p_a)^{0.5} \qquad (4)$$

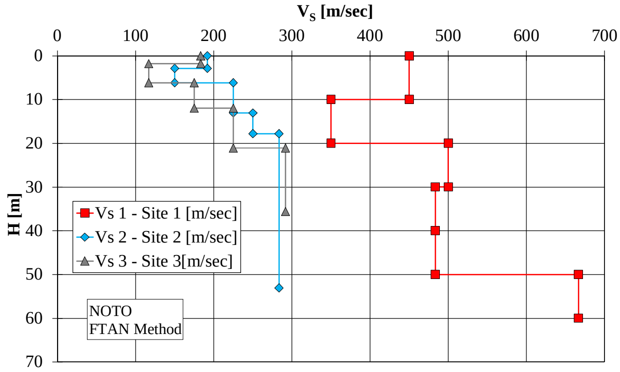

Figure 6. Poisson ratio from in situ tests.

where: G_o, σ'_v and p_a are expressed in the same unit; 1 bar is a reference pressure; are respectively the unit weigth and the coefficient of earth pressure at rest, as inferred from DMT results according to [12].

In Figure 7 the G_o values obtained by equation (4) based on DMT results are plotted against depth.

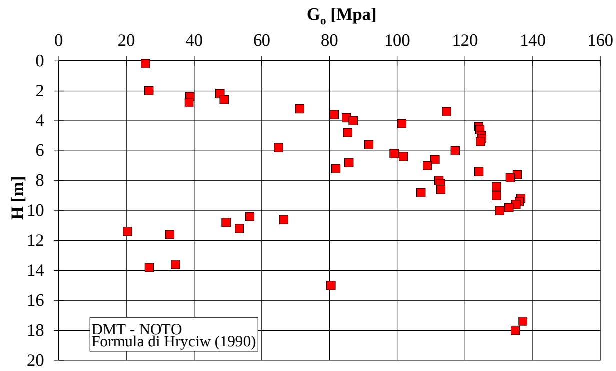

Figure 7. G_o from empirical correlation by DMT.

VI. GROUND RESPONSE ANALYSIS

Since the areas studied here appear rather flat and characterized by lithological units trending sub-horizontal, it was performed a one dimensional local seismic response analysis to assess the ground amplification due to local stratigraphic conditions. So, the analyses was performed using 1-D code, assuming a geometric and geological model of substrate as 1-D physical model. These analyses were carried out here with EERA [21] and STRATA [22], both linear equivalent codes operating in the frequency domain. The layers characteristic of the model have been carried out from geological surveys. The 16 1-D columns have a height of 35 m and are excited at the base by the synthetic scaled seismograms of 1693 earthquake, with a PGA of 0.200-0.225g corresponding to a return period of 475 years in the current Italian seismic code “seismic hazard and seismic classification criteria for the National territory” obtained by a probabilistic approach in the interactive seismic hazard maps. Further analyses have been performed using scaled accelerograms of 1990 earthquake in the Sortino recording station. Figures 8-10 show the results i.e. for site 1 respectively in terms of maximum accelerations with depth, in terms of amplification ratio and in terms of response spectra.

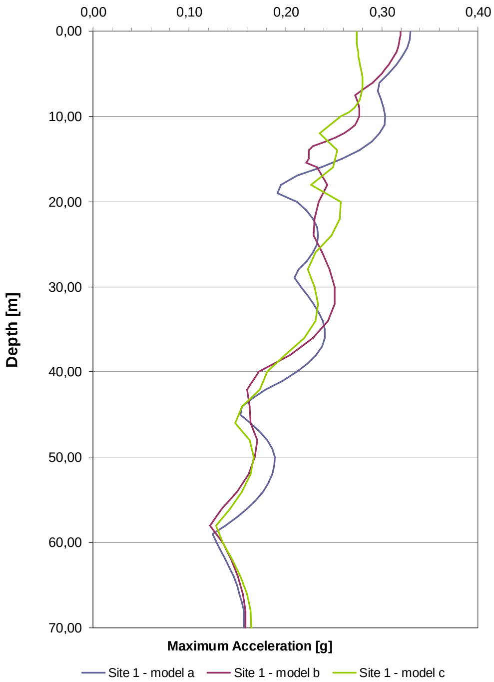

Figure 8. Maximum acceleration with depth.

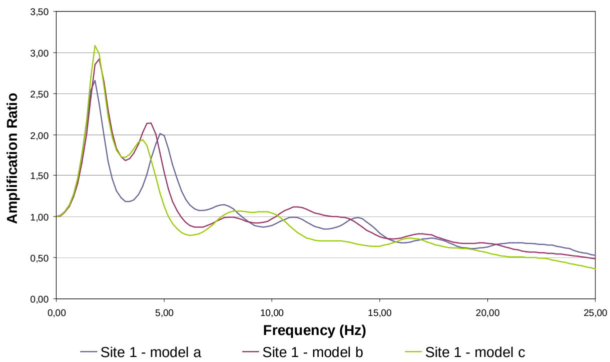

Figure 9. Fourier amplification ratio against Frequency.

Similar studies have been performed for the zonation on seismic geotechnical hazards in the city of Catania (Italy) [23-28] and for the Abruzzo Region (Italy) during L'Aquila earthquake [29-32]. Results of site response analysis are useful for soil-structure interaction behaviour in the mitigation of seismic risk of buildings [33-37].

VII. CONCLUSIONS

In this paper some information on the geotechnical characterisation of the city of Noto have been presented.

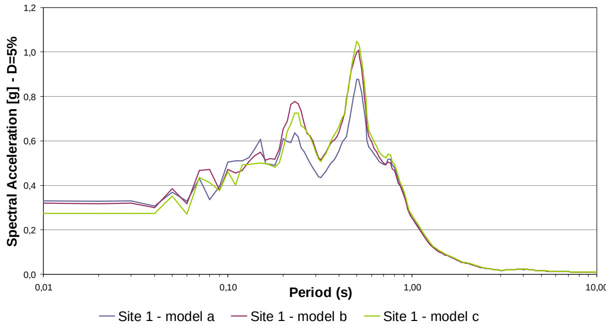

Figure 10. Response spectra against period.

Available data enabled one to define the small strain for uncohesive soil and empirical equations to describe the G and D variation with strain level. Trough 1-D numerical analyses performed it has been possible to evaluate the influence of stratigraphic effects in seismic response of Noto central area. In some cases results show an important amplification of the seismic signal imposed on the basis of the model.

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