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"TWO-DIMENSIONAL SITE SEISMIC RESPONSE ANALYSIS FOR A STRATEGIC BUILDING IN CATANIA"

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ABSTRACT
This study is part of a more extensive research aimed to the seismic risk mitigation in Eastern Sicily. The earthquakes that occurred in Sicily in 1169, 1542, 1693, 1818, 1908 and more recently in 1990, testify the high level of seismic hazard in this region. It is well recognized that local seismic effects can exert a significant influence on the distribution of damage during earthquake. Traditionally, these effects are studied by means of simple one–dimensional (1-D) models of seismic wave propagation, which take only the influence of the stratigraphic profile and soil proprieties into to account for the site seismic response. It is known that the seismic response is strongly influenced by stratigraphic and topographic features that can reduce or amplify the earthquake induced ground motion depending on the soil stiffness and on the ground topography. This paper concerns the results of a two-dimensional (2-D) finite element analysis carried out to evaluate the response of the site where the National Institute of Geophysics and Volcanology (INGV) building is located in the town of Catania. The analysis, performed using as seismic input the accelerogram recorded in 1990 during the Santa Lucia earthquake, allowed to make some considerations about the expected accelerations at that the site and some comparison with the peak accelerations prescribed by Italian seismic code.

1. INTRODUCTION
The town of Catania is located in the eastern coast of Sicily (Italy) at the south of Mt. Etna. The high level of seismicity that affects the city, and the considerably high density of people living in its urban area, contributes to classify it as one of the town having the highest seismic risk in Italy [e.g. Biondi and Maugeri, 2005]. At the same time it is also high the potential damage to which its historic-architectural patrimony could undergo even in the case of small magnitude events [Imposa et al., 2016]. In order to analyse the hazard level of some historical building, a seismic response study of the site in which the "Istituto Nazionale di Geofisica e Vulcanologia" (INGV) building is locatedwas carried outby means of 1-D and 2-D numerical analyses, also to clarify the role played by both stratigraphic and topographic effects.The INGV building in Catania is located on a slightly sloping area at the south/south-east of the town (Figure 1). The area lies in the middle of a terraced alluvial deposit (Figure 2), wide around 300 m and develops in the direction NNW-SSE for about 700 m. This formation consists of silty-clayey sands or sandy silts and gravels with sandy-loam and clay. The thickness of the most superficial layer has been deduced from results of various geotechnical surveys [Capilleri and Maugeri, 2008; Capilleri et al., 2014]. Figure 2 shows the geological map of the Catania urban area. This is the result of data and surveys performed by several authors [Monaco and Tortorici, 1999]. In this study, the seismic hazard of the site where the INGV strategic building is located, has been evaluated and the main results are presented in terms of amplification factors.

2. SEISMIC AND GEOLOGICAL SETTINGS
Considering recent and past seismic history, the eastern coast of Sicily is one of the high seismic risk areas in Italy. The seismic history of the Sicily is eventful and the earthquakes that involved the area are registered in many seismic catalogues. Most earthquakes that damaged or de-

FIGURE 1. View of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) building in Catania.

Earthquake date						
Years	Month	Day	Epicentre	Lat	Lon	Magnitude
1125	6	7	Siracusa	37,070	15,300	5.8
1169	2	4	Eastern Sicily	37,333	15,200	7.3
1542	12	10	Sortino	37,250	15,067	6.4
1693	1	9	Val of Noto	37,170	15,070	5.9
1693	1	11	Eastern Sicily	37,443	15,192	7.0
1727	1	7	Noto	36,913	15,045	5.1
1818	2	20	Catanese	37,616	15,099	6.2
1846	4	22	Catania	37,500	15,083	4.2
1848	1	11	Augusta	37,217	15,233	5.5
1903	2	10	Noto	36,903	15,014	4.3
1908	12	28	Calabro Messinese	38,133	15,667	7.3
1990	12	13	Southern Eastern Sicily	37,270	15,070	5.3

TABLE 1. Historical earthquakes in the Eastern Sicily.

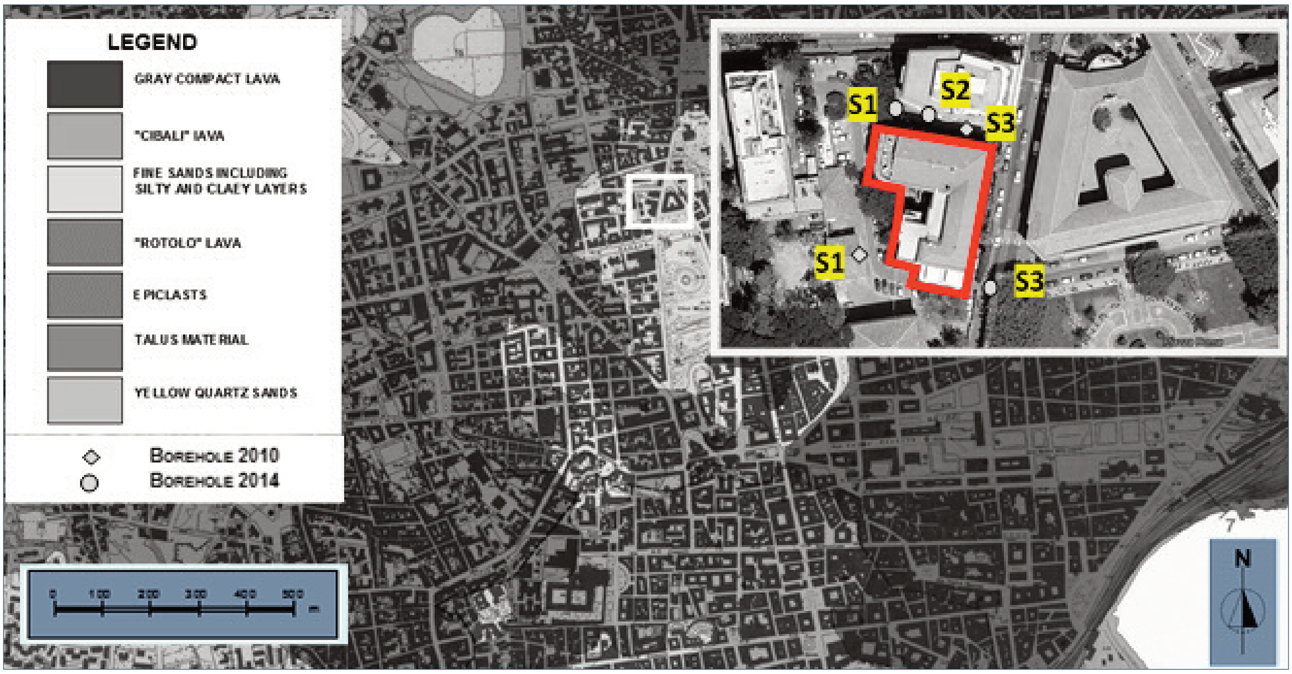

FIGURE 2. Geological map of INGV area (after Monaco and Tortorici, 1999, modified) and detail with the location of the boreholes, realised in the 2010 and 2014 survey.

stroyed the eastern Sicily are reported in Table 1 [Barbano et al., 2000].

The "INGV" site is located in the historical center of Catania. The tectonics of eastern Sicily is quite complex. Available seismic information for south-eastern Sicily suggest the existence of two groups of possible sources for the seismicity that affected the town of Catania in different times.

The sources are located either close to the Ionian coast (Messina Straits and Malta-Hyblean escarpment), or inland, both in the Hyblean foreland and Etna areas. The Malta-Hyblean escarpment, a normal fault system trending NNW-SSE, is considered as the possible source of the destructive earthquakes with estimated magnitude M≈7.0 that struck in past centuries the Catania area [Azzaro and Barbano, 2000]. The soil outcrop of the town comes from the combination of three processes linked to volcanic, tectonic and human activities.

Consequently, the main feature of the area is represented by a complex sedimentary sequence interbedded between a clay basement and an upper volcanic layer made of lava flows and pyroclastic products that sometimes are covered by detritus and ruins due to past earthquakes. The bedrock of the area is composed of a Lower-Middle Pleistocene sequence of marly clays, having thickness up to about 600 m. In the upper part of this succession, sand and sandy clays levels are found frequently. These layers are followed upwards by some tens meters of fluvial-deltaic sandy clay or sand and coarse gravel. Geological, geomorphological and topographical conditions are usually very important sources of information for the assessment of the seismic potential hazard. These factors play a fundamental role on earthquake ground motions and distribution of damage.

This aspect becomes even more critical in areas with sharp transitions between stiff surface formations and softer soil materials. This condition is typical in a volcanic zone, like Catania, which lies at the base of the Mt. Etna and was affected by many eruptions in historical times.

3. SITE GEOTECHNICAL CHARACTERIZATION

To define the seismic response of "INVG" site, two geotechnical investigations were carried out. The first survey in 2010 consisted in four boreholesand laboratory and in situ tests. Laboratory tests, included soil classification, direct shear tests and oedometer tests. Two Multichannel Analysis of Surface Waves tests (MASW) were also carried out in that site.

Additional investigations, conducted in 2014, consisted in three boreholes with standard penetration tests (SPT), down-hole tests (DH), cross-hole tests (CH) and Seismic Dilatometer tests (SDMT). Also laboratory tests for soil description and classification, direct shear tests, oedometer tests, resonant column tests and torsional shear tests were carried out on undisturbed samples [Castelli et al., this issue].

The main results of the geotechnical properties deduced

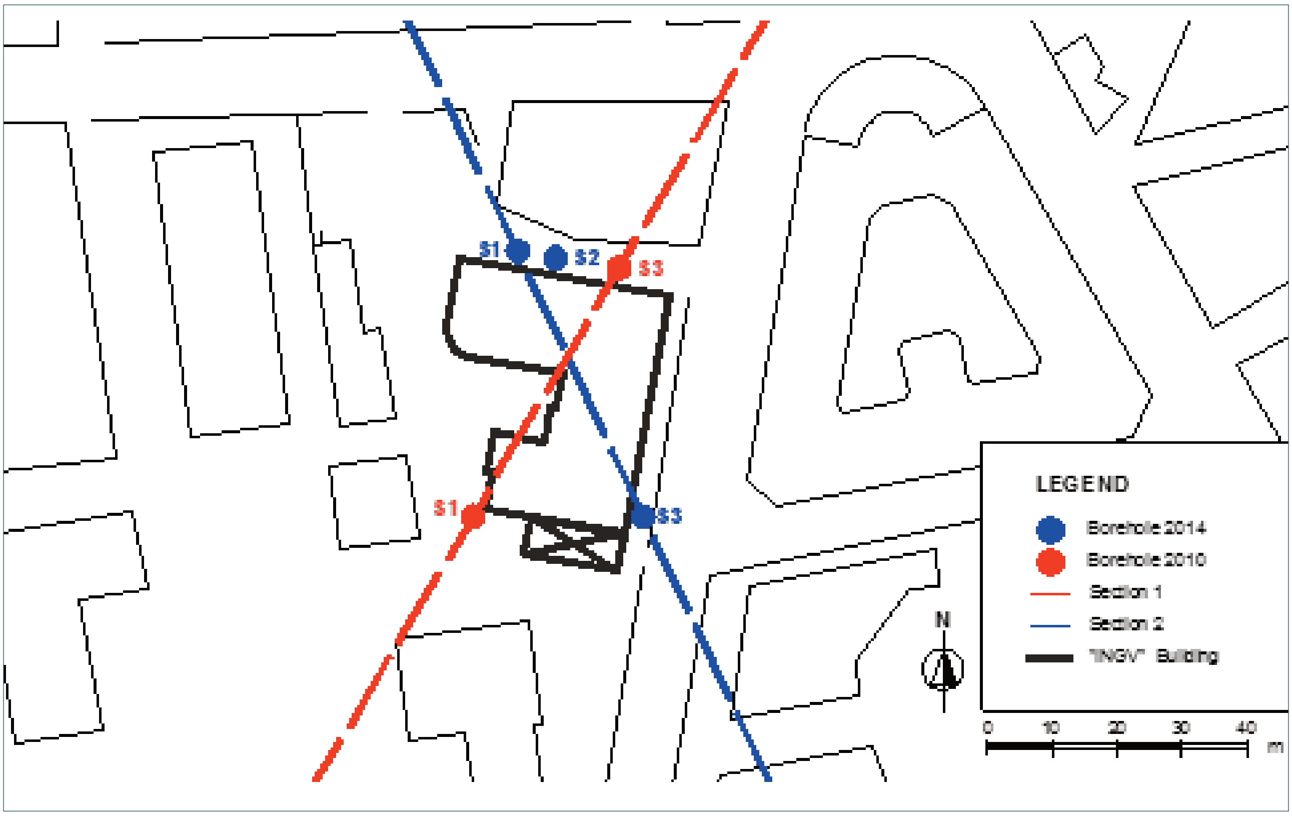

FIGURE 3. Plan view of geotechnical cross sections developed from site investigation results [after Capilleri et al., 2016, modified].

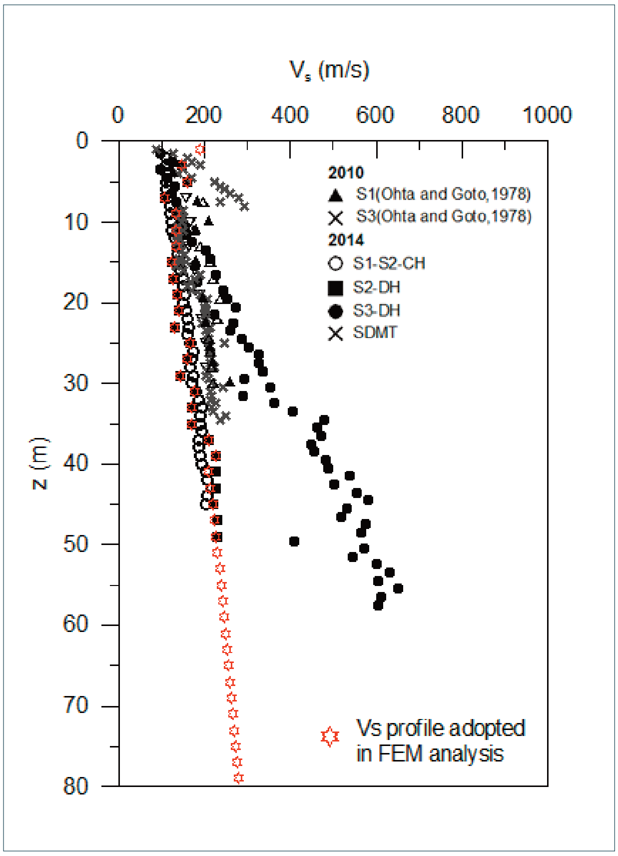

FIGURE 4. Shear wave velocities profile *vs* depth for different tests.

by laboratory tests in 2014 are shown in Table 2. Figure 3 shows location of boreholes and of the in situ tests carried out during the geotechnical investigations. Two cross sections, named section 1 and section 2, were drawn up from site investigations. Section 1 was traced using S1 and S3 soil profiles deducedfrom site investigation in 2010, while section 2 was deduced utilizing S1 and S3 profiles from the site investigation in 2014. Results of the shear wave velocities from DH, CH, SDMT tests are shown in Figure 4. From the comparison between in situ measurements of shear wave velocities it can be observed that the velocities of S3- DH test are significantly greater than the other measurements. For this reasonS3- DH test was excluded in the determination of shear wave profile adopted in the numerical analysis.

To confirm the insitu results, the shear wave profile deduced from SPT data and utilizing the Otha and Goto [1978] expressions are also reported in Figura 4. Except for S3-DH, both in situ measurements and Otha and Goto results are in a good agreement. The adopted profile is also shown in Figure 5 and it is drawn in red. The relationship between the depth and the shear wave velocities of the adopted profile is given by the following equations:

$$z = 0{,}1823 \cdot v_s - 24{,}537 \qquad \text{per } 0{,}0 \text{ m} < z < 40{,}0 \text{ m} \quad (1)$$

$$z = 0{,}0006 \cdot v_s^2 - 0{,}1316 \cdot v_s + 17{,}829 \text{ per } z < 40{,}0 \text{ m} \quad (2)$$

Sample	Depth [m]	γ [kN/m³]	c' [kN/m³]	ϕ' [°]	c_u [kN/m³]
S1 C1	4.0-4.5	20.4	11	29	-
S1 C2	9.0-9.5	20.1	38	16	55
S1 C3	34.0-34.5	20	51	20	-
S2 C1	5.0-5.4	18.6	14	26	-
S2 C2	7.2-7.7	19.6	28	22	104

TABLE 2. Geotechnical parameters from laboratory tests performed in 2014.

4 TWO-DIMENSIONAL DYNAMIC FINITE ELEMENT ANALYSIS

A 2-D FEM analysis was carried out to evaluate the seismic response. To this aim a scenario seismic input was selected. Guidelines on procedures for the selection of appropriate acceleration time-series are given by Bommer and Acevedo [2004]. The accelerogram utilised for the seismic response refers to the main shock of 13 December 1990 [Boschi et al., 1997] that was considered significant, having caused severe damage and recently.Both the N-S and E-W horizontal components of the Sortino records were adopted for the analysis, however in the present paper, only the results for Sortino E-W component are presented. The accelerogram is shown in Figure 5. For this component of the record, the strong motion duration and the Arias intensity are $D_{5\text{-}95}$ = 10.98 s and I_a = 5.54 cm/s, respectively; the number of equivalent loading cycles, evaluated according to the procedure proposed by Biondi et al. [2012], is N_{eq} = 5.4.

The analyses were carried out scaling the accelerogram at the peak values prescribed by theItalian code for different limit states that is damage, life and collapse. Bommer and Acevedo [2004] suggest to not exceed a scaling factor 2.5 while the input for the collapse limit state analysis required a scaling factor about 4, thus the results concerning the collapse limit state must be taken with caution. A dynamic model using the two-dimensional Plaxis code [Brinkgreve et al., 2002], was implemented. The finite element mesh was modelled to ensure theaccuracy of the dynamic analysis. The mesh was 4800 m in width and 200 m in depth.This depth was considered as the bedrock since, according to the velocity profile of shear waves, at that depth the velocity of shear wave was almost 800 m/s.The lateral and vertical extensions of the mesh were considered enough to minimize wave reflection. In addition, at the lateral sides of the mesh, absorbent boundary conditions were applied to avoid wave reflection. Viscous adsorbent boundaries have been introduced, based on the method described by Lysmer and Kuhlmeyer [1969]. The mesh was modelled with horizontal layers to take the change in shear wave velocity and damping with depth into account. [Rizzitano et al., 2015].

The material damping was simulated with the well-known Rayleigh formulation. The damping matrix C was assumed proportional to the mass matrix M and the stiffness matrix K by means of two coefficients, α_R and β_R according to:

$$[C]=\alpha_R[M]+\beta_R[K] \tag{1}$$

The constants α_R and β_R are obtained by the following expression:

$$\begin{Bmatrix}\alpha_R\\ \beta_R\end{Bmatrix}=\frac{2D}{\omega_n+\omega_m}\begin{Bmatrix}\omega_n\,\omega_m\\ 1\end{Bmatrix} \tag{2}$$

where D is the soil damping ratio, ω_n and ω_m are the control angular frequencies. In particular, ω_n is the

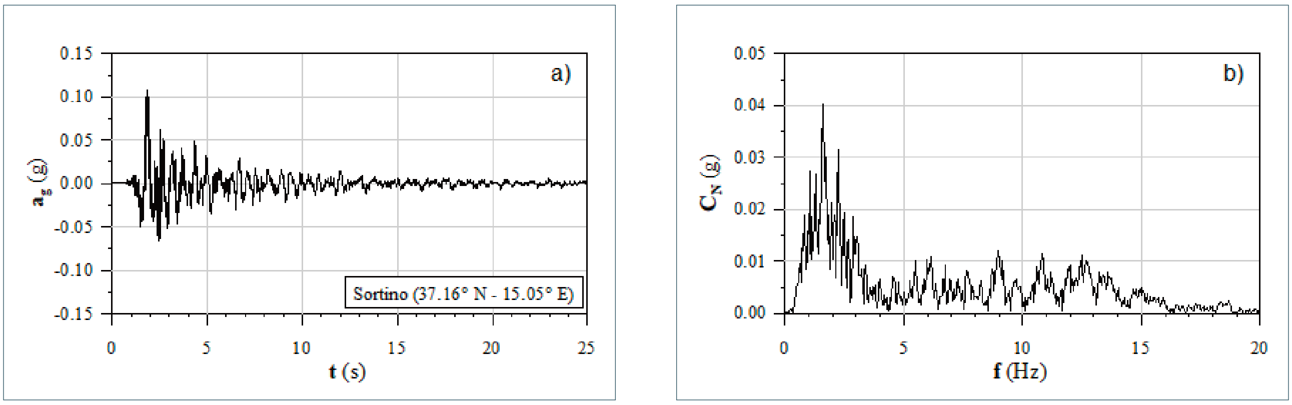

FIGURE 5. Seismic input of Sortino earthquake: a) E-W component accelerogram; b) Fourier spectrum.

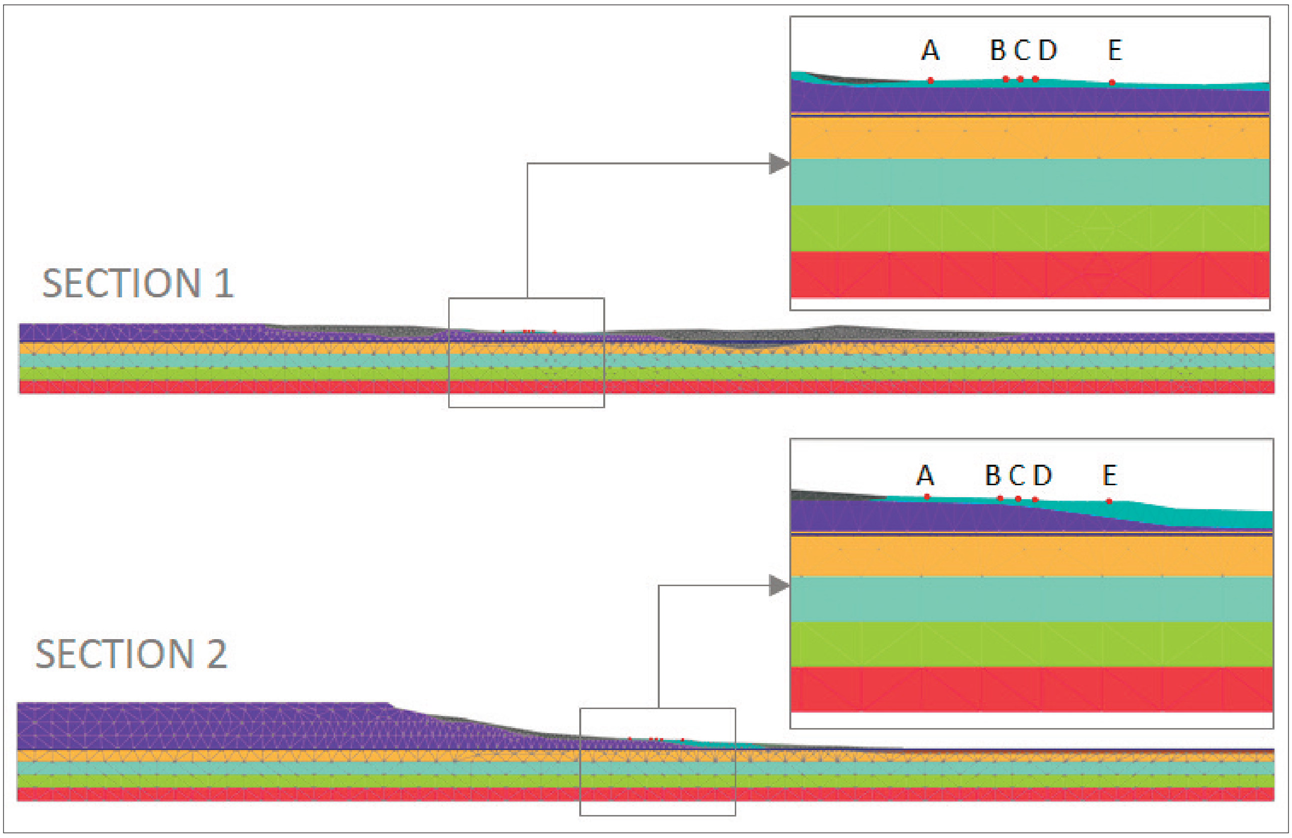

FIGURE 6. Geometrical models for FEM analysis.

system fundamental frequency and ω_m is the later frequency to ω_n [Sica et al., 2007]. In the analysis a initial damping ratio D = 5% was utilized, while the frequencies ω_n and ω_m were evaluated by utilizing the spectrum determined by one-dimensional EERA code [Bardet et al., 2000].

To ensure the numerical accuracy of wave transmission, that is affected by both the frequency content of input wave and the wave velocity characteristics of system, the spatial element size was chosen smaller than 1/10 to 1/8 of the wavelength (λ) associated with the highest frequency component of input wave [Kuhlemeyer and Lysmer, 1973]. According to the above mentioned criteria, the element size ΔL was defined small enough to allow the seismic wave propagation throughout the analysis:

$$\Delta L = \frac{\lambda}{8} = \frac{1}{8}\frac{V_S}{f_n} \tag{3}$$

State	Tr [years]	PVR [%]	ag [g]	Ss
Damage	101	63%	0.102	1.50
Life	949	10%	0.282	1.29
Collapse	1950	5%	0.397	1.13

TABLE 3. Seismic parameters according to Italian code. [Capilleri et al., 2016].

On the basis of the shear wave profile adopted (Figure 4) and geological settings, the bedrock was estimated at a depth of about 200 m. However, some analysis performed with bedrock located up to 600 m did not give results significantly different in terms of amplification factors.Although two-dimensional FEM analysis is widespread used in geotechnical engineering, in this work the two-dimensional numerical analysis has been carried to evaluate the seismic response in terms of both the stratigraphic and the topographic effects [Capilleri et al., 2005; Biondi et al., 2004].

In order to detect accelerations at the ground surface, five investigation points, named A, B, C, D and E, were selected. The INGV building is located at the point C in Figure 6. The Mohr-Coulomb elasto-perfectly plastic constitutive model with a non-associate flow rule was considered for the soil. Computed amplification factors S in the five selected points and for different re-

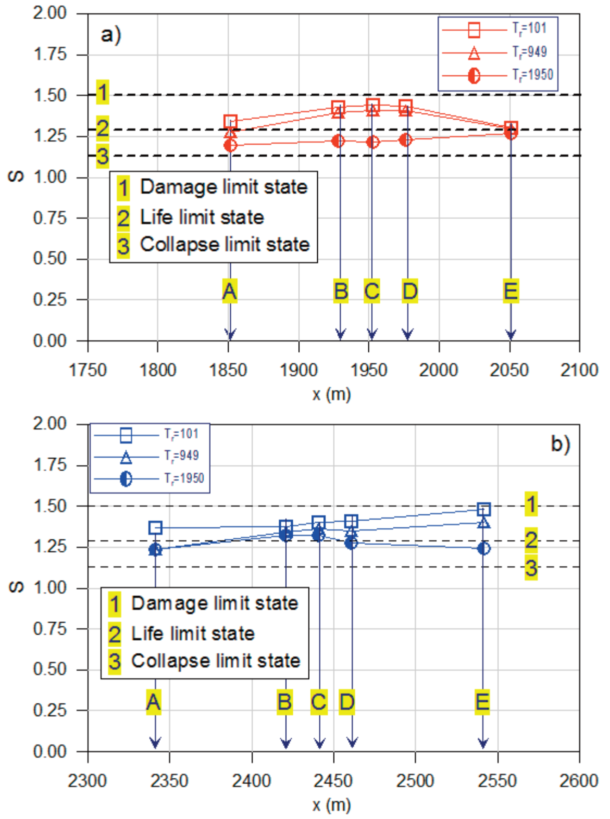

FIGURE 7. Amplification factors at the different selected points (A, B, C, D, E) to vary the return period (Tr): a) Section 1; b) Section 2.

turn periods (T_r) are shown in Figure 8. It should be pointed out that a 2D- FEM analysis gives both stratigraphic and topographic effects; however on the basis of the low slope of the site it is evident that topographic effect was negligible in this case. Details for amplification factors areshown in Figure 7 for all the selected points. Referring to point C, results give average amplification factors S=1.48 for the damage limit state, S=1,41 for the life limit state and S=1,32 for the collapse limit state. These values are in a fair agreement with numerical and experimental data available in the literature [e.g. Massimino and Biondi, 2015].For comparison, Table 3 shows the acceleration at bedrock (a_g) and the amplification factors (S_S) for the different limit states prescribed by Italian code (NTC08).

A comparative study was also performed between 1-D and 2-D analysis. The 1-D analysis (Caruso et al., this issue) was carried out for the life limit state, using seven accelerograms, concerning the 1693 earthquake (three synthetic records), the 1818 earthquake (three synthetic records) andthe 1990 natural earthquake. Considering all the earthquakes, the average value of 1-D amplification factor was 1.56 while for 2-D FEM analysis the computed amplification factor for the life limit state was about 1.5 (Figure 7). Limited to results of the present analysis, the amplification factors given by the analysis and determined for life and collapse limit states, are greater than the amplification factors given by Italian code. On the contrary, for the damage limit state, the Italian code gives an amplification factor in good agreement with that determined by the FEM analysis.

5. CONCLUSIONS

Seismic response analysis represents a powerful tool to evaluate the seismic hazard and to reduce the vulnerability of existing and new construction buildings. In this paper a two-dimensional FEM analysis has been presented for the evaluation of the seismic response of the site in the centre of Catania where the INGV strategic building is located. This study is part of a more extensive activity aimed to “Seismic risk reduction in eastern Sicily” project, where the seismic hazard was evaluated both in 1-D and 2-D analysis. Usually the two-dimensional analysis is to be preferred since it allows to detect both stratigraphic and topographic effects for the amplifications of acceleration at the ground surface. A comparison with the 1-D analysis, that gave similar amplification factors, indicated that in this case topographic effects are negligible. This however was an expected result since the slope of the analyzed site is very low. Limited to results of both 1-D and 2-D analysis, some difference in theamplification factors with respect to Italian code requirements was found for the collapse and the life limit states while a good agreement was found for the damage limit state.

REFERENCES

Azzaro R., Barbano M.S. (2000). Analysis of seismicity of Southeastern Sicily: proposal of a tectonic interpretation. Ann. Geofis., 43: 1-18.

Barbano M.S. , R. Rigano, R. Azzaro (2000).“ Analisi storico-sismologiche sugli eventi sismici principali che hanno interessato le città di Augusta Noto e Siracusa”. A cura di: L. Decanini e G.F. Panza. Scenari di pericolosità sismica ad Augusta, Siracusa e Noto. CNR- Gruppo Nazionale per la Difesa dai Terremoti - Roma, 2000, pp. 14-31. (in italian).

Bardet, J. P., Ichii, K., Lin, C.H., 2000. EERA - A computer Program for Equivalent-linear Earthquake Site Response Analyses of Layered Soil Deposits. University of Southern California, Department of Civil Engineering.

Biondi, G., Condorelli, A., Maugeri, M., Mussumeci, G.

(2004). Earthquake-triggered landslide hazards in the Catania area(Article). Management Information Systems, Volume 9, 1 January 2004, Pages 115-130.

Biondi G., Maugeri M. (2005). Seismic response analysis of Monte Po hill (Catania). Advances in Earthquake Engineering, Volume 14, 2005, Pages 177-195.

Biondi, G., Cascone, E., Di Filippo, G. (2012). Reliability of empirical relationships for the evaluation of the number of equivalent loading cycles. [Affidabilità di alcune correlazioni empiriche per la stima del numero di cicli di carico equivalente]. Rivista Italiana di Geotecnica Volume 2012, Issue 2, 2012, Pages 11-41.

Bommer and Acevedo, 2004. "The use of real earthquake accelerograms as input to dynamic analysis". Journal of Earthquake Engineering, Vol. 8 No. 1 (2004) 43-91. Imperial College Press.

Boschi, E., Guidoboni, E., Ferrari, G., Valensise, G., Gasperini, P. (1997)." Catalogo dei forti terremoti in Italia dal 461 a.C. al 1990". ING-SGA, Ozzano Emilia, 644 pp. (in italian).

Brinkgreve, R.B.J., Al-Khoury R., Bakker K.J., Bonnier P.G., Brand P.J.W., Broere, W. (2002)."Plaxis 2d-version8 generalinformation." Delft University of Technology & Plaxis b.v., The Netherlands.

Capilleri P., Lanzo G., Maugeri M., Pagliaroli A. (2005)."Site Effects Evaluation in Sellano (Italy) by means of 1-D and 2-D numerical analysis (Italy)" 5th World Conference on Earthquake Resistant Engineering Structures, ERES 2005; Skiathos; Greece; 30 May 2005 Volume 81, 2005, Pages 73-82.WIT Press.

Capilleri P., Maugeri M. (2008)."Geotechnical seismic hazard evaluation at Sellano (Umbria,Italy) using GIS technique". MERCEA '08 8-11 Luglio 2008, Reggio Calabria Italia. Vol. 1020 pp. 232-239 Part 1-2 CPI1020, 2008 Seismic Engineering Conference Commemorating the 1908 Messina and Reggio Calabria Earthquake, edited by A. Santini and N. Moraci © 2008 American Institute of Physics.

Capilleri P., Cavallaro A., Maugeri M., (2014)."Static and dynamic soil characterization at Roio Piano (AQ)". Italian Geotechnical Journal, Volume XXXV, n0 2 pp 38-52.

Capilleri P.P., M.R. Massimino, E.Motta, and M. Todaro. "Site seismic response for a strategic building in the city of Messina by two-dimensional finite element analysis" Annals of Geophysics. This issue .

Caruso S., Ferraro A., Grasso S., Massimino M.R. (2016). "Site Response Analysis in eastern Sicily based on direct and indirect Vs measurements". 1st IMEKO TC4 International Workshop on Metrology for Geotechnics, Metro Geotechnics 20162016, Pages 115-120.

Castelli F., Cavallaro A., Ferraro A., Grasso S., Lentini V., Massimino M.R. (2018)."Static and dynamic properties of soils in Catania (Italy)". Annals of Geophysics. This issue..

Imposa S., Motta E., Capilleri P., Imposa G. (2016). HVSR and MASW seismic survey for characterizing the local seismic response: a case study in Catania area (Italy). 1st International Workshop on Metrology for Geotechnics, Benevento, Italy, March 17-18, 2016.

Kuhlemeyer R. L. and Lysmer J. (1973). Finite element method for accuracy for wave propagation problems, Journal of Soil Mechanics & Foundation Division, ASCE Vol. 99, No. SM5, pp. 421-427.

Lysmer J., Kuhlmeyer R.L. (1969). "Finite Dynamic Model for Infinite Media", ASCE, Journal of Engineering and Mechanical Division, Vol. 90 No. 4, pp. 859-877.

Massimino M.R., Biondi G. (2015). "Some experimetnal evidences on dynamic soil-structure interaction". COMPDYN 2015 - 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering2015, Pages 2761-2774.

Monaco C., Tortorici L. (1999). Carta geologica dell'area urbana di Catania. S.E.L.C.A., Firenze, Italy.

N.T.C. (2008). Norme Tecniche per le Costruzioni (Italian Technical Regulation for Constructions). Decreto del Ministro delle Infrastrutture 14.01.2008, published on Gazzetta Ufficiale 04.02.2008, Roma, 2008.

Ohta, Y. and Goto, N. 1978. Empirical shear wave velocity equations in terms of characteristic soil indexes. Earthquake Engineering and Structural Dynamics, Vol.6.

Rizzitano, S.,Cascone, Biondi, G. (2015). Coupling of topographic and stratigraphic effects on seismic response of slopes through 2D linear and equivalent linear analyses. Soil Dynamics and Earthquake Engineering . Vol. 67, December 01, 2014, Pages 66-84.

Sica S., Melazzo A., Santuccio De Magistris F. (2007). Propagazione e isolamento delle vibrazioni del terreno prodotte dai treni ad alta velocità.Rivista Italiana di Geotecnica,No.4, 149-159.

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