ANNALS OF GEOPHYSICS, 61, 2, SE224, 2018; doi: 10.4401/ag-7708

"SITE EFFECTS EVALUATION IN CATANIA (ITALY) BY MEANS OF 1-D NUMERICAL ANALYSIS"

Antonio Ferraro[1], Salvatore Grasso[1,*], Maria Rossella Massimino[1]

[(1)] Department of Civil Engineering and Architecture (DICAr), University of Catania, Catania, Italy

Article history
Receveid July 27, 2017; accepted February 23, 2018.
Subject classification:
Site response analysis; Scenario earthquakes; Catania; Messina.

ABSTRACT

A probabilistic seismic hazard analysis (PSHA) determines the probability rate of exceeding of various levels of ground motion in a specified period of time, in a given area. On the other hand, the neo-deterministic seismic hazard assessment (NDSHA) is based on modeling techniques, developed from physical knowledge of the seismic source process and of the propagation of seismic waves, which can realistically simulate the ground motion due to an earthquake by means of synthetic seismograms. The NDSHA confirms that peak ground acceleration values are larger than those given by the PSHA in areas where large earthquakes are observed and in areas identified as prone to large earthquakes, such as in the case of the city of Catania (Italy). The city of Catania, located on the eastern part of Sicily, is one of the most seismically active areas of Italy. The Val di Noto earthquake of January 11, 1693 is considered one of the biggest earthquakes which occurred in Italy. Site response analyses have been developed for a group of 3 test sites in the city of Catania (Italy). On the sites are localised some strategic buildings to upgrade against seismic risk. The analysis of seismic ground response at the sites was conducted using a numerical method, which is developed in three main phases: the definition of the geometric, geological and geotechnical model of the subsurface, the definition of the seismic input (synthetic or recorded), the choice of one or more computer codes to use and process the results. The reconstruction of the geological and geotechnical model of the subsurface has highlighted a morphology quite irregular especially with regard to the covers. One-dimensional local site response analyses have been performed assuming that all geologic boundaries are horizontal and the response of soil deposits is predominantly caused by waves propagating vertically from the underlying bedrock. Equivalent linear analysis using EERA code has been performed in this study. One of the targets of the paper is the development of measures for the seismic retrofitting of buildings. Seismic retrofitting and/or improving have to be definitely considered a multidisciplinary subject, which depends in fact on many factors, such as: local site effects and the dynamic interaction between the foundation soil and the structure. The accurate investigation on the structure and the surrounding soil is the first fundamental step for a realistic evaluation of the structure seismic performance.

1. INTRODUCTION

In the period 2014-2016, a Project financed by the European Community was carried out to investigate the seismic hazard of some areas in eastern Sicily. Within this project, four strategic test sites in Messina (1) and Catania (3) have been studied, because of the fact that these cities are at high seismic risk [Abate et al., 2006; 2017]. Messina suffered the destructive earthquake of 1908 that caused thousands of deaths, injured and displaced, while Catania suffered, since 1169, a number of destructive earthquakes, among which we mainly remember the earthquakes of 1169, 1693, 1818 and 1990 [De Rubeis et al., 1991].

In order to study the dynamic characteristics of soils in three Catania test sites, laboratory and in situ investigations have been carried out to obtain soil profiles with special attention being paid to the variation of the shear modulus G and damping ratio D with depth. Seismic Dilatometer Marchetti Tests (SDMT) have been also carried out in the area of the "National Institute of Geophysics and Volcanology" building (INGV) and in the "Madre Teresa di Calcutta" building school (CD MTC), with the aim of an accurate geotechnical characterisation, including the evaluation of the shear wave velocity V_s profile, as well as the profile of the horizontal stress index K_d.

Shear wave velocity has been measured by different tests. The soil profiles in terms of the shear modulus G_0 and in terms of the shear wave velocity V_s have been evaluated and compared by different in situ tests.

The redundancy of measurements is very useful, for instance, for site response and liquefaction analyses, which can be based either on V_s values or K_d values.

Boreholes were driven and undisturbed samples were retrieved for laboratory tests. Because of their relevance on the estimation of local ground shaking and site effects, data from in-hole geophysical surveys (Down-Hole and Seismic Dilatometer Marchetti Test) have been examined with special attention, particularly for S wave velocity measurements. It must be noted that the shear wave velocity V_s was evaluated on the basis of both empirical correlations with in situ or laboratory tests and a few direct measurements.

One-dimensional local site response analyses have been performed assuming that all geologic boundaries are horizontal and the response of soil deposits is predominantly caused by waves propagating vertically from the underlying bedrock. Among the programs that adopt the equivalent linear analysis EERA code [Bardet et al., 2000] has been used in this study.

The three test sites in Catania are two school buildings in the province of Catania, the Catania division of the National Institute of Geophysics and Volcanology (indicated by the INGV acronym) and finally the fourth test site is the Messina's Regional Department of Civil Defence (indicated by the DRPC acronym). In this paper, the results of local seismic response analysis at the INGV site in Catania and at the DRPC site in Messina are presented.

2. THE STUDY AREAS

The first test site is the building of the INGV (National Institute of Geophysics and Volcanology), that is a public scientific institution which carries out research, monitoring and surveillance in the fields of geophysics and volcanology [Abate et al., 2016a; Abate and Massimino, 2016]. The building (Figure 1) is located at the historical center of the high seismic risk city of Catania [Cavallaro et al., 2008]. Among the main earthquakes that struck Catania, the most important is the 1693 event, also know as the "1693 Val di Noto earthquake" that struck also part of southern Italy, Calabria and Malta on January 11 at around 21:00 local time.

This earthquake was preceded by a damaging foreshock on January 9. It had an estimated magnitude of 7.4 on the moment magnitude scale and a maximum intensity of XI on the MCS, destroying at least 70 towns and cities, seriously affecting an area of 5,600 square kilometers and causing the death of about 60,000 people [Grasso and Maugeri, 2009a, 2009b, 2012, 2014; Castelli et al., 2016a, Maugeri et al., 2012]. The earthquake was followed by tsunamis that devastated the coastal villages on the Ionian Sea and in the Straits of Messina. Almost two thirds of the entire population of Catania were killed. The extent and degree of destruction caused by the earthquake resulted in extensive rebuilding of the towns and cities of southeastern Sicily, particularly the Val di Noto [Castelli et al., 2016b, 2016c, 2016d], in a homogeneous late Baroque style, described as "the culmination and final flowering of Baroque art in Europe".

Landsliding events triggered also by rainfall during earthquakes should be studied in these cases [Castelli and Lentini, 2013; Castelli et al., 2017], including also lateral spreading and liquefaction [Castelli et al., 2016e].

The second test site is the building of the Messina division of the DRPC (Regional Department of Civil Defence), located at the city center of Messina (Figure 2).

The most important historical earthquake was the 1908 Messina earthquake (also known as the 1908 Messina and Reggio Calabria earthquake), with a moment magnitude of 7.1 and a maximum MCS of XI. The cities of Messina and Reggio Calabria were almost completely destroyed and between 75,000 and 200,000 lives were lost.

The earthquake's epicenter was in the Strait of Messina which separates the busy port city of Messina in Sicily and Reggio Calabria on the Italian mainland. Its precise epicenter has been pinpointed to the northern Ionian Sea area close to the narrowest section of the Strait, the location of Messina. It had a depth of 5-6 miles (8-10 km).

At least 91% of structures in Messina were destroyed or strongly damaged and some 75,000 people were killed in the city and suburbs. Reggio Calabria and other locations in Calabria also suffered heavy damage, with some 25.000 people killed. Reggio Calabria historic centre was almost completely erased. The number of casualties is based on the 1901 and 1911 census data. The ground shook for about 30 to 40 seconds, and the damage was widespread, with destruction felt within a 300-kilometer radius. In Calabria Region, the ground shook violently from Scilla to the south of Reggio Calabria and caused landslides in the Reggio Calabria area.

FIGURE 1. INGV - Catania building.

FIGURE 2. INGV - DRPC - Messina Building.

3. GEOTECHNICAL SITE CHARACTERISATION

An intensive geotechnical site characterization was carried out performing in situ and laboratory tests, in order to determine the most appropriate static and dynamic soil parameters [Ferraro et al., 2015]. By means of laboratory tests the values of unit weight, natural water content, void ratio, porosity, saturation ratio have been obtained. Resonant Column Tests (RCT) and Cyclic Loading Torsional Shear Tests (CLTST) have been

FIGURE 3. INGV - Boreholes location.

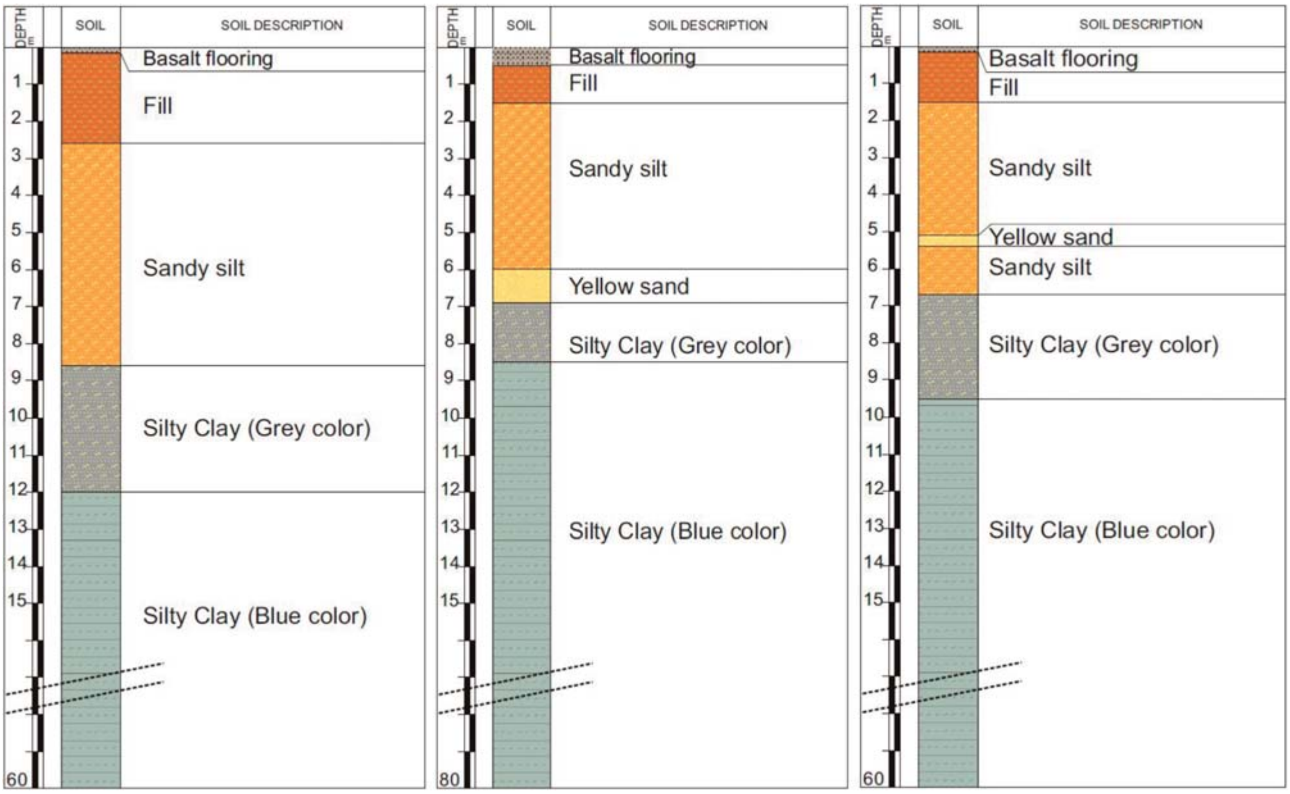

FIGURE 4. INGV - Soil stratigraphy in the order S1, S2, S3.

also performed [Cavallaro et al., 2012; Caruso et al., 2016; Castelli et al., 2016f; Cavallaro et al., 2016a; 2016b].

The types of tests performed are the same for both sites (INGV and DRPC), in fact, for each site, three boreholes were carried out, with undisturbed soil sampling. The three surveys were also equipped in order to perform Down Hole (D-H) and Cross Hole (C-H) tests according to this sequence: S1 and S2 boreholes for the execution of a

List of soil samples			
n.	Borehole	Name	Depth (m)
1	S1	C1	4,00 – 4,50
2	S2	C3	14,00 – 14,50
3	S2	C5	72,00 – 72,50
4	S3	C1	5,50 – 5,90

TABLE 1. INGV - List of samples.

Cross Hole test and S3 boreholes for the execution of the Down Hole test. Seismic Dilatometer Marchetti Tests SDMTs have been also performed in each site.

3.1 INGV CATANIA TEST SITE

Figure 3 shows the location of the three boreholes in the INGV Catania test site and Figure 4 shows the soil stratigraphy of the boreholes. The S1 and S3 boreholes have a depth of 60 meters, the S2 borehole has a depth of 80 meters. Table 1 shows the list of soil samples for laboratory tests; for the geotechnical model considered in the numerical analysis, the following four soil samples were used: S1C1 (retrieved at 4,00 - 4,50 m), S2C3 (retrieved at 14,00-14,40 m), S2C5 (retrieved at 72,00 - 72,50 m), S3C4 (retrieved at 5,50 - 5,90 m). Figure 4 - INGV - Soil stratigraphy in the order S1, S2, S3.

Figure 5 shows the V_s profiles obtained by D-H, C-H and SDMT tests and their comparison. The Down Hole test shows a V_s profile that increases with depth almost according to a linear trend with values variables from 190 m/s to 1000 m/s; at the depth of 35 m the V_s profile reaches the value of 800 m/s.

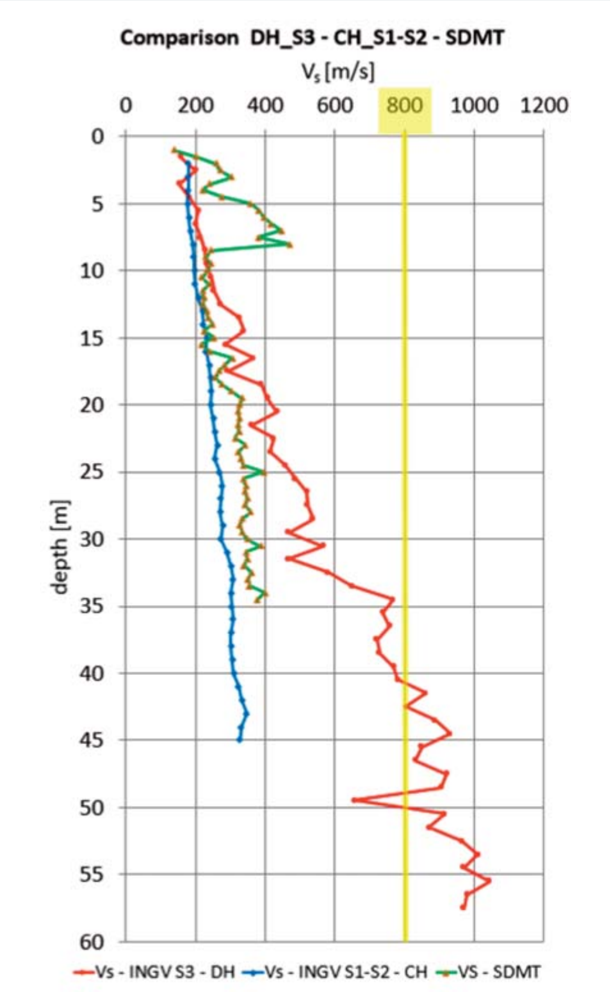

FIGURE 5. INGV - V_s profiles obtained by D-H, C-H and SDMT tests and their comparison.

The Cross Hole test is in good agreement with the D-H test up to the depth of 7.5 meters. The C-H test shows a V_s profile that linearly increase with depth with values variable between 190 m/s and 380 m/s at the depth of 45,00 m. The C-H V_s profile never reaches

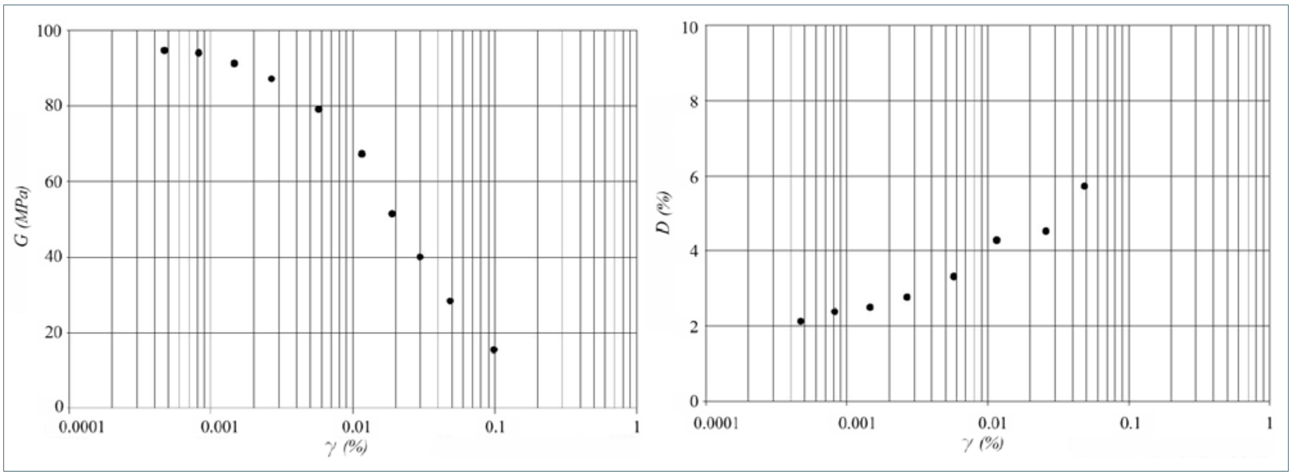

FIGURE 6. INGV - RCT results for S1C1 soil sample.

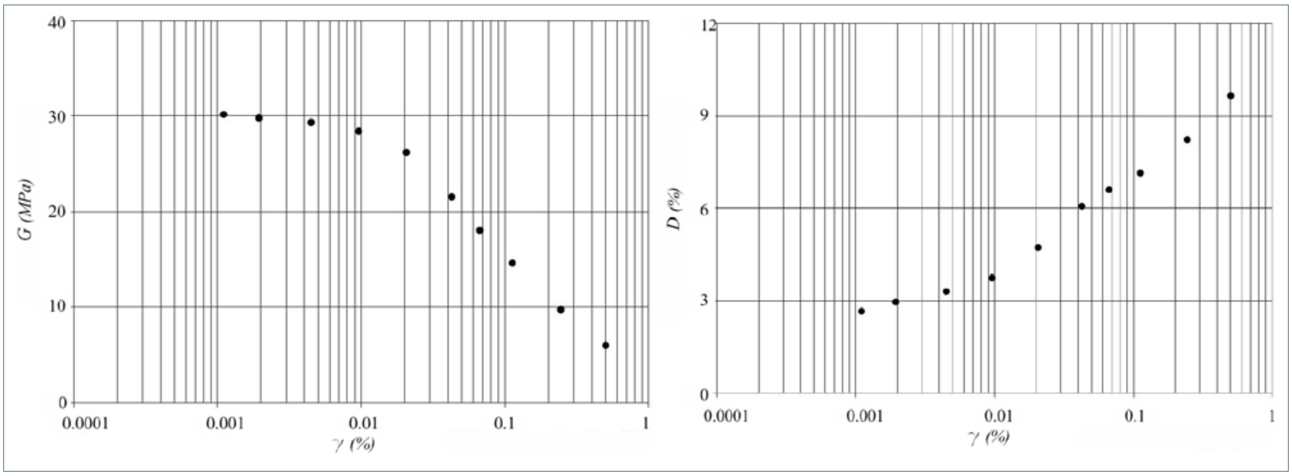

FIGURE 7. INGV - RCT results for S2C3 soil sample.

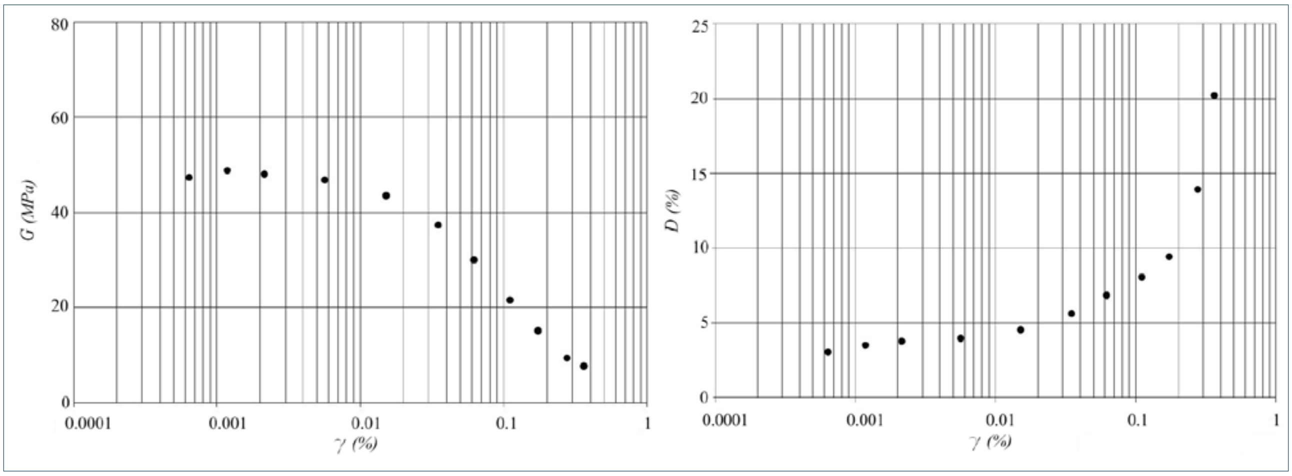

FIGURE 8. INGV - RCT results for S2C5 soil sample.

the 800 m/s value. The SDMT test shows a dual behaviour: up to the depth of 7.5 m it seems to overestimate V_s values compared to D-H and C-H tests, while from 7.5 m to 45 m it shows a linear trend with values that lie in the middle between the results of the D-H test and the C-H test results. This apparatus was also used in offshore condition by Cavallaro et al. [2013a, 2013b]. Results of Resonant Column Tests (RCT) and Cyclic Loading Torsional Shear Tests (CLTST) are presented in Figures 6-8 to evaluate the shear modulus G and damping ratio D variation with the shear strain level γ. These tests are fundamental for the accurate evaluation of local site response analyses, as well as for the evaluation of the dynamic behavior of full-coupled soil-structure systems [Abate et al., 2007; 2015; Massimino et al., 2015]. The specimen was anisotropically reconsolidated to the best estimate of the in situ effective vertical and horizontal stress. The same specimen was first subjected to RCT, then to CLTST after a rest period of 24 hrs with opened drainage. CLTSTs were performed under stress control condition by applying a torque with triangular time history at a frequency of 0.1 Hz.

3.2 DRPC MESSINA TEST SITE

Figure 9 shows the location of the three boreholes in the DRPC Messina site while Figure 10 shows the soil stratigraphy of the boreholes. Table 2 shows the list of the soils samples involved in the RCTs and CLTSTs. For the geotechnical model considered in the numerical analysis, the following five soil samples were used: S2C1 (retrieved at 3,00 - 3,50 m), S1C1 (retrieved at 7,00-7,40 m), S3C2 (retrieved at 14,60 - 15,00 m), S2C3 (retrieved at 18,00 - 18,50 m), S3C4 (retrieved at 27,00 - 27,50 m).

Results of Resonant Column Tests (RCT) and Cyclic Loading Torsional Shear Tests (CLTST) are presented in Figures 11-15 to evaluate the shear modulus G and damping ratio D. The specimen was anisotropically reconsolidated to the best estimate of the in situ effective vertical and horizontal stress. The same specimen was first subjected to RCT, then to CLTST after a rest period of 24 hrs with opened drainage. CLTSTs were performed

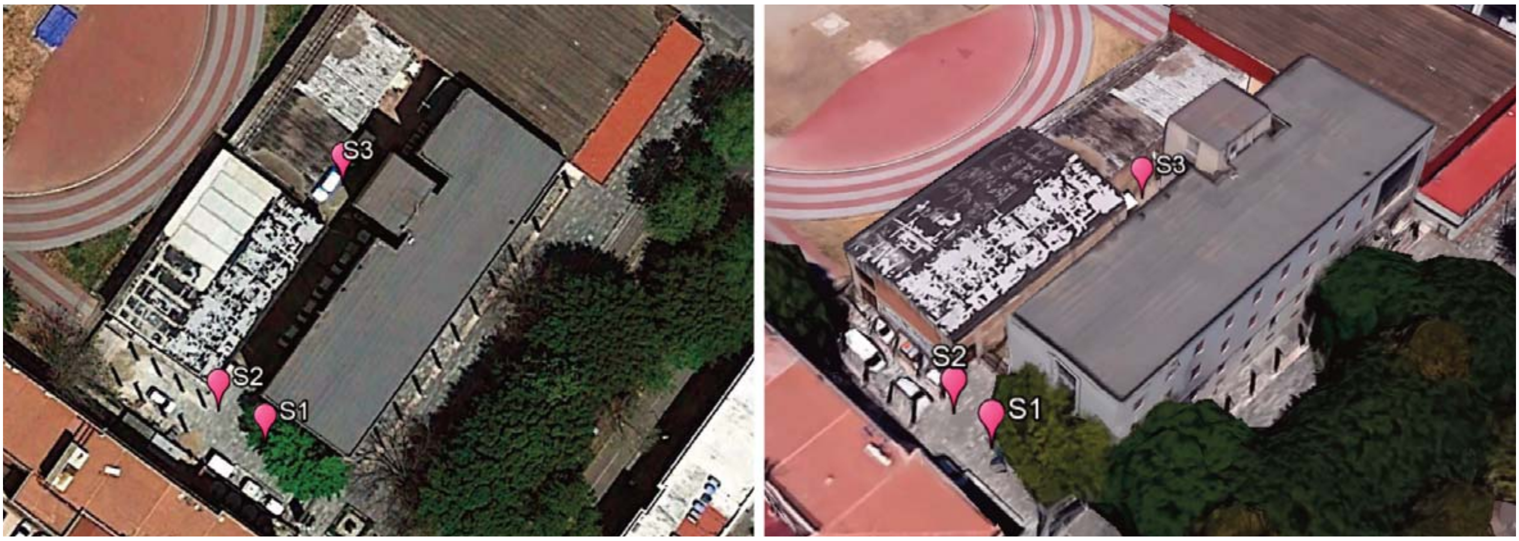

FIGURE 9. DRPC - Messina building.

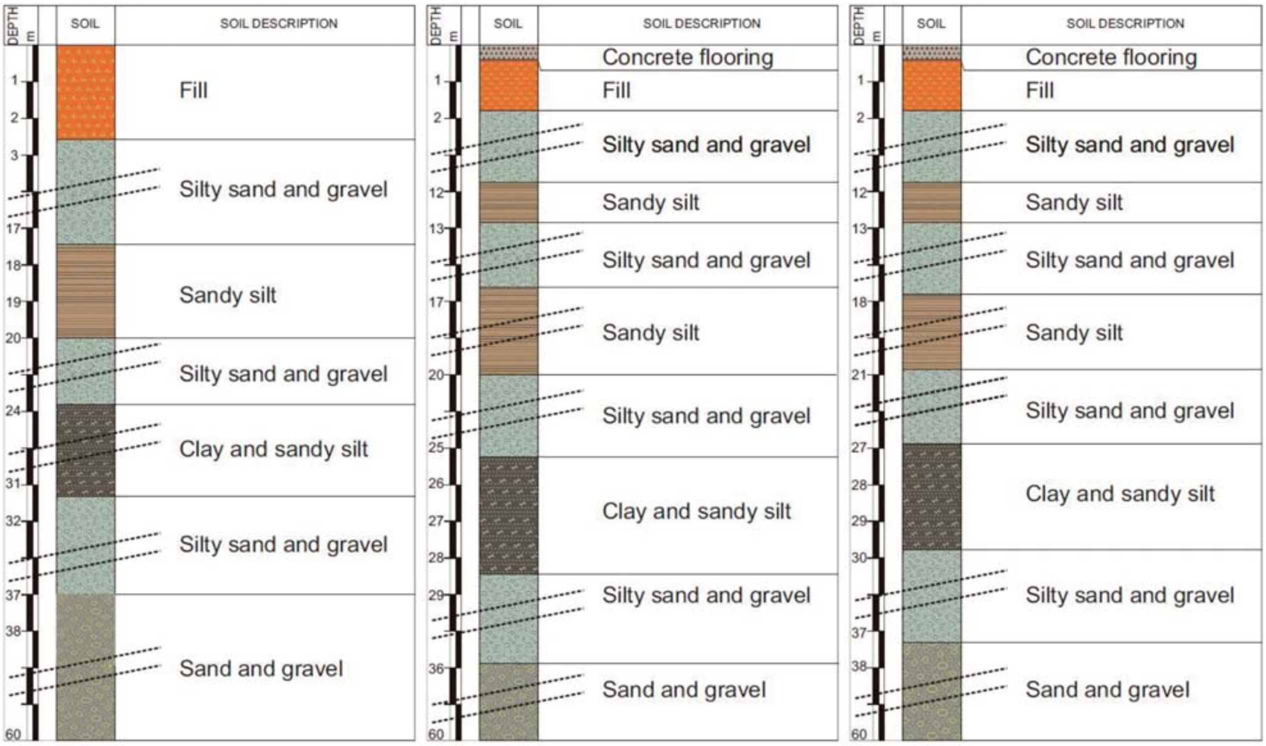

FIGURE 10. DRPC - Soil stratigraphy in the order S1, S2, S3.

under stress control condition by applying a torque with triangular time history at a frequency of 0.1 Hz.

Figure 16 shows the V_s profiles obtained by D-H, C-H and SDMT tests and their comparison. The Down Hole test shows a V_s profile that increase with depth almost according to a linear trend with values variables from 190 m/s to 1000 m/s; at the depth of about 50 m the V_s profile reaches the value of 800 m/s. The Cross Hole test is in good agreement with the Down Hole test. The C-H test shows a V_s profile that linearly increase with depth with values variable between 190 m/s and 800 m/s at the depth of about 50,00 m. The SDMT test shows V_s values which are in good agreement if compared to D-H and C-H tests, up to the depth of 30 m.

4. NUMERICAL ANALYSES IN THE TEST SITES

One-dimensional local site response analyses assume that all geologic boundaries are horizontal and the response of soil deposits is predominantly caused by waves propagating vertically from the underlying

List of soil samples			
n.	Borehole	Name	Depth (m)
1	S1	C1	7,00 – 7,40
2	S1	C2	19,50 – 19,90
3	S2	C1	3,00 – 3,50
4	S2	C3	18,00 – 18,50
5	S3	C1	5,50 – 6,00
6	S3	C2	14,60 – 15,00
7	S3	C4	27,00 – 27,50

TABLE 2. DRPC - List of soil samples.

bedrock. So, one-dimensional numerical codes are valid for modelling plane-parallel layers along a vertical column, assuming laterally-homogeneous stratigraphy. Under these assumptions, the main factors responsible for seismic motion amplifications are: 1) impedance contrasts between ground layers, particularly with bedrock; 2) resonance effects due to the closeness between the frequencies of the motion at the substrate and the natural vibration of the deposit. Calculation procedures consider, in the solution of the dynamic equilibrium of the system, the non-linear relation through two types of analyses: equivalent linear and nonlinear analyses. The equivalent linear analysis consists in the execution of a sequence of complete linear analysis with subsequent update of the parameters of stiffness and damping until the satisfaction of a predetermined convergence criterion. There parameters depend on the state of deformation of the ground. The nonlinear analysis consists in the integration step-by-step of the equations of motion, simultaneously changing the parameter values of stiffness and damping.

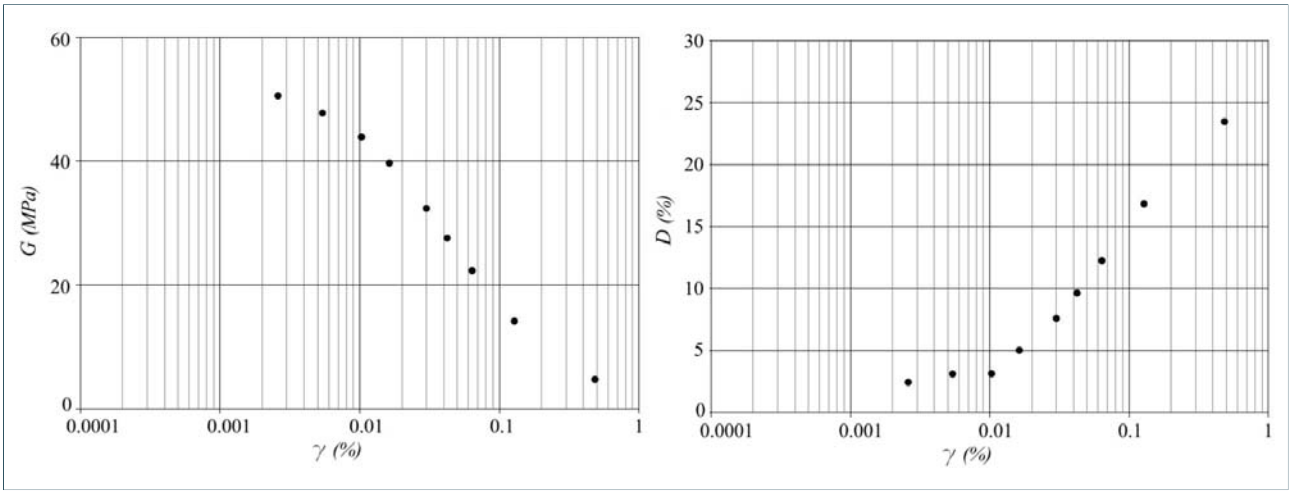

FIGURE 11. DRPC RCT results for S2C1 soil sample.

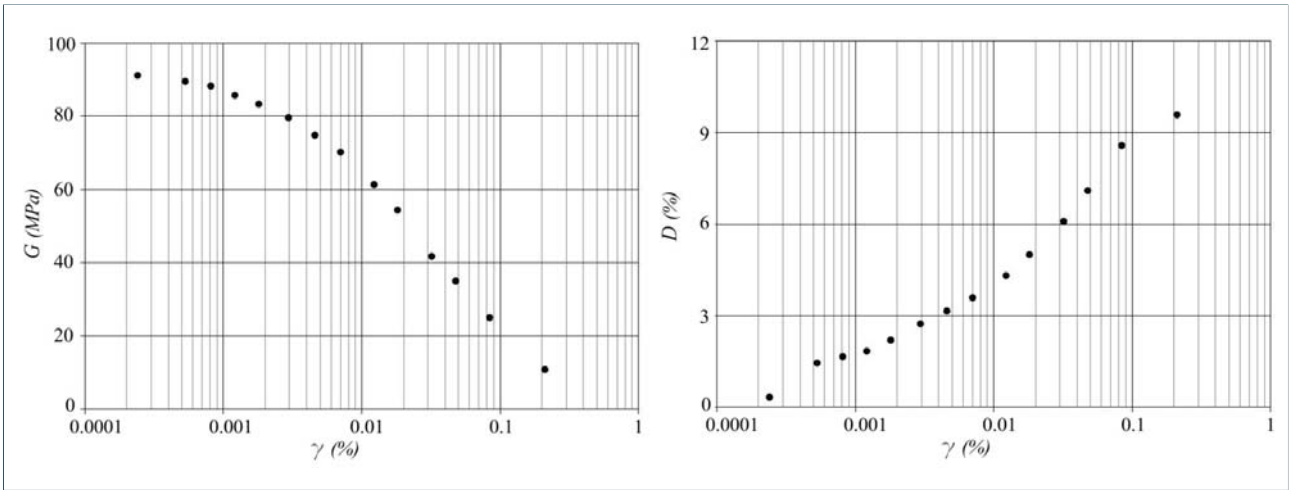

FIGURE 12. DRPC RCT results for S1C1 soil sample.

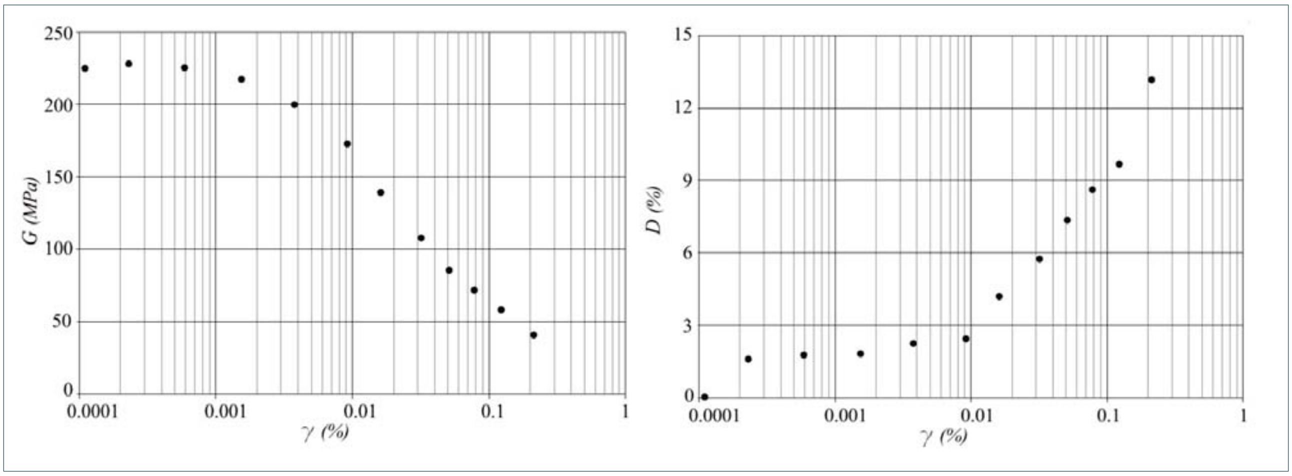

FIGURE 13. DRPC RCT results for S3C2 soil sample.

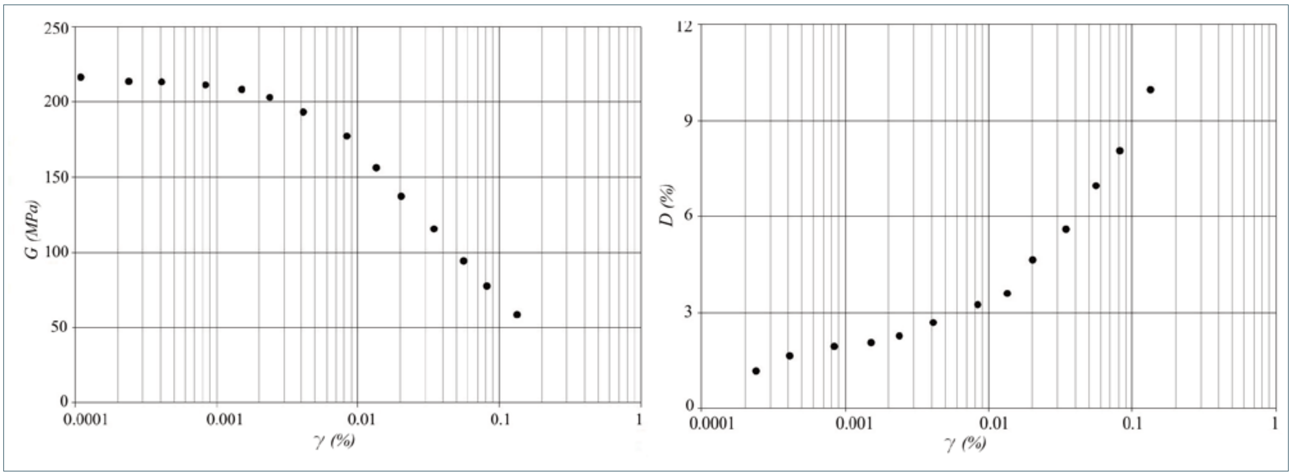

FIGURE 14. DRPC RCT results for S2C3 soil sample.

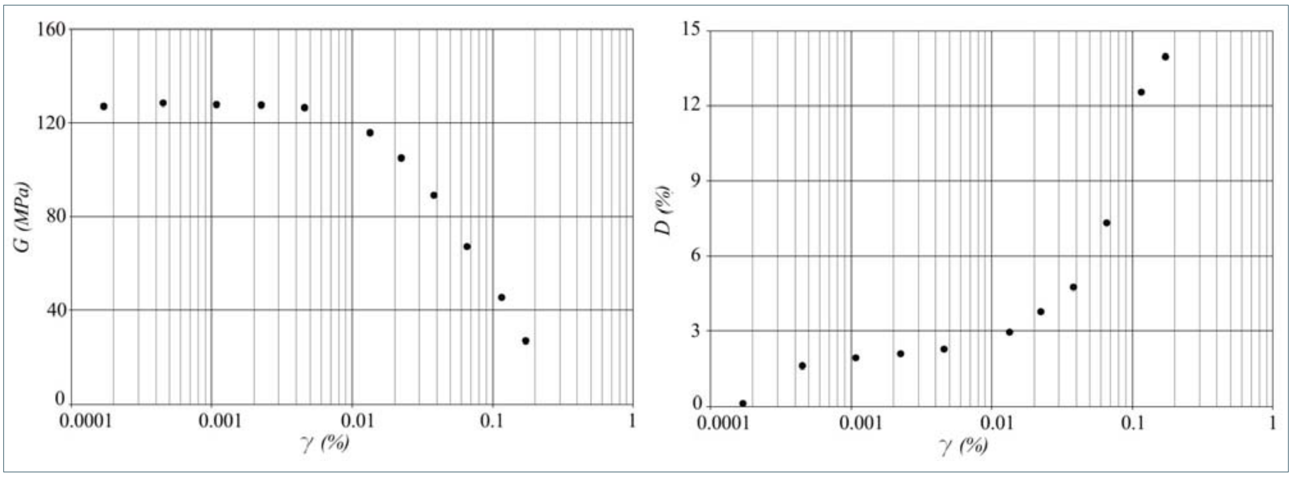

FIGURE 15. DRPC RCT results for S3C4 soil sample.

The first analysis provides satisfactory results at not excessive deformation of the ground, less than 1%, for higher deformation is necessary to use non-linear incremental analysis. Among the programs that adopt the equivalent linear analysis the best known and most frequently used is the computer code SHAKE [Schnabel et al., 1972a, 1972b; Idriss and Sun, 1992] and later revisions like EERA [Bardet et al., 2000], which has been used in this study. They work in the total stresses field using the Kelvin-Voigt physical model (continuous and

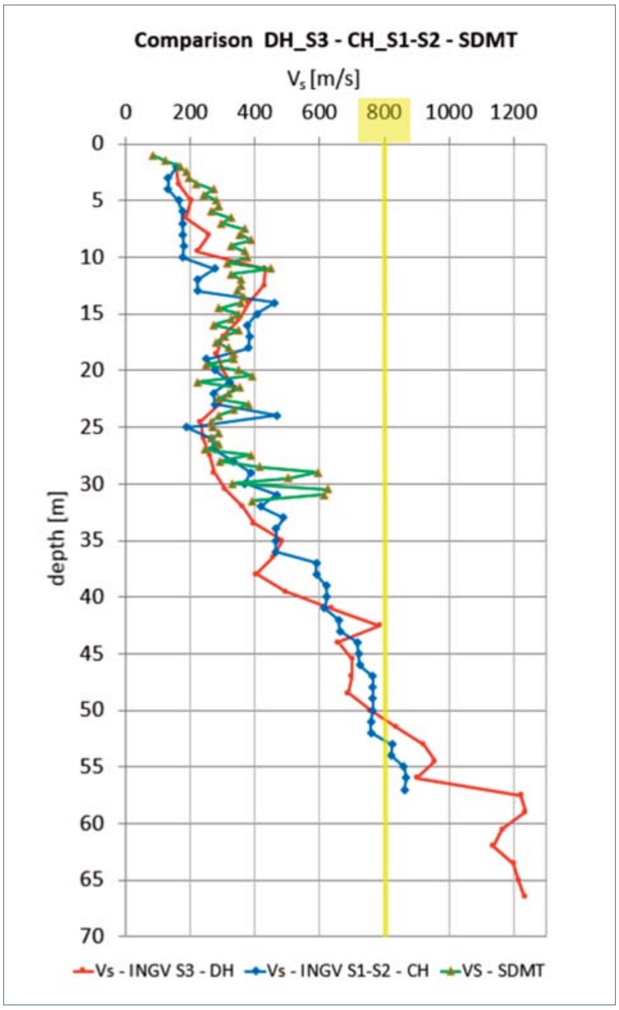

FIGURE 16. DRPC - D-H, C-H and SDMT V_s profiles and their comparison.

homogeneous layers with linearized visco-elastic behaviour).

It consists of flat and parallel layers of infinite horizontal extension on an outcropping half-space corresponding to the bedrock, on which the input motion is applied.

Each layer is considered to be homogeneous and isotropic and characterized by the thickness h, the density, the shear modulus G and the damping ratio ξ. The input motion propagates in the direction perpendicular to the free surface. Figure 17 shows the calculation scheme for N layers with these properties: shear modulus G, damping ratio ξ, thickness h. The amplitude of incident and reflected waves in each layer, and reflected waves F_N at the bedrock are unknown. The incident wave E_N at the bedrock is given. The calculation method considers the motion equations applied in each layer under two conditions: 1) the congruence between displacements and stresses at the interfaces; 2) equilibrium between incident and reflected waves at the surface.

Finally, in order to take into account the non linear soil behaviour, an iterative procedure is carried out by considering the behaviour of the shear modulus G and of the damping ratio D, as functions of shear strain γ. The main steps of the iterative procedure are: 1) estimation for G and ξ in each layer; 2) ground response calculation in each layer; 3) effective shear strain calculation based on the maximum shear strain; 4) new iteration based on G and ξ new values and new ground response calculation until the desired convergence value is reached.

The results are presented in terms of acceleration time history, Fourier spectra, response spectra at the surface and in terms of maximum acceleration profiles as function of the depth [Ferraro et al., 2009].

One dimensional equivalent linear analyses have been carried out at the Catania INGV test site with different bedrock depths (200 m, 300 m, 400 m, 600m) and at the Messina DRPC test site (DRPC-S1S2 and DRPC-S3).

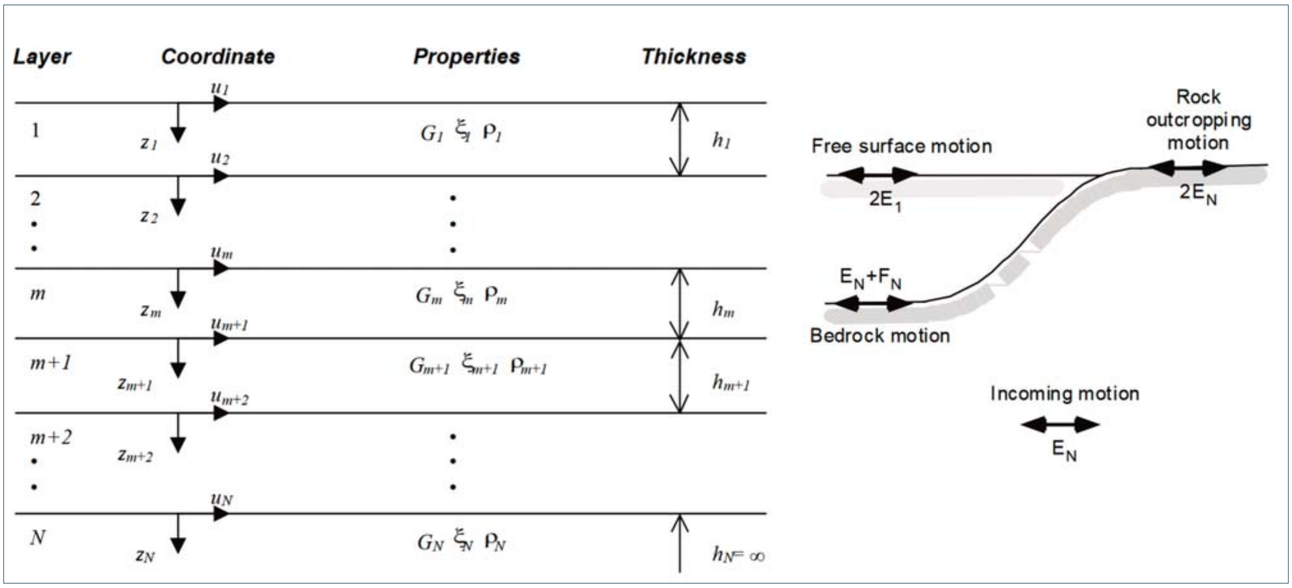

FIGURE 17. One-dimensional layered soil deposit system [after Schnabel et al., 1972].

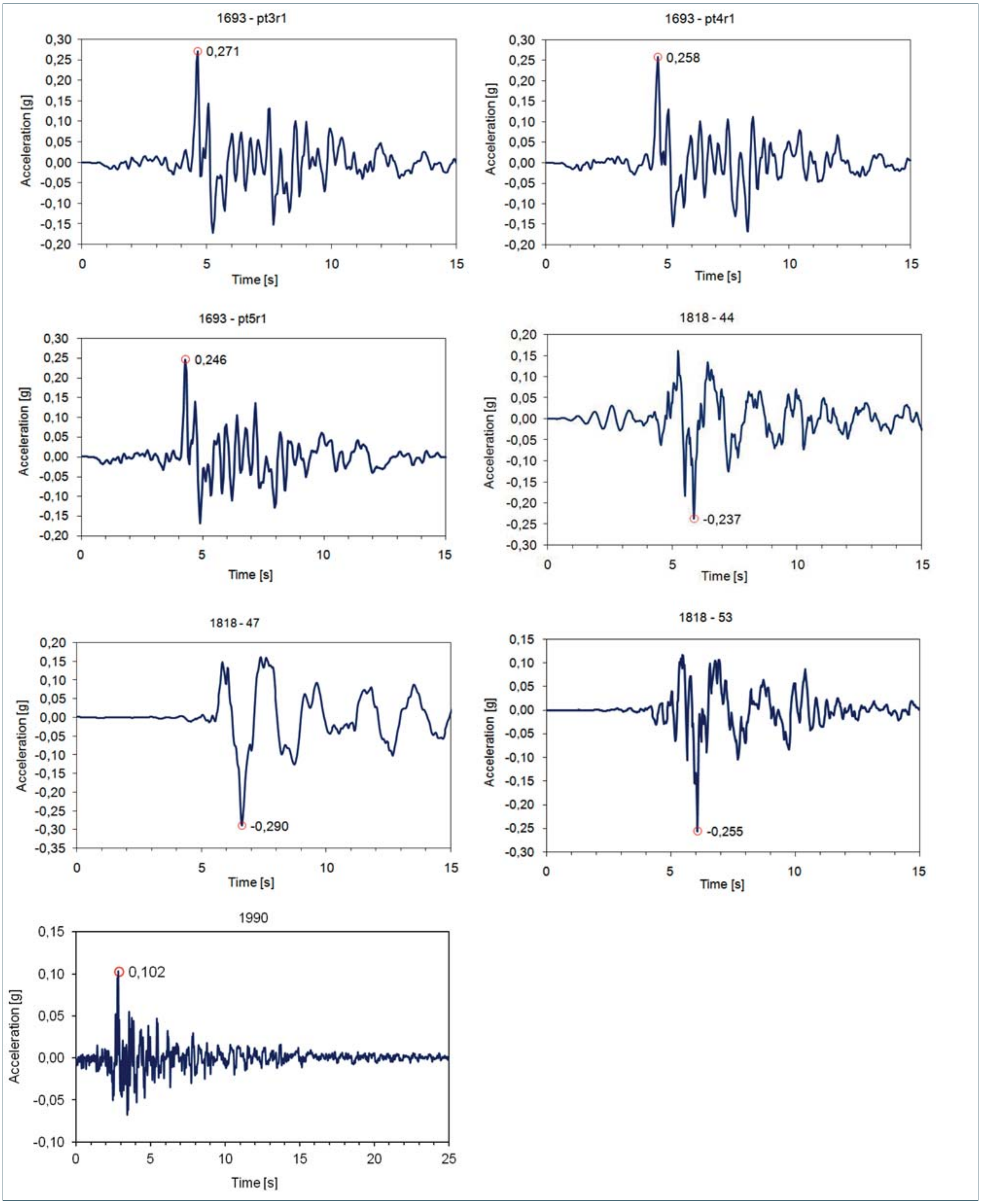

FIGURE 18. INGV test site - Set of input motion for numerical analyses.

4.1 INGV TEST SITE NUMERICAL ANALYSES

As regards the input motion at the Ultimate Limit State (ULS), the site response analyses at the INGV test site were made using as excitation at the base of the models both synthetic seismograms and recorded accelerograms, the first obtained by the 1693 Val di Noto and 1818 Etna earthquakes, the second by the recordings of the December 13, 1990 earthquake, at the Sortino (a_{max} = 1.00 m/sec^2) recording station. The approach of using synthetic seismograms for generating

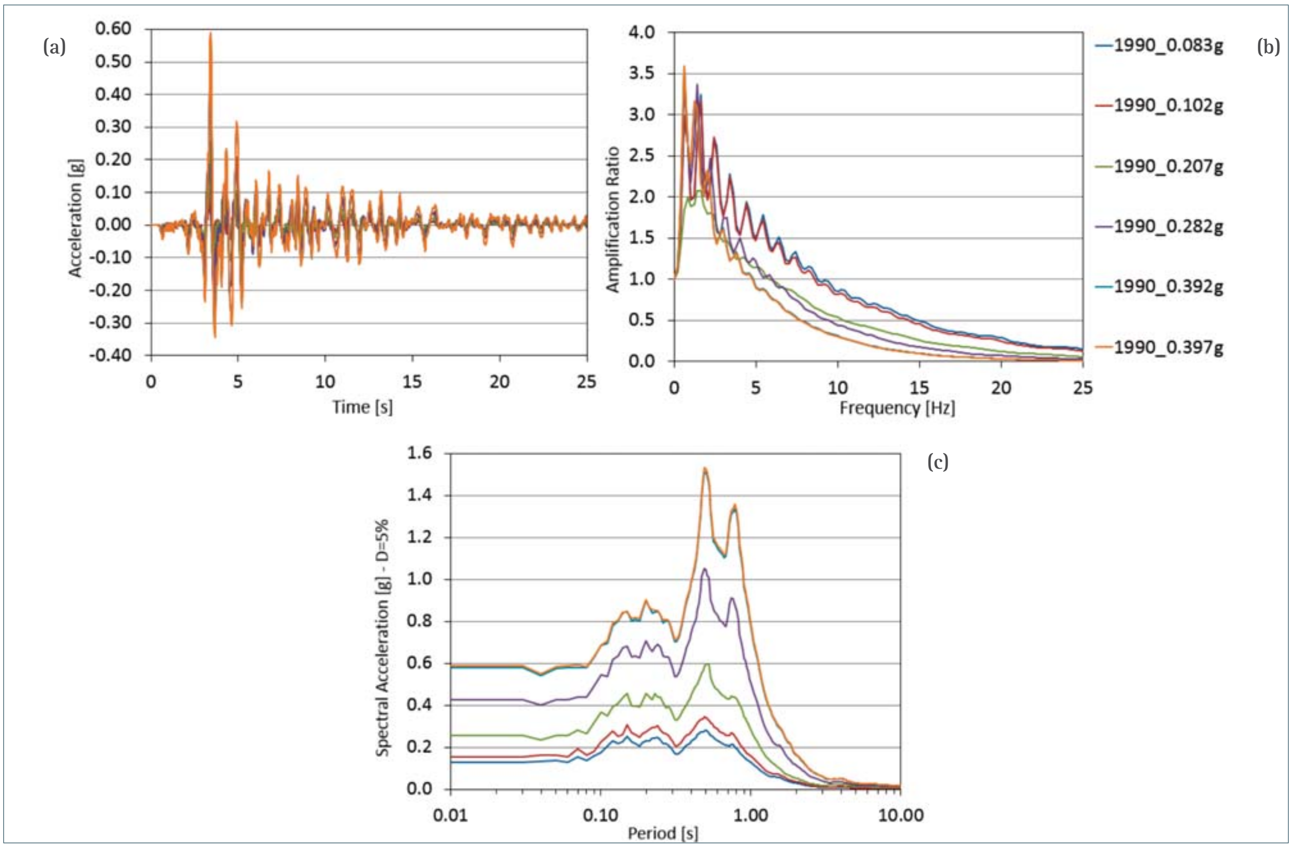

FIGURE 19. Soil model with bedrock at the depth of 200 m. Time history of surface acceleration (a), amplification ratio (b), spectral acceleration (c).

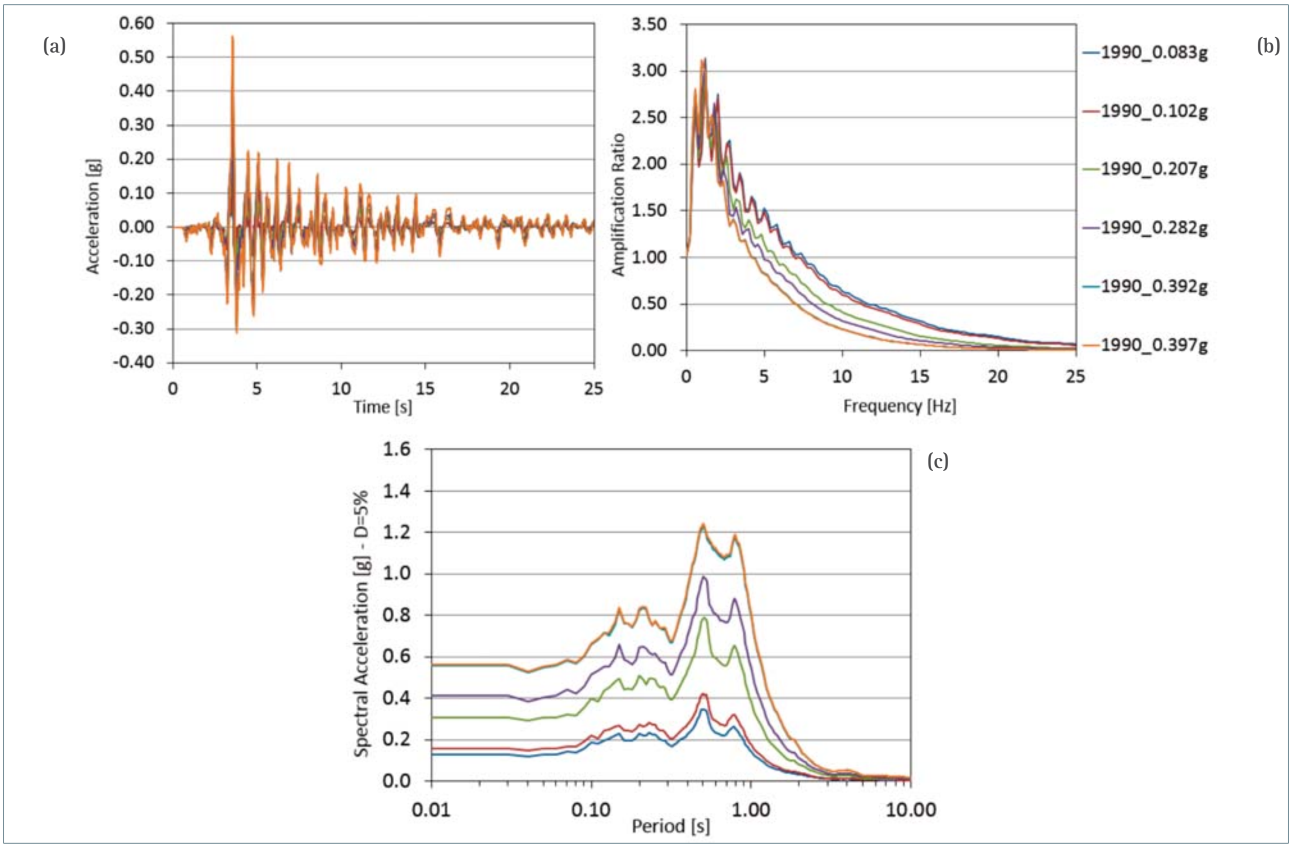

FIGURE 20. Soil model with bedrock at the depth of 300 m. Time history of surface acceleration (a), amplification ratio (b), spectral acceleration (c).

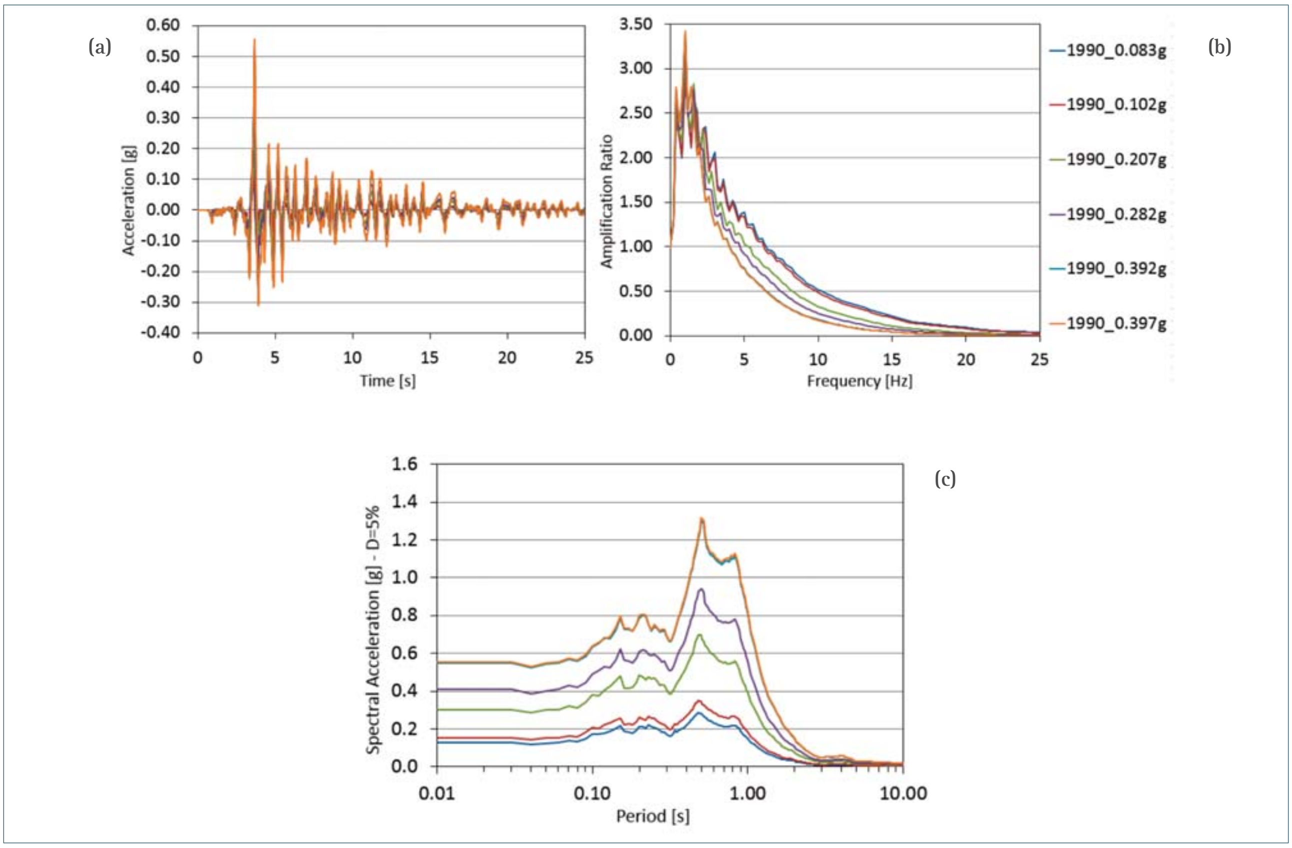

FIGURE 21. Soil model with bedrock at the depth of 400 m. Time history of surface acceleration (a), amplification ratio (b), spectral acceleration (c).

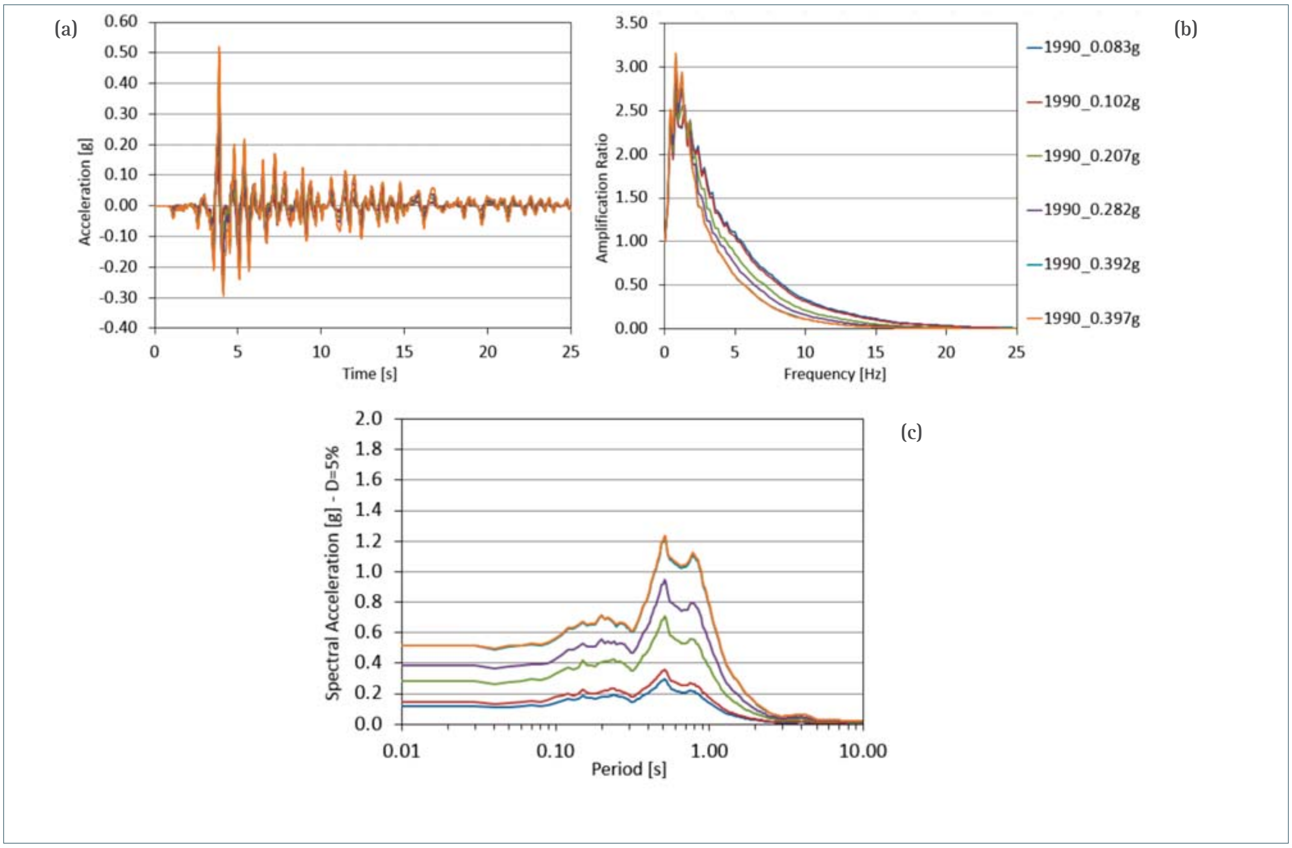

FIGURE 22 Soil model with bedrock at the depth of 600 m. Time history of surface acceleration (a), amplification ratio (b), spectral acceleration (c).

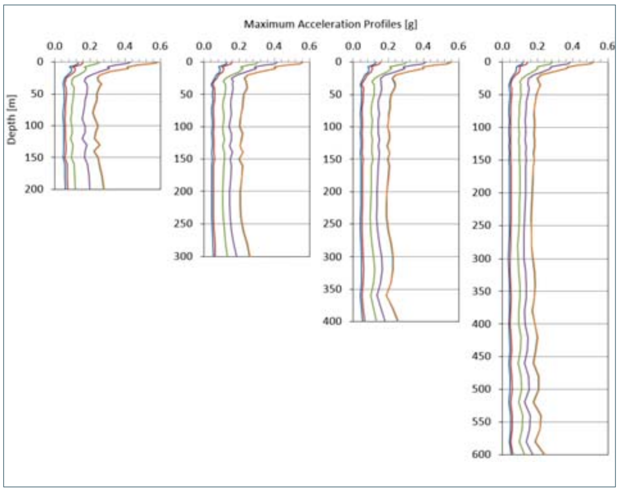

FIGURE 23. Comparison in terms of maximum acceleration profiles, for the different soil models considered in the numerical analysis.

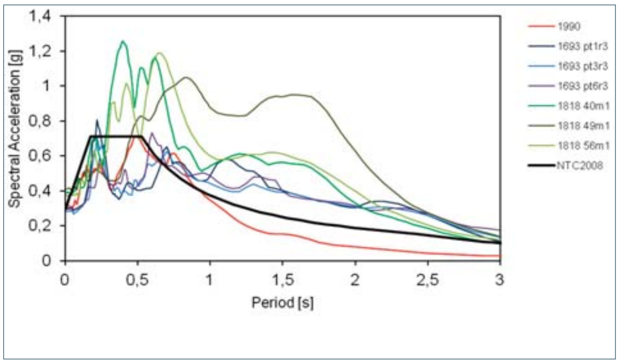

FIGURE 24. Comparison between spectral acceleration at the surface obtained by numerical analyses for the 200 m seismic bedrock soil model, and input acceleration of 0.207 g, with the spectral acceleration provided by the Italian seismic code NTC2008. Labels of different colours in the legend represent different synthetic seismograms at various depths of 1693 (20m, 31m, 40m) and 1818 (40m, 49m, 56m) scenario earthquakes used for in the numerical analyses.

a seismic ground motion scenario at the bedrock has been so used in the present work. The reference events were the catastrophic earthquakes that struck Eastern Sicily: on January 11, 1693, assumed as a level I maximum credible earthquake scenario; on February 20, 1818, assumed as a level II base operative earthquake scenario.

The epicentre of the source in the case of 1693 scenario is about 13 km far from the coast, which is considered as the coordinate system source. A magnitude M = 7.0, corresponding to the destructive event which struck Catania in 1693, has been taken into account. The source has been simulated through the overlaying of 5 sources placed at different depths and activated at different times, simulating approximately the propagation of the rupture on the segment fault. Seismograms

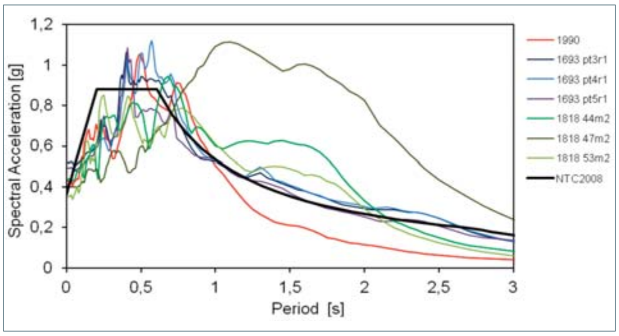

FIGURE 26. Comparison between spectral acceleration at the surface obtained by numerical analyses for the 200 m seismic bedrock soil model and input acceleration of 0.282 g, with the spectral acceleration provided by the Italian seismic code NTC2008. Labels of different colours in the legend represent different synthetic seismograms at various depths of 1693 (20m, 31m, 40m) and 1818 (40m, 49m, 56m) scenario earthquakes used for in the numerical analyses.

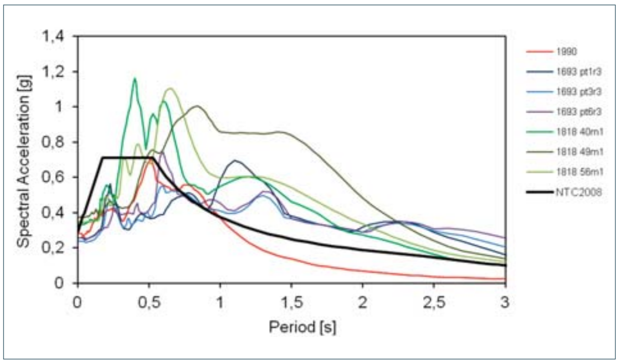

FIGURE 25. Comparison between spectral acceleration at the surface obtained by numerical analyses for the 600 m seismic bedrock soil model and input acceleration of 0.207 g, with the spectral acceleration provided by the Italian seismic code NTC2008. Labels of different colours in the legend represent different synthetic seismograms at various depths of 1693 (20m, 31m, 40m) and 1818 (40m, 49m, 56m) scenario earthquakes used for in the numerical analyses.

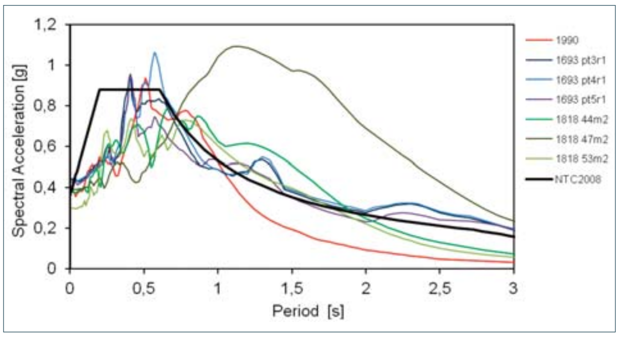

FIGURE 27. Comparison between spectral acceleration at the surface obtained by numerical analyses for the 600 m seismic bedrock soil model and input acceleration of 0.282 g, with the spectral acceleration provided by the Italian seismic code NTC2008. Labels of different colours in the legend represent different synthetic seismograms at various depths of 1693 (20m, 31m, 40m) and 1818 (40m, 49m, 56m) scenario earthquakes used for in the numerical analyses.

	200 m soil model						
	1693 pt1r3	1693 pt3r3	1693 pt6r3	1818 40m1	1818 49m1	1818 56m1	1990
$PGA_{NTC\ 2008\ soil\ A}$	0,207	0,207	0,207	0,207	0,207	0,207	0,207
PGA_{output_EERA}	0,300	0,282	0,296	0,387	0,411	0,372	0,315
$R = PGA_{output\_EERA/PGANTC\ 2008}$	1,45	1,36	1,43	1,87	1,99	1,80	1,52

TABLE 3. Results in terms of maximum acceleration at the surface and soil amplification factor R, for the 200 m soil model, using as input ag = 0.207 g acceleration value.

	600 m soil model						
	1693 pt1r3	1693 pt3r3	1693 pt6r3	1818 40m1	1818 49m1	1818 56m1	1990
$PGA_{NTC\ 2008\ soil\ A}$	0,207	0,207	0,207	0,207	0,207	0,207	0,207
PGA_{output_EERA}	0,255	0,236	0,257	0,335	0,374	0,346	0,283
$R = PGA_{output\_EERA/PGANTC\ 2008}$	1,45	1,36	1,43	1,87	1,99	1,80	1,52

TABLE 4. Results in terms of maximum acceleration at the surface and soil amplification factor R, for the 600 m soil model, using as input ag = 0.207 g acceleration value.

	200 m soil model						
	1693 pt3r1	1693 pt4r1	1693 pt5r1	1818 44m2	1818 47m2	1818 53m2	1990
$PGA_{NTC\ 2008\ soil\ A}$	0,282	0,282	0,282	0,282	0,282	0,282	0,282
PGA_{output_EERA}	0,519	0,493	0,492	0,434	0,401	0,354	0,429
$R = PGA_{output\_EERA}/PGA_{NTC\ 2008soil\ A}$	1,84	1,75	1,74	1,54	1,42	1,26	1,52

TABLE 5. Results in terms of maximum acceleration at the surface and soil amplification factor R, for the 200 m soil model, using as input ag = 0.282 g acceleration value.

	S2 - bedrock 600 m						
	1693 pt3r1	1693 pt4r1	1693 pt5r1	1818 44m2	1818 47m2	1818 53m2	1990
$PGA_{NTC\ 2008\ soil\ A}$	0,282	0,282	0,282	0,282	0,282	0,282	0,282
PGA_{output_EERA}	0,439	0,446	0,430	0,382	0,393	0,300	0,380
$R = PGA_{output\_EERA}/PGA_{NTC\ 2008soil\ A}$	1,56	1,58	1,52	1,35	1,39	1,06	1,35

TABLE 6. Results in terms of maximum acceleration at the surface and soil amplification factor R, for the 600 m soil model, using as input ag = 0.282 g acceleration value.

Cross-Hole DRPC S1-S2

	from [m]	to [m]	Thickness of layer [m]	V_s [m/s]	G/γ - D/γ	γ [kN/m³]
1	0,00	**2,00**	2,00	158,14	**S2C1 - CTS**	18,64
2	2,00	**5,00**	3,00	146,41	**S2C1 - CTS**	18,64
3	5,00	**8,00**	3,00	172,78	**S1C1-RCT**	18,34
4	8,00	**11,00**	3,00	201,74	**S1C1-RCT**	18,34
5	11,00	**14,00**	3,00	295,04	**S3C2-RCT**	19,91
6	14,00	**17,00**	3,00	406,51	**S3C2-RCT**	19,91
7	17,00	**20,00**	3,00	322,12	**S2C3 - RCT**	24,23
8	20,00	**23,00**	3,00	286,46	**S3C2-RCT**	19,91
9	23,00	**26,00**	3,00	299,43	**S3C2-RCT**	17,95
10	26,00	**29,00**	3,00	314,72	**S3C4 - CTS**	17,95
11	29,00	**32,00**	3,00	410,10	**S3C2-RCT**	19,91
12	32,00	**35,00**	3,00	458,92	**S3C2-RCT**	19,91
13	35,00	**38,00**	3,00	526,81	**S3C2-RCT**	19,91
14	38,00	**41,00**	3,00	612,02	**S3C2-RCT**	19,91
15	41,00	**44,00**	3,00	663,15	**S3C2-RCT**	19,91
16	44,00	**47,00**	3,00	731,02	**S3C2-RCT**	19,91
17	47,00	**50,00**	3,00	764,69	**S3C2-RCT**	19,91
18	50,00	**53,00**	3,00	776,22	**S3C2-RCT**	19,91
19	53,00	**56,00**	3,00	843,10	**S3C2-RCT**	19,91
20	**BEDROCK**			**1500,00**		**24,53**

FIGURE 28. DRPC soil model based on Cross-Hole test.

Cross-Hole DRPC S1-S2

	from [m]	to [m]	Thickness of layer [m]	V_s [m/s]	G/γ - D/γ	γ [kN/m³]
1	0,00	**2,00**	2,00	158,14	**S2C1 - CTS**	18,64
2	2,00	**5,00**	3,00	146,41	**S2C1 - CTS**	18,64
3	5,00	**8,00**	3,00	172,78	**S1C1-RCT**	18,34
4	8,00	**11,00**	3,00	201,74	**S1C1-RCT**	18,34
5	11,00	**14,00**	3,00	295,04	**S3C2-RCT**	19,91
6	14,00	**17,00**	3,00	406,51	**S3C2-RCT**	19,91
7	17,00	**20,00**	3,00	322,12	**S2C3 - RCT**	24,23
8	20,00	**23,00**	3,00	286,46	**S3C2-RCT**	19,91
9	23,00	**26,00**	3,00	299,43	**S3C2-RCT**	17,95
10	26,00	**29,00**	3,00	314,72	**S3C4 - CTS**	17,95
11	29,00	**32,00**	3,00	410,10	**S3C2-RCT**	19,91
12	32,00	**35,00**	3,00	458,92	**S3C2-RCT**	19,91
13	35,00	**38,00**	3,00	526,81	**S3C2-RCT**	19,91
14	38,00	**41,00**	3,00	612,02	**S3C2-RCT**	19,91
15	41,00	**44,00**	3,00	663,15	**S3C2-RCT**	19,91
16	44,00	**47,00**	3,00	731,02	**S3C2-RCT**	19,91
17	47,00	**50,00**	3,00	764,69	**S3C2-RCT**	19,91
18	50,00	**53,00**	3,00	776,22	**S3C2-RCT**	19,91
19	53,00	**56,00**	3,00	843,10	**S3C2-RCT**	19,91
20	**BEDROCK**			**1500,00**		**24,53**

FIGURE 29. DRPC soil model based on Down-Hole test.

	CHS1S2						
	Amoruso et al. [2002]	Bottari et al. [1986]	DISS Aspromonte Est	DISS Gioia Tauro	DISS Messina Straits	Tortorici et al. [1995]	1693
$PGA_{NTC\ 2008}$	0,332	0,332	0,332	0,332	0,332	0,332	0,332
PGA_{output_EERA}	0,516	0,664	0,443	0,619	0,764	0,584	0,419
$R = PGA_{output\_EERA}/PGA_{NTC\ 2008}$	1,55	2,00	1,33	1,86	2,30	1,76	1,26

TABLE 7. Results in terms of maximum acceleration at the surface and soil amplification factor R, for the Cross-Hole S1-S2 soil model.

	DHS3						
	Amoruso et al. [2002]	Bottari et al. [1986]	DISS Aspromonte Est	DISS Gioia Tauro	DISS Messina Straits	Tortorici et al. [1995]	1693
$PGA_{NTC\ 2008}$	0,332	0,332	0,332	0,332	0,332	0,332	0,332
PGA_{output_EERA}	0,518	0,487	0,444	0,502	0,436	0,453	0,411
$R = PGA_{output\_EERA}/PGA_{NTC\ 2008}$	1,56	1,47	1,34	1,51	1,31	1,36	1,24

TABLE 8. Results in terms of maximum acceleration at the surface and soil amplification factor R, for the Down-Hole S3 soil model.

have been drawn for each site long a set of six receivers placed at different depths, starting from the surface up to almost 170 m [Grasso et al., 2005].

In the case of level II 1818 earthquake scenario seis-

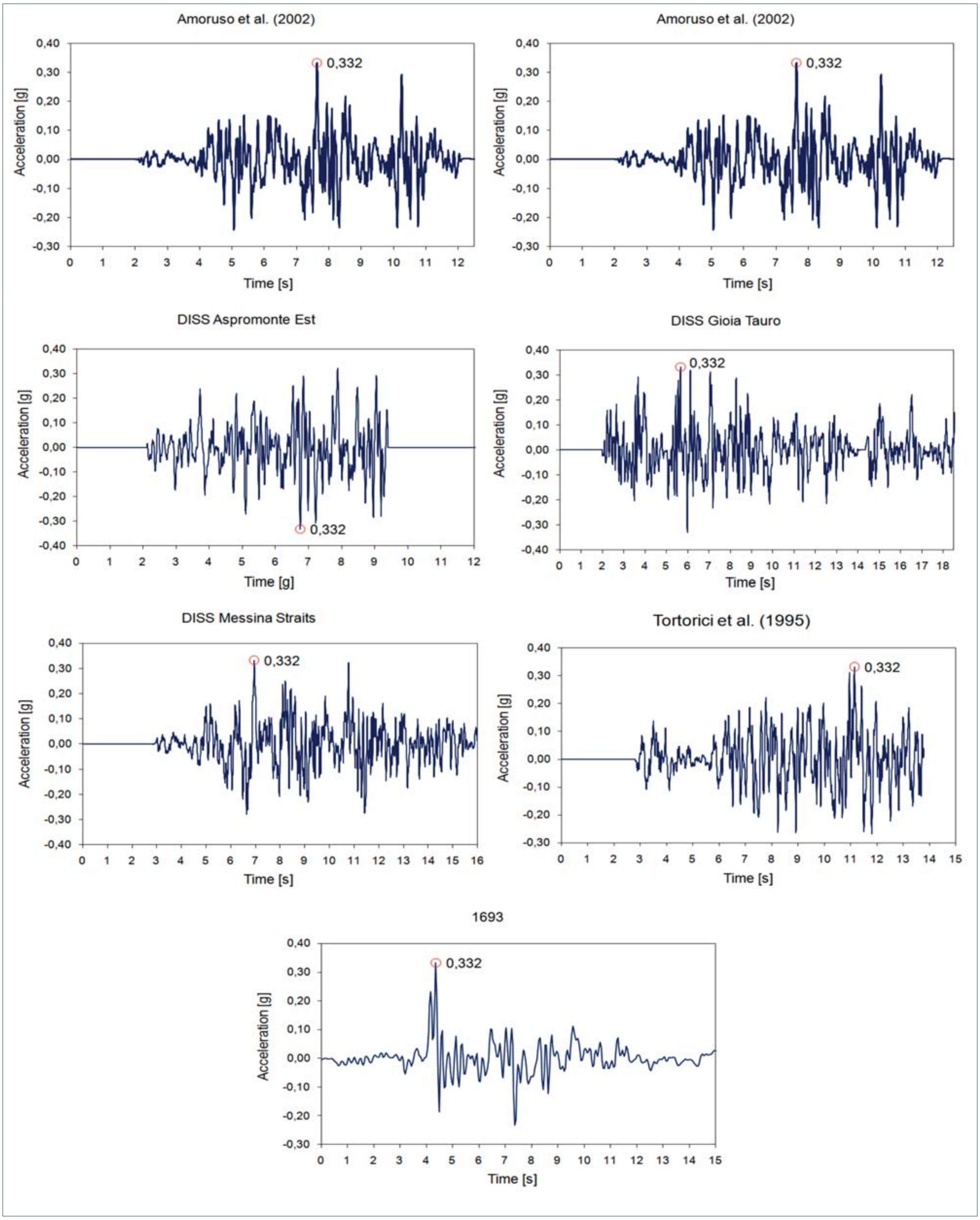

FIGURE 30. DRPC- Set of input seismograms used for numerical analyses.

mograms have been evaluated by Laurenzano et al., 2004, using the 3-D hybrid stochastic-deterministic method EXWIM. This method has been used to compute strong motion seismograms in the near-field of extended earthquake source. The computational procedure consisted of: 1) discretizing the area into a grid of elementary point sources; 2) computing the wavefield generated by each point source with unitary seismic moment; 3) computing seismograms for each point source according to the given distribution of slip; and

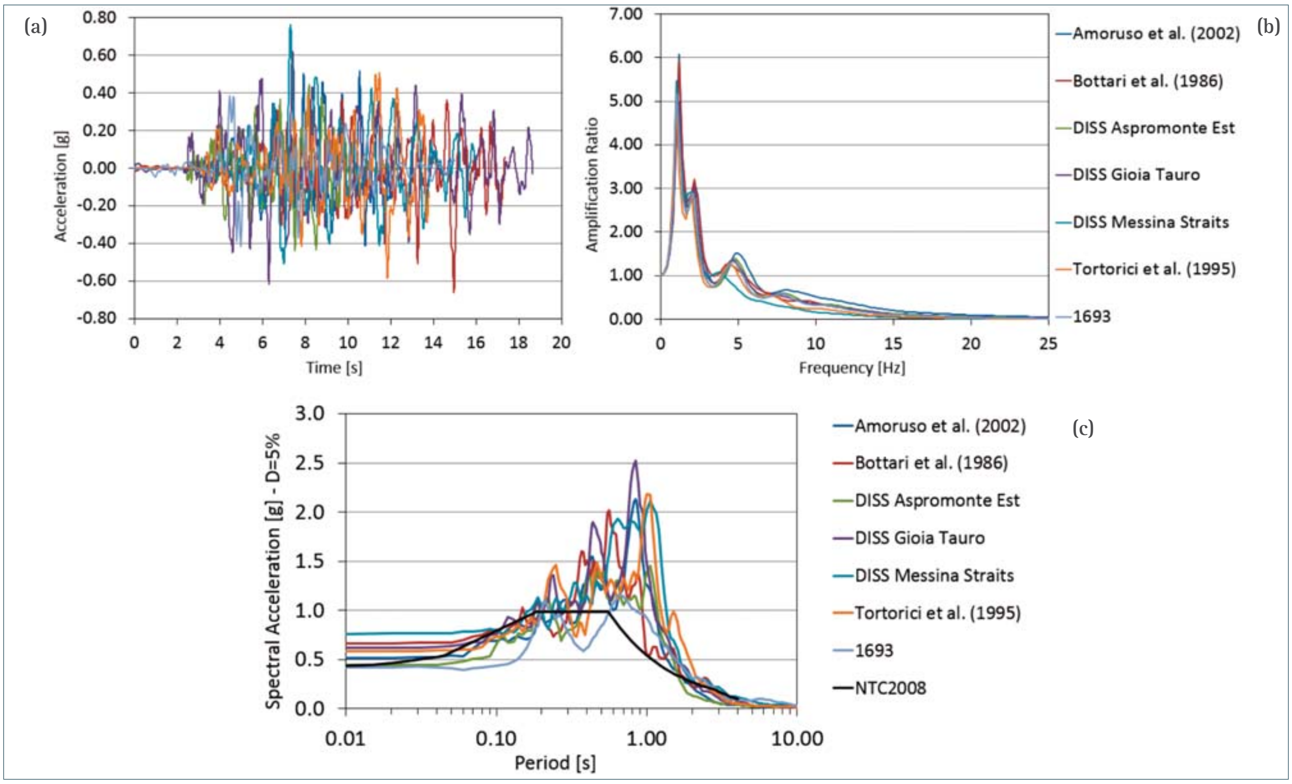

FIGURE 31. DRPC - CH-S1-S2 model. Results at the surface in terms of acceleration time history (a), amplification ratio (b) and spectral acceleration (c). Labels of different colours in the legend represent different synthetic seismograms obtained from different source models.

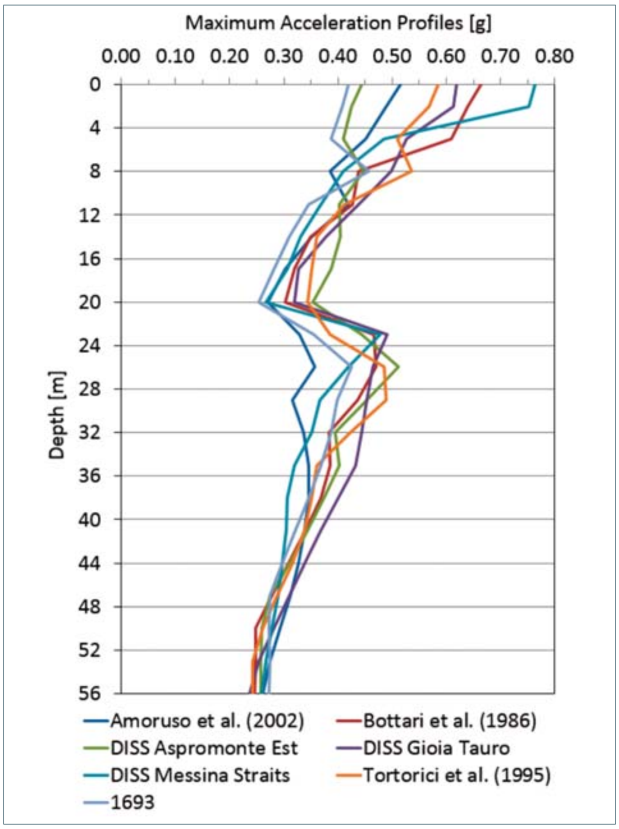

FIGURE 32. DRPC- CH-S1-S2 model. Maximum acceleration profiles. Labels of different colours in the legend represent different synthetic seismograms obtained from different source models.

4) summing up each contribution synchronized in time to simulate the propagation of the rupture. Seismograms have been computed up to a maximum frequency of 20 Hz. The deterministic-stochastic transition has been set at 1.5-2 Hz. The maximum fault size has been set at 26.6 km x 16.6 km, and it has been discretized into 4895 elementary sources, with inter-spacing of 300 m. The ground motion has been computed at a regular grid of receivers covering the Catania municipal area. This area is sampled with 470 receivers, with inter-spacing of 300 m. The use of advanced methods capable of generating of synthetic seismograms can give a valuable insight into the evaluation of a seismic ground motion scenario.

Recorded accelerograms of December 13, 1990 earthquake and synthetic seismograms by 1693 and 1818 have been scaled to different values of the PGA at the bedrock corresponding to different return periods in the current Italian seismic code *"seismic hazard and seismic classification criteria for the national territory"* obtained by a probabilistic approach at ULS in the interactive seismic hazard maps.

Figure 18 shows some of the synthetic seismograms by 1693 and 1818 scenario earthquakes and the recorded accelerogram of December 13, 1990 earthquake used as input for seismic response analyses.

Preliminary numerical analyses have been carried

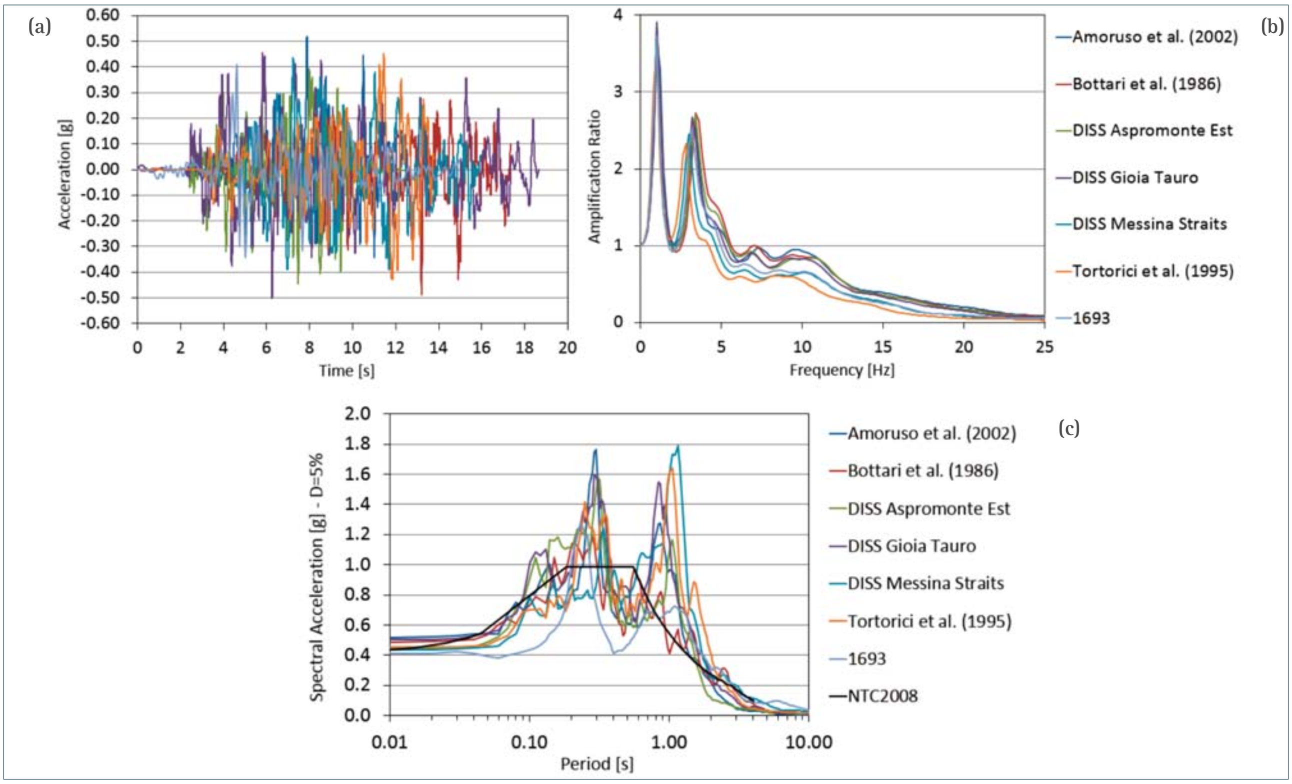

FIGURE 33. DRPC - DH-S3 model. Results at the surface in terms of acceleration time history (a), amplification ratio (b), spectral acceleration. Labels of different colours in the legend represent different synthetic seismograms obtained from different source models.

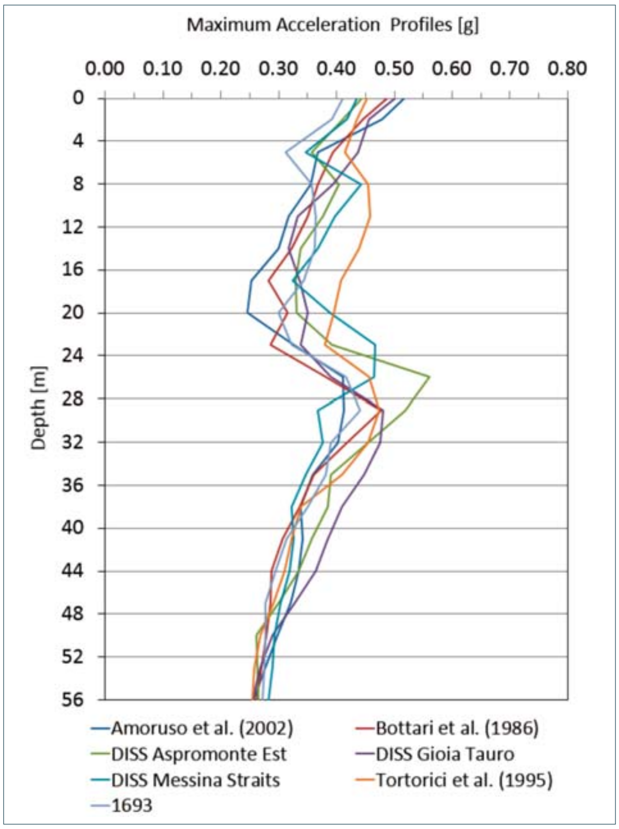

FIGURE 34. DRPC-ME - DH-S3 model. Maximum acceleration profiles. Labels of different colours in the legend represent different synthetic seismograms obtained from different source models.

out based on the 1990 recorded input motion scaled to six different values of PGA provided by the current Italian seismic code for different ULS and the different return periods of 60, 101, 475, 949, 1898 and 1950 years: 0.083 g; 0.102 g; 0.207 g; 0.282 g; 0.392 g; 0.397 g. In Figures 19-22 the results of site response analyses are presented, for different bedrock depths (200 m, 300 m, 400 m, 600m), in terms of time history of surface acceleration, amplification ratio and spectral acceleration [Caruso et al., 2016]. Finally, the Figure 23 shows the comparison in terms of maximum acceleration profiles, for the different soil models considered in the numerical analysis. Additional seismic response analyses have been carried out [Ferraro et al., 2016] for the 200 m and 600 m seismic bedrock soil models, by using the same input seismograms of Figure 18, scaled to the different values of acceleration of 0.207 g and 0.282 g provided by the Italian seismic code (ultimate limit state with return periods of 475 and 949 years). The numerical analyses results are shown in terms of response spectra at surface (Figures 24-27), and in terms of surface maximum acceleration and amplification ratio (Tables 3-6).

4.2 DRPC TEST SITE NUMERICAL ANALYSES

Numerical analyses have been carried out considering two soil models, based on the Cross-Hole test results (Figure 28) performed in the S1 and S2 boreholes, and on the Down-Hole test results (Figure 29) performed in the S3 borehole, by using the seven input seismograms [Amoruso et al., 2002] shown in Figure 30 obtained by a source modeling of 1908 Messina and Reggio Calabria earthquake and 1693 Val di Noto earthquake, scaled to the value of 0.332 g, provided by the Italian seismic code NTC2008 (ultimate state limit with a return period of 949 years).

The numerical analyses results are shown in Figures 31-34 in terms of time history of surface maximum acceleration, amplification ratio and response spectra, and in terms of surface maximum acceleration and soil amplification factor R values (Tables 7-8).

5. CONCLUSIONS

In this study it was benefited of a great availability of borehole data, geophysical surveys and laboratory tests carried out from various campaigns of geological surveys that, in different phases, have interested the area of two tests sites in the cities of Catania and Messina seismic areas. In order to study the dynamic characteristics of soils in the test sites, in situ and laboratory investigations have been carried out to obtain soil profiles with special attention being paid to the variation of the shear modulus G and damping ratio D with depth.

Local site response analyses have been brought for the site area at Ultimate Limitation State ULS by 1-D linear equivalent computer codes for the evaluation of the amplification factors of the maximum acceleration. Results of the site response analysis show high values in soil amplification effects of the soil. The horizontal acceleration at the surface obtained by the site response analysis is in some cases higher than 0.500 g, with soil amplification factors up to 2.30, higher than the soil amplification factor Ss on the basis of the average shear waves velocity (Vs30) according to the current Italian seismic code. The difference between the two soil amplification factors is due to the fact that (Vs30) is not a key parameter in the evaluation of soil amplification. Through 1-D performed numerical analyses it has been possible to evaluate the influence of stratigraphic effects in seismic response of the site.

Finally elastic pseudo-acceleration response spectra at the ground surface have been compared (graphically) with the reference ones, provided by the NTC 2008 Italian seismic code at ULS.

Seismic retrofitting and/or improving have to be definitely considered a multidisciplinary subject, which depends in fact on many factors, such as: local site effects and the dynamic interaction between the foundation soil and the structure. The accurate investigation on the structure and the surrounding soil is the first fundamental step for a realistic evaluation of the structure seismic performance.

REFERENCES

Abate, G., Massimino, M.R. (2016): “Dynamic soil-structure interaction analysis by experimental and numerical modelling”. Rivista Italiana di Geotecnica. Volume 50, Issue 2, 2016, Pages 44-70.

Abate G., Bosco M., Massimino M.R., Maugeri M., (2006): “Limit state analysis for the Catania firestation (Italy)”. 8th US National Conference on Earthquake Engineering 2006. San Francisco, CA; United States; 18 - 22 April 2006; Code 92446. ISBN: 978-161567044-4. 11(2006): 6532-6541.

Abate G., Caruso C., Massimino M.R., Maugeri M., (2007): “Validation of a new soil constitutive model for cyclic loading by FEM analysis”. Solid Mechanics and its Applications. 146(2007): 759-768. ISSN: 09250042.

Abate G., Massimino M.R., Maugeri M., (2015): “Numerical modelling of centrifuge tests on tunnel-soil systems”. Bulletin of Earthquake Engineering. DOI: 10.1007/s10518-014-9703-0. ISSN: 1570-761X. 13(7): 1927-1951.

Abate G., Massimino M.R., Romano S., (2016): “Finite element analysis of DSSI effects for a building of strategic importance in Catania (Italy)”. VI Italian Conference of Researchers in Geotechnical Engineering - Geotechnical Engineering in Multidisciplinary Research: from Microscale to Regional Scale, CNRIG2016. Procedia Engineering. ISSN: 1877-7058. 158(2016): 374-379.

Abate G., Massimino M.R., (2017): “Numerical modelling of the seismic response of a tunnel-soil-aboveground building system in Catania (Italy)”. Bulletin of Earthquake Engineering. ISSN 1570-761X. DOI 10.1007/s10518-016-9973-9. 15(1): 469-491.

Amoruso, A., L. Crescentini, and R. Scarpa, (2002): “Source parameters of the 1908 Messina Straits, Italy, earthquake from geodetic and seismic data”, J. Geophys. Res., 107(B4), doi: 10.1029/2001JB000434, 2002.

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, Dept of Civil Eng.

Bottari, A., Carapezza, E., Carapezza, M., Carveni, P., Cefali, F., Lo Giudice, E., & Pandolfo, C. (1986): "The 1908 Messina Strait earthquake in the regional geostructural framework". Journal of geodynamics, 5(3), 275-302.

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 Tc-4 International Workshop On Metrology For Geotechnics. Benevento (Italy). March 17-18, 2016. Isbn: 978-92-990075-0-1, Pp. 115-120.

Castelli, F., Lentini, V., (2013): "Landsliding events triggered by rainfalls in the Enna area (South Italy)". Proceedings Second World Landslide Forum, WLF2 2011, October 3 - 7 2011, Rome, Springer eds., Vol. 2, pp.39-47, ISBN 978-3-642-31444-5.

Castelli, F., Cavallaro, A., Grasso, S., Lentini, V. (2016a): "Seismic Microzoning from Synthetic Ground Motion Earthquake Scenarios Parameters: the Case Study of the City of Catania (Italy)". Soil Dynamics and Earthquake Engineering, vol. 88 (Sept.), pp 307-327. 10.1016/j.soildyn.2016.07.010.

Castelli, F., Cavallaro, A., Grasso, S. and Ferraro, A., (2016b): In Situ and Laboratory Tests for Site Response Analysis in the Ancient City of Noto (Italy); Proceedings of the 1st IMEKO TC4 International Workshop on Metrology for Geotechnics, Benevento, 17 - 18 March 2016, pp. 85 - 90.

Castelli, F., Cavallaro, A., Ferraro, A., Grasso, S. and Lentini, V., (2016c): A Seismic Geotechnical Hazard Study in the Ancient City of Noto (Italy); Proceedings of the 6th Italian Conference of Researchers in Geotechnical Engineering (CNRIG), Bologna, 22 - 23 September 2016, Procedia Engineering (2016), Vol. 158, pp. 535 - 540.

Castelli, F., Castellano, E., Contino, F., Lentini, V. (2016d): "A Web-based GIS system for landslide risk zonation: the case of Enna area (Italy)". Proceedings of 12TH International Symposium on Landslides, Napoli, Italy, June 12 - 19, 2016 ISBN 9781138029880.

Castelli, F., Grasso, S., Lentini, V., Massimino, M.R. (2016e): "In situ measurements for evaluating liquefaction potential under cyclic loading". 1st IMEKO TC4 International Workshop on Metrology for Geotechnics, MetroGeotechnics 2016. 2016, Pages 79-84.

Castelli, F., Cavallaro, A., Grasso, S., (2016f): "SDMT Soil Testing For The Local Site Response Analysis". 1st IMEKO TC-4 International Workshop On Metrology For Geotechnics. Benevento (Italy). March 17-18, 2016. ISBN: 978-92-990075-0-1, Pp. 143-148.

Castelli, F., Freni, G., Lentini, V., Fichera A. (2017): "Modelling of a debris flow event in the Enna area for hazard assessment. Proceedings of 1st International Conference on the Material Point Method, MPM 2017, Delft, January 10-13, 2017, Procedia Engineering 175 (2017), 287 - 292. DOI: 10.1016/j.proeng.2017.01.026.

Cavallaro, A., Ferraro, A., Grasso, S. and Maugeri, M., (2008): Site Response Analysis of the Monte Po Hill in the City of Catania; Proceedings of the 2008 Seismic Engineering International Conference Commemorating the 1908 Messina and Reggio Calabria Earthquake MERCEA'08, Reggio Calabria and Messina, 8 - 11 July 2008, pp. 240 - 251. AIP Conference Proceedings, Volume 1020, Issue PART 1, 2008, pp. 583 - 594.

Cavallaro, A., Ferraro, A., Grasso, S., Maugeri, M., (2012): "Topographic effects on the Monte Po Hill in Catania (Italy)". Soil Dynamics and Earthquake Engineering. 43, 2012: 97-113.

Cavallaro, A., Grasso, S., Maugeri, M. and Motta, E., (2013a): "An Innovative Low-Cost SDMT Marine Investigation for the Evaluation of the Liquefaction Potential in the Genova Harbour (Italy) "; Proceedings of the 4th International Conference on Geotechnical and Geophysical Site Characterization, ISC'4, Porto de Galinhas, 18 - 21 September 2012, Geotechnical and Geophysical Site Characterization 4, Vol. 1, 2013, pp. 415 - 422.

Cavallaro, A., Grasso, S., Maugeri, M. and Motta, E., (2013b): "Site Characterisation by in Situ and Laboratory Tests of the Sea Bed in the Genova Harbour (Italy)"; Proceedings of the 4th International Conference on Geotechnical and Geophysical Site Characterization, ISC'4, Porto de Galinhas, 18 - 21 September 2012, Geotechnical and Geophysical Site Characterization 4, Vol. 1, 2013, pp. 637 - 644.

Cavallaro, A., Grasso, S., Ferraro, A., (2016a): "Study on Seismic Response Analysis in "Vincenzo Bellini" Garden area by Seismic Dilatometer Marchetti Tests". 5th International Conference on Geotechnical and Geophysical Site Characterisation ISC'5. 5-9 September 2016, Queensland, Australia. ISBN: 978-0-9946261-0-3.

Cavallaro, A., Grasso, S. and Ferraro, A., (2016b): "A Geotechnical Engineering Study for the Safeguard, Restoration and Strengthening of Historical Heritage"; Proceedings of the 6th Italian Conference of Researchers in Geotechnical Engineering (CNRIG), Bologna, 22 - 23 September 2016, Procedia Engineering (2016), Vol. 158, pp. 134 - 139.

De Rubeis, V., Gasparini, C., Maramai, A. and Anzidei, M., (1991): “Il Terremoto Siciliano del 13 Dicembre 1990” (in italian); Proc. Contributi allo studio del Terremoto della Sicilia Orientale del 13 Dicembre 1990. National Institute of Geophysics, Roma.

Ferraro, A., Grasso, S., Maugeri, M., (2009): “Seismic vulnerability of a slope in central Italy”. WIT Transactions on the Built Environment, 110, pp. 345-355.

Ferraro, A., Grasso, S., Massimino, M.R., Maugeri, M., (2015): Influence of geotechnical parameters and numerical modelling on local seismic response analysis. Geotechnical Engineering for Infrastructure and Development - Proceedings of the XVI European Conference on Soil Mechanics and Geotechnical Engineering, ECSMGE 2015, 4, pp. 2183-2188.

Ferraro, A., Grasso, S., Maugeri, M., Totani, F. (2016): Seismic response analysis in the southern part of the historic centre of the City of L’Aquila (Italy). Soil Dynamics and Earthquake Engineering, 88, pp. 256-264.

Grasso, S., Maugeri, M., (2009): “The Road Map for Seismic Risk Analysis in a Mediterranean City”. Soil Dynamics and Earthquake Engineering. ISSN: 0267-7261. 29 (6), 2009: 1034-1045.

Grasso, S., Maugeri, M., (2009): “The Seismic Microzonation of the City of Catania (Italy) for the Maximum Expected Scenario Earthquake of January 11, 1693”. Soil Dynamics and Earthquake Engineering, 29 (6), 2009: 953-962.

Grasso, S., Maugeri, M., (2012): “The Seismic Microzonation of the City of Catania (Italy) for the Etna Scenario Earthquake (M=6.2) of February 20, 1818”. Earthquake Spectra. 28 (2), 2012: 573-594. ISSN: 8755-2930.

Grasso, S., Maugeri, M., (2014): “Seismic microzonation studies for the city of Ragusa (Italy)”. Soil Dynamics and Earthquake Engineering. ISSN: 0267-7261. 2014, (56): 86-97.

Idriss, I.M., Sun, J.I., (1992): User’s Manual for SHAKE91. Center for Geotechnical Modeling, Dept. of Civil & Environmental Engineering, Univ. of California, Davis, California.

Massimino M.R., Biondi G., (2015): “Some experimental evidences on dynamic soil-structure interaction”. 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, COMPDYN 2015. M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.). Crete Island, Greece, 25-27 May 2015. Code 113952. ISBN: 978-960-99994-7-2. pp. 2761-2774.

Maugeri M., Abate G., Massimino M.R., (2012): “Soil-Structure Interaction for Seismic Improvement of Noto Cathedral (Italy)”. Geotechnical, Geological and Earthquake Engineering, 16(2012): 217-239.

Schnabel, P, Seed, H.B,, Lysmer, J., (1972a): Modification of Seismograph Records for Effects of Local Soil Conditions. Bulletin of the Seismological Society of America; 62 (6): 1649-1664.

Schnabel, P,B,, Lysmer, J., Seed, H,B., (1972b): SHAKE: A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites. College of Engineering, University of California, Berkeley, California. Report No. EERC 72-12.

Tortorici, L., Monaco, C., Tansi, C., & Cocina, O. (1995): “Recent and active tectonics in the Calabrian arc (Southern Italy)”. Tectonophysics, 243(1), 37-55.

*CORRESPONDING AUTHOR: Salvatore GRASSO,
Department of Civil Engineering and Architecture (DICAr)
University of Catania, Catania, Italy;
email: sgrasso@dica.unict.it