SEISMIC MICROZONATION OF GROUND MOTION AND SITE EFFECTS: STATE OF DEVELOPMENT AND APPLICATIONS FOR ITALY

MICROZONACIÓN SÍSMICA DEL MOVIMIENTO TERRESTRE Y EFECTOS DEL SITIO: ESTADO DE DESARROLLO Y APLICACIONES PARA ITALIA

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ABSTRACT

Seismic microzonation is a more rational and general design approach, particularly for seismic regions, in which the design criteria are expressed in terms of achieving stated performance objectives. In this approach it is relevant the performance required to structures and to geotechnical works subjected to stated levels of seismic hazard, as well as the geotechnical constitutive model used to predict the performance. The parameters of the constitutive models are related in turn to soil properties. Earthquake hazard zonation in urban areas is the first and most important step towards a seismic risk analysis in densely populated Regions. The Seismic Microzonation is nowadays a world-wide accepted tool for the mitigation of seismic risk. It is a complex process involving different disciplines ranging from Geology and Applied Seismology to Geotechnical and Structural Engineering. The aim achieved in seismic hazard microzonation studies throughout the last 20 years performed at the presented typical case histories in Italy was to quantify the spatial variability of the site response on some typical historical scenario earthquakes that would be expected in the area. In order to quantify the expected ground motion, the manner in which the seismic signal is propagating through the subsurface was defined. Propagation was particularly affected by the local geology and by the geotechnical dynamic ground conditions. Large amplification of the seismic signals generally occurs in areas where layers of low seismic shear wave velocity overlie material with high seismic wave velocity, i.e. where soft sediments cover bedrock or more stiff soils. Therefore, essential key issue here is to obtain a good understanding of the local subsurface conditions. The study builds on the recent experience of seismic microzonation studies in Sicily (Italy), after the effects of the 2018 seismic sequence. Examples of ground response analysis are presented by using some 1-D and 2-D codes, including methodologies taking into account soil uncertainties for site characterisation.

RESUMEN

La microzonificación sísmica es un enfoque de diseño más racional y general, particularmente para regiones sísmicas, en el que los criterios de diseño se expresan en términos de lograr los objetivos de desempeño establecidos. En este enfoque es relevante el desempeño requerido para estructuras y trabajos geotécnicos sujetos a niveles establecidos de riesgo sísmico, así como el modelo constitutivo geotécnico utilizado para predecir el desempeño. Los parámetros de los modelos constitutivos se relacionan a su vez con las propiedades del suelo. La zonificación de peligro de terremoto en áreas urbanas es el primer y más importante paso hacia un análisis de riesgo sísmico en Regiones densamente pobladas. La Microzonificación Sísmica es hoy en día una herramienta mundialmente aceptada para la mitigación del riesgo sísmico. Es un proceso complejo que involucra diferentes disciplinas que van desde la geología y la sismología aplicada hasta la ingeniería geotécnica y estructural. El objetivo logrado en los estudios de microzonificación de peligros sísmicos a lo largo de los últimos 20 años realizados en las historias de casos típicas presentadas en Italia fue cuantificar la variabilidad espacial de la respuesta del sitio en algunos terremotos de escenarios históricos típicos que se esperarían en el área. Para cuantificar el movimiento del suelo esperado, se definió la forma en que la señal sísmica se propaga a través del subsuelo. La propagación se vio particularmente afectada por la geología local y por las condiciones dinámicas geotécnicas del terreno. La gran amplificación de las señales sísmicas generalmente ocurre en áreas donde capas de baja velocidad de onda de corte sísmico se superponen al material con alta velocidad de onda sísmica, es decir, donde los sedimentos blandos cubren el lecho rocoso o suelos más rígidos. Por lo tanto, la cuestión clave esencial aquí es obtener una buena comprensión de las condiciones locales del subsuelo. El estudio se basa en la experiencia reciente de estudios de microzonificación sísmica en Sicilia (Italia), después de los efectos de la secuencia sísmica de 2018. Se presentan ejemplos de análisis de respuesta del suelo utilizando algunos códigos 1-D y 2-D, incluidas las metodologías que tienen en cuenta las incertidumbres del suelo para la caracterización del sitio.

Keywords: Seismic Microzonation, Ground Motion, Site Effects.

Palabras clave: Microzonificación Sísmica, Movimiento del Suelo, Efectos del Sitio.

Highlights:

- Zoning for earthquake ground motions addresses one of the most fundamental aspects of seismic hazard assessment. In fact, the ground motion are directly related to the seismic forces acting on structures;
- During strong earthquakes the soil tends to behave as non-linear material. To take into account the soil non linearity, laws of shear modulus and damping ratio against strain have to be considered;
- The accuracy of zoning based on local site investigation data can be further enhanced using computer modelling of ground response.

Titulares:

- La zonificación de los movimientos del suelo en caso de terremoto aborda uno de los aspectos más fundamentales de la evaluación de peligros sísmicos. De hecho, el movimiento del suelo está directamente relacionado con las fuerzas sísmicas que actúan sobre las estructuras;
- Durante fuertes terremotos el suelo tiende a comportarse como material no lineal. Para tener en cuenta la no linealidad del suelo, se deben considerar las leyes del módulo de corte y la relación de amortiguamiento frente a la deformación;
- La precisión de la zonificación basada en los datos de investigación del sitio local se puede mejorar aún más mediante el modelado por computadora de la respuesta del terreno.

Abbreviations:

PSHA: probabilistic seismic hazard analysis.
DSHA: deterministic seismic hazard analysis.

1. Introduction

Zoning for earthquake ground motions addresses one of the most fundamental aspects of seismic hazard assessment. In fact, the ground motion are directly related to the seismic forces acting on structures [1-3].
The seismic hazard analysis can be performed by means of a deterministic or probabilistic evaluation. A PSHA determines the probability rate of exceeding of various levels of ground motion in a specified period of time, in a given area. Instead, the DSHA is based on modelling 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 seismogram [4-6].
The actual Italian seismic code NTC 2018 [7] links the seismic design actions on structures directly to the PSHA [8-9]. However, the DSHA confirms that peak ground acceleration values are larger than those given by the PSHA in area where large earthquake are observed [10-12].
This paper describes the results of numerical modeling studies in six municipalities located in the region of Sicily (Italy). It was affected in the past by some destructive earthquakes (1169, 1693, 1783, 1818 and

1908) that damaged a large territory of Sicily [13-16]. In order to determine the soil profile and geotechnical characteristics, laboratory and in situ investigations have been performed in 8 test sites. Local site response analyses have been carried out using 1-D linear equivalent code STRATA [17] assuming geometric and geological models of substrate as 1-D physical models. During strong earthquakes the soil tends to behave as non-linear material. To take into account the soil non linearity, laws of shear modulus and damping ratio against strain have been also inserted in the code.

2. Study Areas

Site response analyses have been developed for six municipalities (Alì Terme, Termini Imerese, Campofelice di Roccella, Finale di Pollina, Trabia and Cefalù) of Messina (ME) and Palermo (PA) provinces in Sicily (Figure 1).

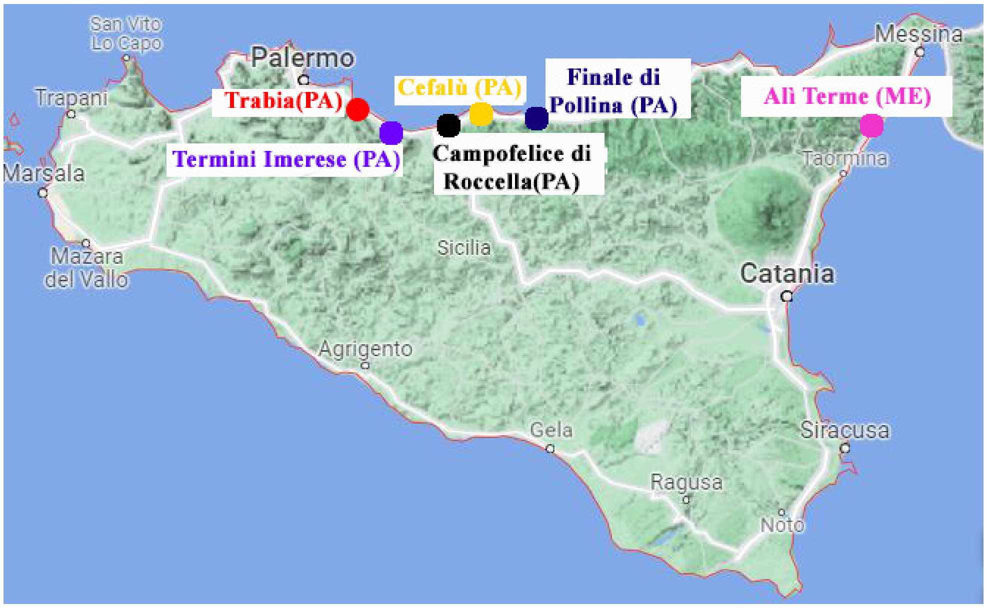
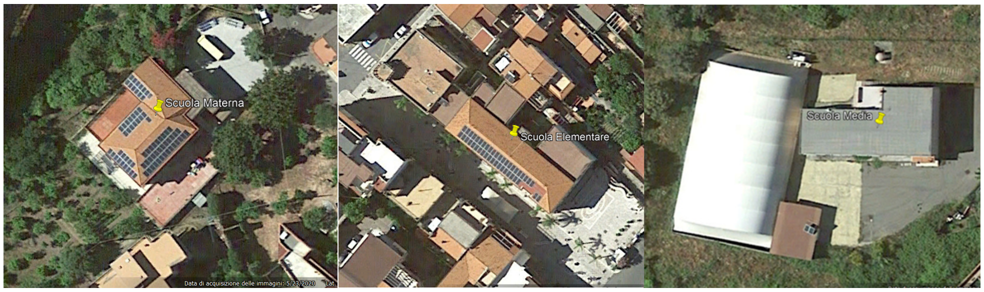


Fig. 1. Study Areas

In particular, three different test sites have been selected for Alì Terme municipality (ME): the Nursery School in M. Teresa Federico Street, the "Nino Prestia" Elementary School and the "Stefano D'Arrigo" Middle School (Figure 2).



(a) (b) (c)

Fig. 2. Tests sites for Alì Terme (ME): a) Nursery School in M. Teresa Federico Street; b) "Nino Prestia" Elementary School; c) "Stefano D'Arrigo" Middle School.

The seismic event that occurred in December 1908 has been chosen as scenario earthquake for these test sites. The Southern Calabria-Messina earthquake (Intensity MSC XI, Mw 7.24) was the strongest seismic event of the 20th century in Italy with the most ruinous in term of casualties (at least 80,000) [11]. Figure 3 shows the intensity map for 1908 earthquake.

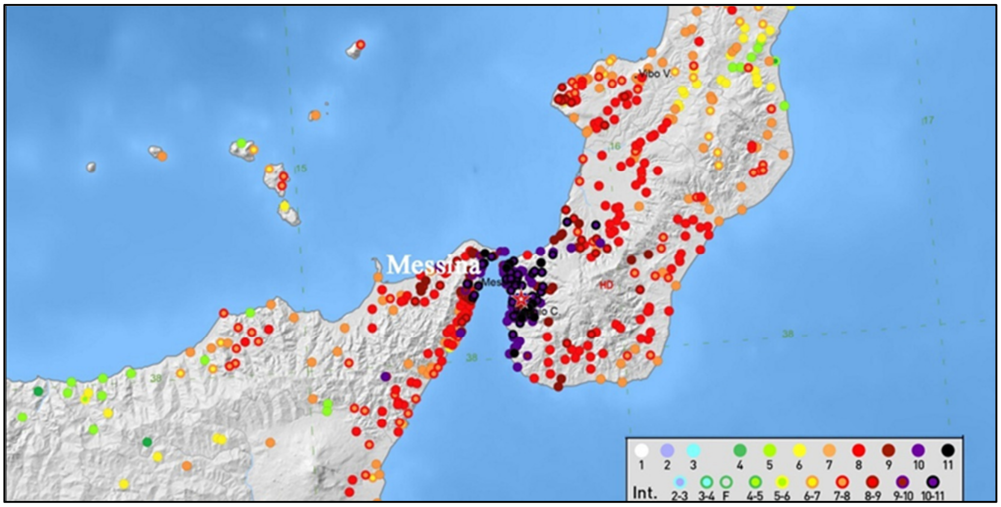


Fig. 3. Intensity map. Earthquake of December 28, 1908 (After [19-20])

3. Geotechnical Soil Properties

In order to evaluate geotechnical characteristics of the soil, an intensive geotechnical site characterization has been carried out in each of the 8 test sites.

Geotechnical investigations performed in the three test sites of Alì Terme (ME) include: n. 3 active MASW tests, n. 1 seismic refraction test, n. 2 dynamic penetrometric tests, n. 1 HVSR test, n. 2 electrical tomographies. Results of the MASW test obtained for the Nursery School in M. Teresa Federico Street, as an example, are reported in Table 1.

n.	Depth [m]	Thickness [m]	V_P [m/s]	V_S [m/s]
1	4.98	4.98	340.9	208.8
2	9.13	4.15	419.8	257.1
3	14.80	5.67	636.8	390.0
4	22.31	7.52	760.3	456.6
5	31.04	8.73	814.4	198.7
6	∞	∞	1399.6	857.1

Table 1: Results of the MASW test obtained for the Nursery School in M. Teresa Federico Street

Proceeding from the surface in depth, it has been possible to define the following soil stratigraphy in all of the three test sites: vegetation layer, alluvial deposits and alum conglomerates.

The types of tests performed are the same for the five municipalities of the Palermo province (Termini Imerese, Campofelice di Roccella, Finale di Pollina, Trabia and Cefalù). In fact, for each site, a borehole has been carried out, with undisturbed soil sampling. All boreholes have been also equipped in order to perform a Down Hole (D-H) test.

As an example, Figure 4 shows the location of the borehole in the municipality of Termini Imerese. Moreover, Figure 5 reports the shear wave velocities against depth obtained by D-H test.

Fig. 4. Borehole location in the municipality of Termini Imerese (PA)

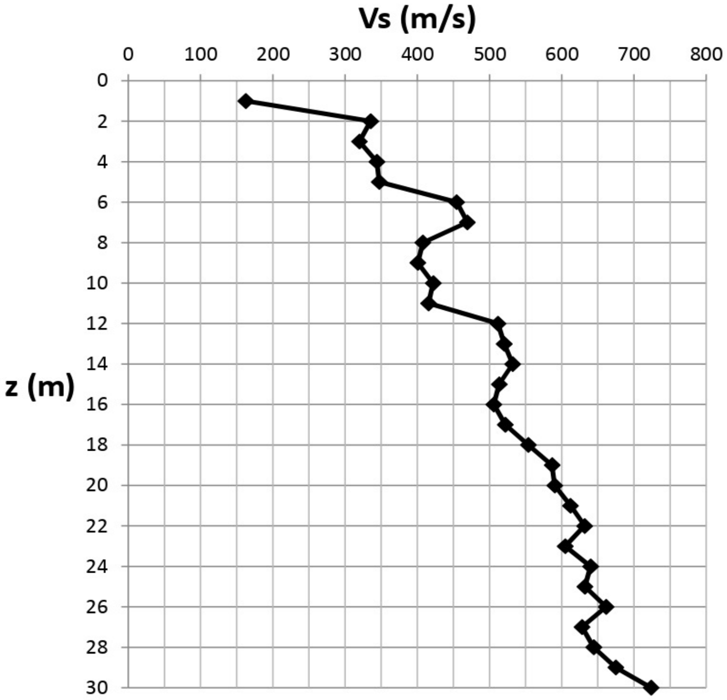


Fig. 5. V_S profile obtained by D-H test performed in S1.

In order to consider the degradation of the shear modulus and the increase of the damping ratio with the shear strain levels, Equations (1) and (2) suggested by Yokota et al. [21], calibrated to the soil under consideration, have been used.

$$\frac{G(\gamma)}{G_0} = \frac{1}{1+\alpha\gamma(\%)^{\beta}} \qquad (1)$$

in which: G(γ) = strain dependent shear modulus; γ = shear strain; α,β= soil constants.

$$D(\gamma)(\%) = \eta exp\left[-\lambda\frac{G(\gamma)}{G_0}\right] \qquad (2)$$

in which: D(γ) = strain dependent damping ratio; γ= shear strain; η, λ = soil constants.
The G-γ and D-γ curves are reported in Table 2 and in Figures 6-7.

Curve	**α**	**β**	**η**	**λ**
1	7.5	0.897	90	4.5
2	6.9	1	23	2.21
3	16	1.2	33	2.4
4	linear	linear	linear	linear
5	9	0.815	80	4
6	20	0.87	19	2.3
7	22	1.05	10	1.05

Table 2: G- γ and D- γ curves used for site response analyses

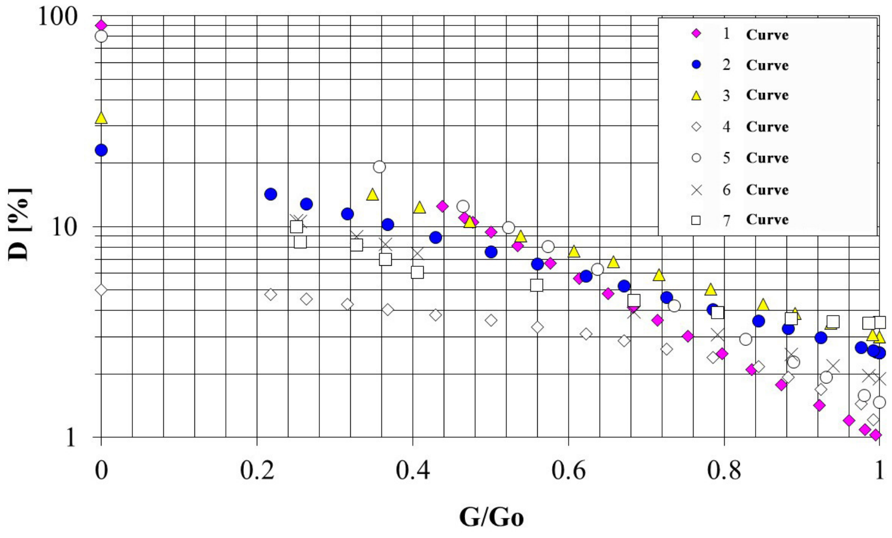


Fig. 6. D [%]-G/G_0 curves used for site response analyses

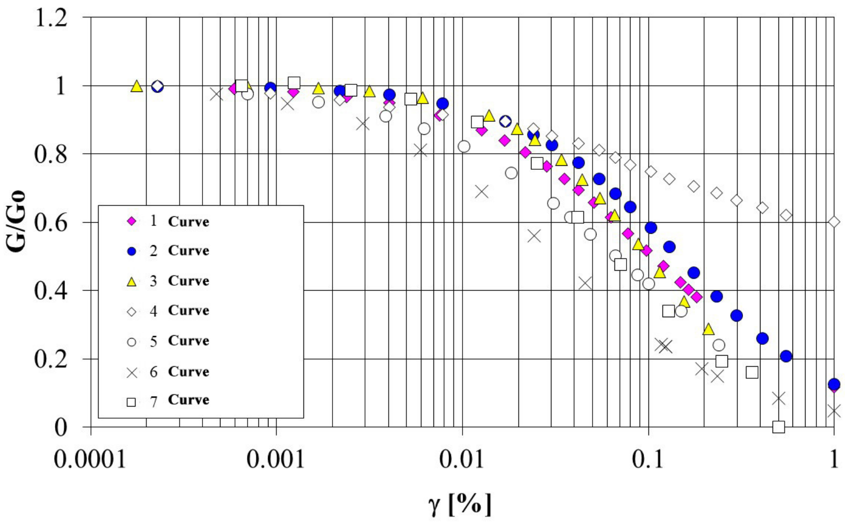


Fig. 7. G/G_0- γ curves used for site response analyses

4. Seismic ground response

Local site effects can be defined as the modification of predicted rock outcrop "reference" motions to give actual motions at the local site in question. The accuracy of zoning based on local site investigation data can be further enhanced using computer modelling of ground response [1-2].
The analyses of the ground motion have been conducted in three main phases: the definition of the geometric and geotechnical model, the definition of the seismic inputs and the analysis of the results.

4.1. Geometric and geotechnical model

Local site response analyses have been performed using 1-D linear equivalent code STRATA. The shear wave velocity plays a fundamental role in seismic analyses. The V_S profiles used for soil response analyses are obtained from geophysical tests described in Paragraph 3. The value of the other parameters have been taken from the geotechnical characterization obtained through in situ and laboratory tests. The soil model for Termini Imerese, as an example, is shown in Table 3.

Layer	Depth [m]	Thickness [m]	V_S [m/s]	G/γ-D/γ	γ [kN/m^3]
1	0	1	163	6	22.8
2	1	1	336	6	22.8
3	2	1	320	2	22.8
4	3	1	344	2	22.8
5	4	1	347	2	22.8
6	5	1	455	1	22.8
7	6	1	469	1	22.8
8	7	1	408	6	22.8
9	8	1	401	6	22.8
10	9	1	422	6	22.8
11	10	1	416	6	22.8

12	11	1	512	2	22.8
13	12	1	520	2	22.8
14	13	1	532	2	22.8
15	14	1	513	2	22.8
16	15	1	506	2	22.8
17	16	1	522	2	22.8
18	17	1	554	2	22.8
19	18	1	587	2	22.8
20	19	1	590	2	22.8
21	20	1	612	2	22.8
22	21	1	632	2	22.8
23	22	1	605	2	22.8
24	23	1	640	2	22.8
25	24	1	632	2	22.8
26	25	1	661	2	22.8
27	26	1	628	2	22.8
28	27	1	644	2	22.8
29	28	1	675	2	22.8
30	29	1	724	2	22.8
31	30	1	755	2	22.8
32	31	1	770	2	22.8
33	32	1	786	2	22.8
34	33	-	802	BEDROCK	23.0

Table 3: Soil Model for Termini Imerese

4.2. Seismic Inputs

Numerical analyses have been carried out for Alì Terme (ME) using six input seismograms obtained by a source modeling of 1908 Messina and Reggio Calabria earthquake [22-24], scaled to the value of 0.332 g [4], provided by the Italian seismic code [7].

NTC 2018 [7] links the seismic design actions on structures directly to the PSHA. The Istituto Nazionale di Geofisica e Vulcanologia [INGV] (http://esse1-gis.mi.ingv.it) evaluated probabilistic seismic hazard for each node of a regular grid that covers the Italian territory. This resulted in hazard curves in terms of PGA, disaggregation data and spectral accelerations, Sa(T). Hazard curves are lumped in nine probabilities of exceedance in 50 years (2%, 5%, 10%, 22%, 30%; 39%, 50%, 63% and 81%) [8-9, 25].

The disaggregation data for Termini Imerese (as an example), shown in Figure 8, have been obtained considering a probability of excess of 10% in 50 years (return period of 475 years).

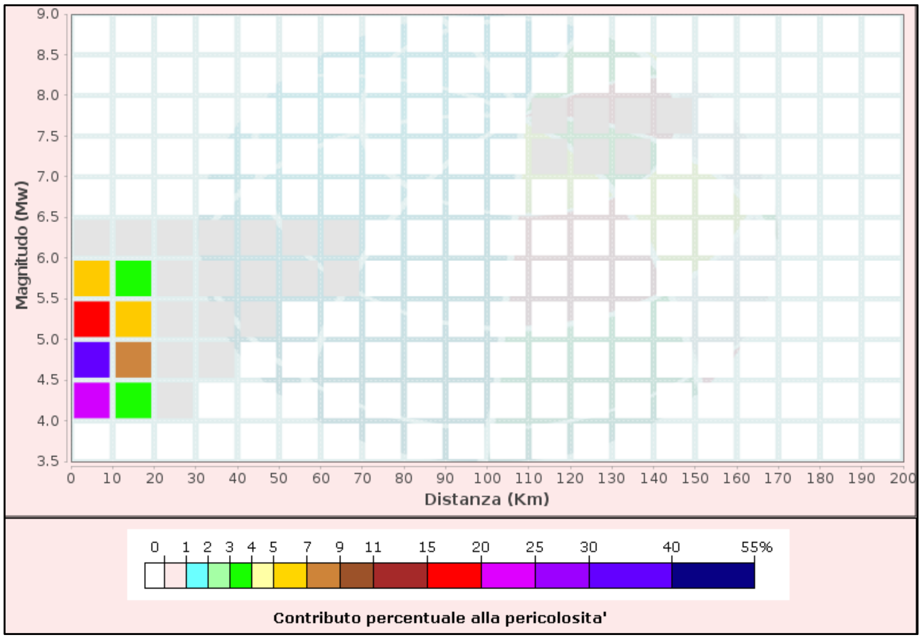


Fig. 8. Disaggregation data for Termini Imerese obtained from *http://esse1-gis.mi.ingv.it*

REXEL v. 3.5 (http://www.reluis.it) allows to search for suites of waveforms, from the European Strong-motion Database, compatible to reference spectra according to the new Italian seismic code [7].
The input parameters used in REXEL v. 3.5 are summarized in Table 4.

Target	NTC18-Italian Building Code (D.M. 2018)
Latitudine	37.97965
Longitudine	13.70369
Soil Type	A
Nominal life	50 years
Functional type	II
Limit State	SLV
Preliminary	
Component	One horizontal component
Soil Type	A
T_1[s]	0.1
T_2[s]	1.0
Criterion	Magnitude-distance
Minimum event magnitude	4.0
Maximum event magnitude	6.5
Minimum epicentral distance [km]	0
Maximum epicentral distance [km]	20
Matching	
Lower tol. [%]	10
Upper tol. [%]	30
T_1[s]	0.1
T_2[s]	1.0
Additional tolerance [%]	0
Set size	7
Number of combinations	10

Table 4: Input parameters used in REXEL v. 3.5

Table 5 and Figure 9 report suites of waveforms compatible to the reference spectra [5] for Termini Imerese, as an example.

Waveform ID	Earthquake ID	Station ID	Earthquake Name	Date	Mw	Epicentral Distance [km]	Site class
982	72	ST309	Friuli (aftershock)	16/09/1977	5.4	9	A
4675	1635	ST2487	South Iceland	17/06/2000	6.5	13	A
242	115	ST225	Valnerina	19/09/1979	5.8	5	A
6115	2029	ST1320	Kozani	13/05/1995	6.5	17	A
5079	1464	ST2552	Mt. Hengill Area	04/06/1998	5.4	6	A
670	291	ST238	Umbria Marche (aftershock)	06/10/1997	5.5	20	A
4674	1635	ST2486	South Iceland	17/06/2000	6.5	5	A
mean					5.9	10.7	

Table 5: Combination of waveforms obtained from REXEL v. 3.5. for site response analyses

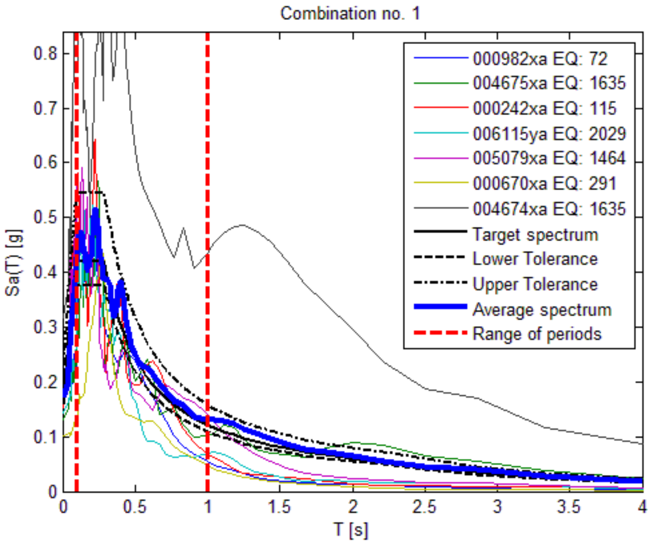
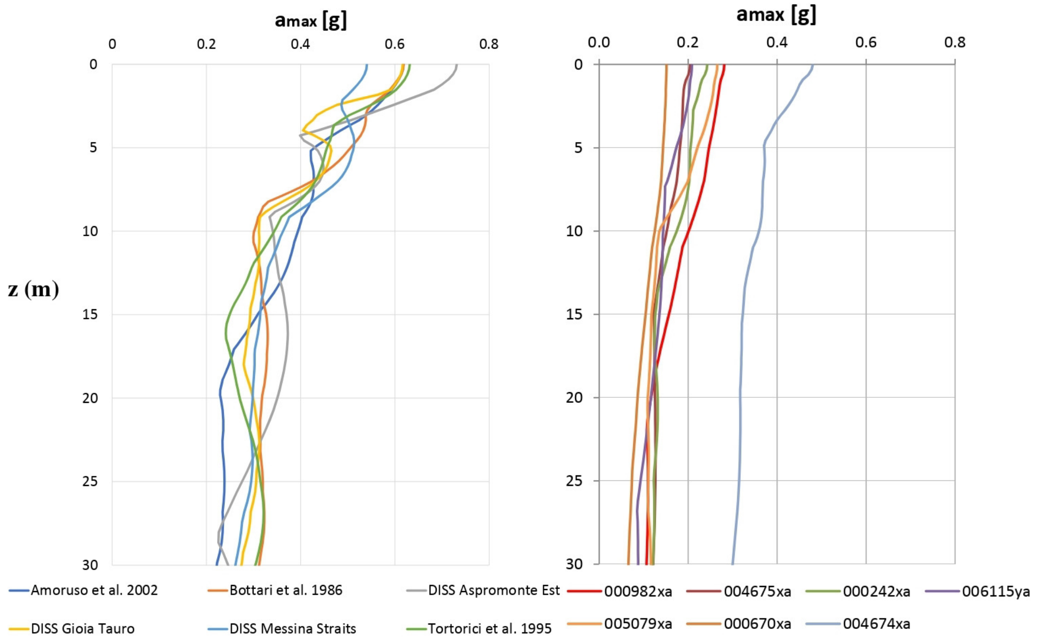


Fig. 9. Combination of waveforms obtained from REXEL v. 3.5. for site response analyses

4.3. Results

The soil dynamic response has been investigated in terms of accelerations, response spectra and amplification functions for the 8 site tests. The numerical results from analyses are shown in Figure 10 for the Nursery School in Alì Terme (Fig. 2 a)) and for Termini Imerese (Fig. 4), as examples, describing maximum accelerations with depth using the 1908 seismograms and the set of accelerograms obtained from REXEL v. 3.5.



(a) (b)

Fig. 10. Maximum accelerations with depth: a) for the Nursery School in Alì Terme (ME) using the 1908 seismograms; b) for Termini Imerese using the set of accelerograms obtained from REXEL v. 3.5.

Values of the surface maximum accelerations and soil amplification factors R for the Nursery School in Alì Terme and for Termini Imerese are reported in Tables 6 and 7, respectively.

	Amoruso et al. [22]	Bottari et al. [24]	DISS Aspomonte Est	DISS Gioia Tauro	DISS Messina Straits	Tortorici et al. [23]
PGA_{input}	0.332 g	0.332g	0.332 g	0.332 g	0.332 g	0.332 g
PGA_{output}	0.618 g	0.618 g	0.729g	0.618 g	0.541 g	0.636 g
R= $PGA_{output/}$ PGA_{input}	1.86	1.86	2.20	1.86	1.63	1.92

Table 5: Values of the surface maximum accelerations and soil amplification factors for the Nursery School in Alì Terme

	00982xa	004675xa	000242xa	006115ya	005079xa	000670xa	004674xa
PGA_{input}	0.19 g	0.13 g	0.15 g	0.14 g	0.17 g	0.10 g	0.32 g
PGA_{output}	0.28 g	0.20 g	0.24 g	0.21 g	0.27 g	0.15 g	0.48 g
R= $PGA_{output/}$ PGA_{input}	1.47	1.55	1.58	1.47	1.53	1.49	1.51

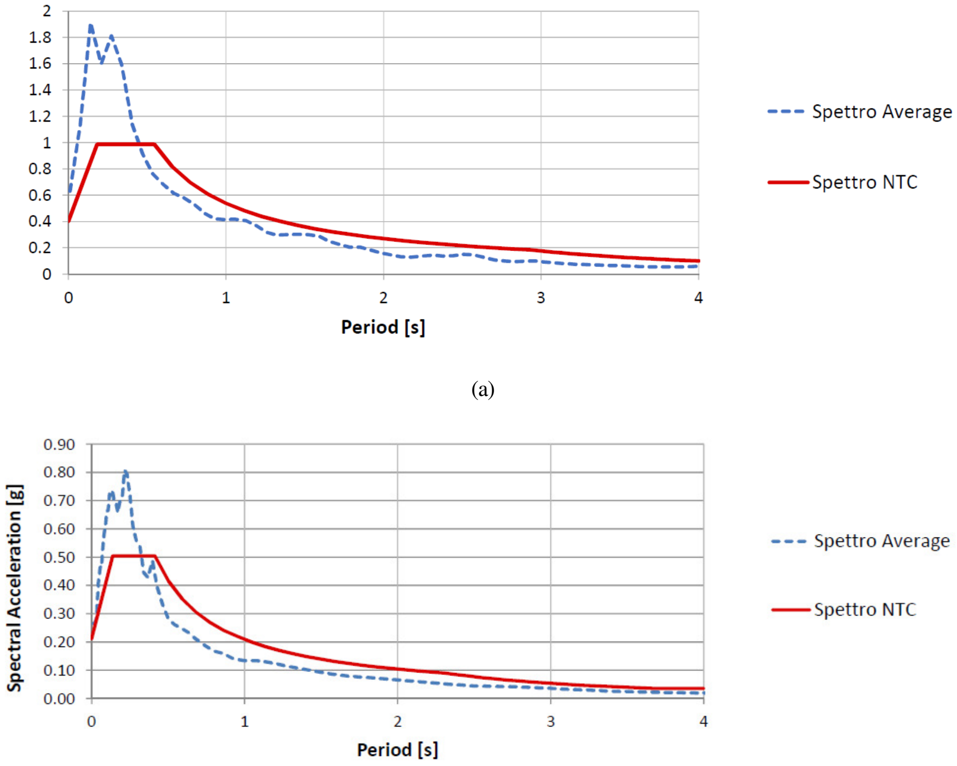
Table 6: Values of the surface maximum accelerations and soil amplification factors for Termini Imerese

In both cases, soil amplification factors obtained from site response analyses are greater than amplification values provided by Italian technical code [7], equal to 1.21 and 1.20, for Alì Terme and Termini Imerese, respectively. Smallest values of R have been found for Termini Imerese using the set of accelerograms obtained from REXEL v. 3.5.

In Figure 11, the results are presented in term of mean response spectrum at the surface for the Nursery School in Alì Terme (Fig. 11 a)) and for Termini Imerese (Fig. 11 b)), obtained by setting a structural damping of 5%. For comparison, elastic response spectra provided by the Italian seismic code [4] are also shown.

Considering the results obtained for the Nursery School in Alì Terme, the maximum spectral acceleration $S_{e,max}$ = 1.91 g at T = 0.14 s is obtained, while, for the Termini Imerese, the maximum spectral acceleration $S_{e,max}$ = 0.81 g at T = 0.22 s is found.

Furthermore, for periods greater than 0.54 s for Alì Terme and 0.34 s for Termini Imerese, the elastic response spectra provided by NTC 2018 [7] are more conservative than those obtained from numerical analyses.

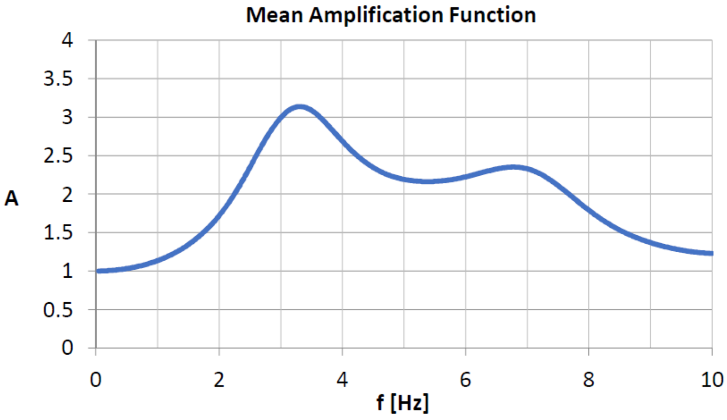


(a)

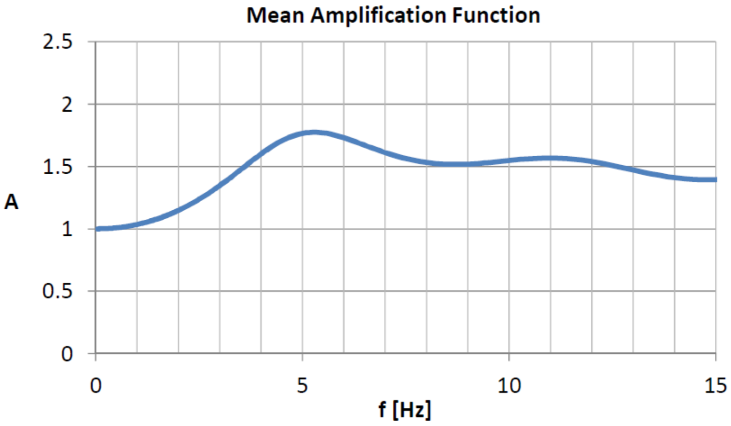
(b)

Fig. 11. Comparison between the elastic response spectra obtained by numerical analyses and the same provided by NTC 2018 [51]: (a) for the Nursery School in Alì Terme; (b) for Termini Imerese.

Finally, Figure 12 shows the mean amplification function A(f) evaluated as the ratio between the Fourier spectrum at the surface level and the Fourier spectrum of the input motions applied at the base of the models. It is possible to observe that that the main resulting frequencies are equal to: f(I) = 3.3 Hz and f(II) = 6.9 Hz for Alì Terme and f(I) = 5.2 Hz and f(II)= 11.1 Hz for Termini Imerese.



(a)



(b)

Fig. 12. Amplification functions obtained by numerical modelling: (a) for the Nursery School in Alì Terme; (b) for Termini Imerese.

5. Conclusions

Zoning for ground motion is an essential part of the information necessary to evaluate the overall nature of geotechnical hazards. Earthquake ground motions are affected by several factors such as source, path and site effects. The accuracy of zoning based on local site investigation data can be further enhanced using computer modelling of ground response.

This study has benefited of a great availability of borehole date, geophysical survey and laboratory tests carried out in 8 test sites. Numerical analyses have been carried out by 1-D linear equivalent computer code STRATA. The dynamic response has been investigated in terms of accelerations, response spectra, and amplification functions. Results of the site response analyses show high values in soil amplification effects. Moreover, soil amplification factors obtained from site response analyses are greater than amplification values provided by Italian technical code. Finally, mean response spectra at the ground surface have been compared with the reference elastic response spectra, provided by NTC 2018.

6. Acknowledgments

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7. References

[1] S. Grasso, and M. Maugeri, "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): 953-962, https://doi.org/10.1016/j.soildyn.2008.11.006, 2009.

[2] S. Grasso, and M, Maugeri, "The Seismic Microzonation of the City of Catania (Italy) for the Etna Scenario Earthquake (M=6.2) of February 20, 1818", Earthquake Spectra, Vol. 28 (2): 573-594, https://doi.org/10.1193/1.4000013, 2012.

[3] S. Grasso and M. Maugeri "Seismic Microzonation Studies for the City of Ragusa (Italy)" Soil Dynamics and Earthquake Engineering. ISSN: 0267-7261. Vol. 56 (2014): 86–97. DOI: 10.1016/j.soildyn.2013.10.004, 2014.

[4] A. Ferraro, S. Grasso, M.R. Massimino, "Site effects evaluation in Catania (Italy) by means of 1-D numerical analysis", Ann. Geophys., 61. 2018.

[5] A. Cavallaro, P.P Capilleri, S. Grasso, S. "Site characterization by dynamic in situ and laboratory tests for liquefaction potential evaluation during Emilia Romagna earthquake" Geosciences (Switzerland). Open Access, Volume 8, Issue 7, number 242, 2018.

[6] A. Cavallaro, F. Castelli, A. Ferraro, S. Grasso, V. Lentini "Site Response Analysis for the Seismic Improvement of a Historical and Monumental Building: The Case Study of Augusta Hangar" Bull. Eng. Geol. Environ. 2018, 77, 1217–1248.

[7] NTC D.M. New Technical Standards for Buildings. 2018. Available online: https://www.gazzettaufficiale.it/eli/gu/2018/02/20/42/so/8/sg/pdf

[8] I. Iervolino, C. Galasso, E. Cosenza, "REXEL: computer aided record selection for code-based seismic structural analysis" , Bull. Earthquake Eng. 8:339-362, DOI 10.1007/s10518-009-9146-1, 2010

[9] I. Iervolino, E. Chioccarelli, V. Convertito "Engineering design earthquakes from multimodal hazard disaggregation, Soil Dynamics and Earthquake Engineering" 1212–1231, 2011

[10] S. Grasso S, M.R. Massimino, M.S.V Sammito "New Stress Reduction Factor for Evaluating Soil Liquefaction in the Coastal Area of Catania (Italy)" Geosciences, 11, 12, https://doi.org/10.3390/geosciences11010012, 2021.

[11] F. Castelli, S. Grasso, V. Lentini, M.S.V. Sammito MSV "Effects of Soil-Foundation-Interaction on the Seismic Response of a Cooling Tower by 3D-FEM Analysis" Geosciences 2021, 11, 200. https://doi.org/ 10.3390/geosciences11050200, 2021.

[12] A. Ferraro, S. Grasso, M. Maugeri, F. Totani "Seismic response analysis in the southern part of the historic centre of the City of L'Aquila (Italy)" Soil Dyn. Earthq. Eng., 88, 256–264, 2016.

[13] F. Castelli, A. Cavallaro, A. Ferraro, S. Grasso "In situ and laboratory tests for site response analysis in the ancient city of Noto (Italy)" 1st IMEKO TC4 International Workshop on Metrology for Geotechnics, MetroGeotechnics: 85-90. ISBN: 978-929900750-1, 2016

[14] S. Caruso, A. Ferraro, S. Grasso and M.R. Massimino "Site Response Analysis in eastern Sicily based on direct and indirect Vs measurements" 1st IMEKO TC4 International Workshop on Metrology for Geotechnics, MetroGeotechnics: 115-120. ISBN: 978-929900750-1, 2016.

[15] F. Castelli, A. Cavallaro, A. Ferraro, S. Grasso, V. Lentini and M.R. Massimino, "Static and dynamic properties of soils in Catania (Italy)" Annals of Geophysics, Vol. 61, Issue 2. Article number SE221. ISSN: 15935213, DOI: 10.4401/ag-7706, 2018

[16] F. Castelli, A. Cavallaro and S. Grasso "SDMT soil testing for the local site response analysis" 1st IMEKO TC4 International Workshop on Metrology for Geotechnics, MetroGeotechnics: 143-148, 2016.

[17] A.R. Kottke, E.M. Rathje, " Technical Manual for STRATA", PEER Report 2008/10; Univ. of California: Berkeley, CA, USA, 2008.

[18] F. Castelli, A. Cavallaro, A. Ferraro, S. Grasso, V. Lentini, M.S. Massimino, "Dynamic characterisation of a test site in Messina (Italy)", Ann Geophys 61(2):222, 2018.

[19] E. Guidoboni, G. Ferrari, D. Mariotti, A. Comastri, G. Tarabusi, G. Sgattoni, G. Valensise, "CFTI5Med, Catalogue of Strong Earthquakes in Itali (461 B.C.-1997) and Mediterranean Area (760 B.C.-1500)", INGV, https://doi.org/10.6092/ingv.it-cfti5 , 2018.

[20] E. Guidoboni, G. Ferrari, G. Tarabusi, G. Sgattoni, A. Comastri, D. Mariotti, C. Ciuccarelli, M.G. Bianchi, G. Valensise "CFTI5Med, the new release of the catalogue of strong earthquakes in Italy and in Mediterranean area", Scientific Data 6, Article number: 80. http://doi.org/10.1038/s41597-019-0091-9, 2019.

[21] K. Yokota, T. Imai, and M. Konno, "Dynamic Deformation Characteristics of Soils Determined by Laboratory Tests" OYO Tec. Rep. 3: 13 – 37, 1981.

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

[23] L. Tortorici, C. Monaco, C. Tansi, O. Cocina "Recent and active tectonics in the Calabrian arc (Southern Italy)", Tectonophysics, 243(1), 37-55, 1995.

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

[25] M. Stucchi, C. Meletti, V. Montaldo, H. Crowley, G. M. Calvi, E. Boschi "Seismic Hazard Assessment (2003-2009) for the Italian Building Code", Bull. Seismol. Soc. Am. 101(4), 1885-1911. DOI: 10.1785/0120100130, 2011.