Analysis of local seismic response in the historical city centre of Nafplio (Greece)

Antonielli Benedetta - Department of Earth Sciences and CERI Research Centre for Geological Risks, Sapienza University of Rome, Italy, benedetta.antonielli@uniroma1.it

Bozzano Francesca - Department of Earth Sciences and CERI Research Centre for Geological Risks, Sapienza University of Rome, Italy, francesca.bozzano@uniroma1.it

Ciampi Paolo - Department of Earth Sciences and CERI Research Centre for Geological Risks, Sapienza University of Rome, Italy, paolo.ciampi@uniroma1.it

Fiorucci Matteo - Department of Earth Sciences and CERI Research Centre for Geological Risks, Sapienza University of Rome, Italy, matteo.fiorucci@uniroma1.it

Iannucci Roberto - Department of Earth Sciences and CERI Research Centre for Geological Risks, Sapienza University of Rome, Italy, roberto.iannucci@uniroma1.it

Inciocchi Daniele - Department of Earth Sciences and CERI Research Centre for Geological Risks, Sapienza University of Rome, Italy, daniele.inciocchi@uniroma1.it

Karastathis Vassilis - Geodynamic Institute of Athens, Athens, Greece, karastathis@noa.gr

Maniatakis Charilaos - Department of Geotechnical Engineering, National Technical University of Athens, Athens, Greece, chamaniatakis@gmail.com

Martino Salvatore - Department of Earth Sciences and CERI Research Centre for Geological Risks, Sapienza University of Rome, Italy, salvatore.martino@uniroma1.it

Mouzakiotis Aggelos - Geodynamic Institute of Athens, Athens, Greece, aggelmo@noa.gr

Rivellino Stefano - Department of Earth Sciences and CERI Research Centre for Geological Risks, Sapienza University of Rome, Italy, stefano.rivellino@uniroma1.it

Saroglou Charalampos - Department of Geotechnical Engineering, National Technical University of Athens, Athens, Greece, saroglou@central.ntua.gr

Tsirogianni Athina - Department of Geotechnical Engineering, National Technical University of Athens, Athens, Greece, athinatsiro@hotmail.com

Spyrakos Constantine - School of Civil Engineering, National Technical University of Athens, Athens, Greece, cspyrakos@gmail.com

Abstract: Local seismic response analysis represents a fundamental tool for assessing the seismic risk of urban areas and Cultural Heritage (CH) sites, nevertheless several open questions remain when complex geological contexts are considered. This study has been carried out in the framework of the research project STABLE (H2020 RISE-Marie Curie Action) which has the aim of evaluating the seismic action on CH sites in the Mediterranean basin. One of them being the city of Nafplio (Greece), a site characterised by a peculiar geological setting and a medium-high regional seismic hazard. Geological and geophysical data have been collected to reconstruct both the subsoil model and the seismotectonic conditions. Several seismic ambient noise measurements were carried out to establish the site resonance frequency and to validate engineering-geological cross-sections for numerical modelling of the seismic wave propagation. Combined engineering-geological, geophysical and numerical modelling allowed evaluating the local seismic response of the urban area of Nafplio, providing a zonation map with homogeneous seismic response zones for which elastic response spectra will be obtained.

Keywords: engineering-geological model; geophysical investigations; local seismic response; seismic numerical modelling

1. Introduction

Mediterranean cultural heritage resources include mostly urban landscapes and historical centres often showing a high density of population, and continuously impacted by both human-induced and natural hazards, first of all, the seismic hazard.

The damages on the historical cities due to seismic shaking mainly depend on the possible amplification phenomena of the seismic waves that caused local site effects (Sextos et al., 2018) that can differ in a very relevant way from one area to another. The cultural heritage sites and historical monumental buildings represent vulnerable assets that need to be protected and carefully monitored for seismic risk mitigation. Therefore, the local seismic response analysis represents a fundamental task, that can be preparatory to perform a structural stability analysis of the historical buildings, in terms of their seismic vulnerability, for specific possible earthquake scenarios.

This study has been developed in the framework of the project PRIN 2017 (Research Projects Of Relevant National Interest), named "URGENT" - Urban Geology and Geohazards: Engineering geology for safer, resilieNt and smart ciTies, and in the framework of an H2020-RISE project, named "STABLE" - Structural stABLity risk assEsment (www.stable-project.eu). The first one concerns the issue of multi-hazard in urban contexts with the aim of defining the space-time distribution of the geological hazards that interact with urban contexts, and the second one concerns the cultural heritage protection in the peri-mediterranean area and in particular the evaluation of the seismic action on some sites of historical and cultural interest in the Mediterranean basin through the construction of geological models of the subsoil and vulnerability analysis of the historic buildings. The historical city centre of Nafplio (Greece) represents a very interesting test site to perform a seismic response analysis, as it provided the opportunity to investigate a complex geological condition in an area affected by medium-high seismic hazard. Nafplio is a seaport city of considerable tourist and cultural importance, located on the head of the Argolic Gulf, in the northeastern Peloponnese, Greece. Nafplio is the capital of the Argolis Municipality, and its old town (historical centre) was the second capital of the First Hellenic Republic and of the Kingdom of Greece, from 1827 until 1834.

The seismic wave propagation models simulate the propagation of seismic waves from the seismic bedrock to the surface and are strictly related to the physical and mechanical properties of the lithologies as well as to the geometrical features of topography and buried geological bodies. For this reason, the precision and the effectiveness of local seismic response studies are directly related to the accuracy of the engineering-geological reconstruction of the near surface subsoil, as it allows to evaluate the expected seismic site effects and the influence of the local site conditions that are important for quantifying the ground motion. The local seismic response study was performed for the Nafplio area according to the following main steps of analysis: i) seismic hazard assessment, ii) engineering-geological modelling with surveys and geophysical investigations, iii) seismic response numerical modelling.

2. Seismic hazard of the study area

Recent seismicity in the Argolis region, where the Nafplio city is located, is characterised mostly by medium-low magnitude events (M<5). Some events with higher magnitudes appear further to the NNE, in the Athikia fault zone and towards the North, within the Gulf of Corinth, which shows significant seismic activity. According to the earthquake catalogue by Papazachos and Papazachou (2003), several seismic events affected the ancient buildings of the old town of Nafplio during historical times. The maximum registered magnitudes are around 6 of Richter scale, with shallow hypocenters from three known major faulted zones (Fig. 1; Papazachos and Papazachou, 2003). These zones are related to the bigger historical earthquake events of the Argolis peninsula and are the following:

• Iria fault ("Argos" fault): M 6.4; last earthquake: 27 June 1769, that caused serious damages to Nafplio castle.

• Epidaurus fault (Eastern continuation of the tectonic lineament of the Iria fault): M 6.3; last earthquake: 20 March 1837.

• Xylokastro fault (south coast of Corinthian gulf): M 6.7; last earthquake: 21 February 1742.

According to the last modification of the Greek Earthquake Resistance Regulation, the wider area is classified in the category I of seismic hazard, with seismic acceleration of 0.16 g. Anyhow, as the urban area of Nafplio is built on soft soil sediments and on a relief, it is important to evaluate possible amplification effects of the seismic waves (Georgiou and Galanakis, 2010) by performing a site-specific seismic response study.

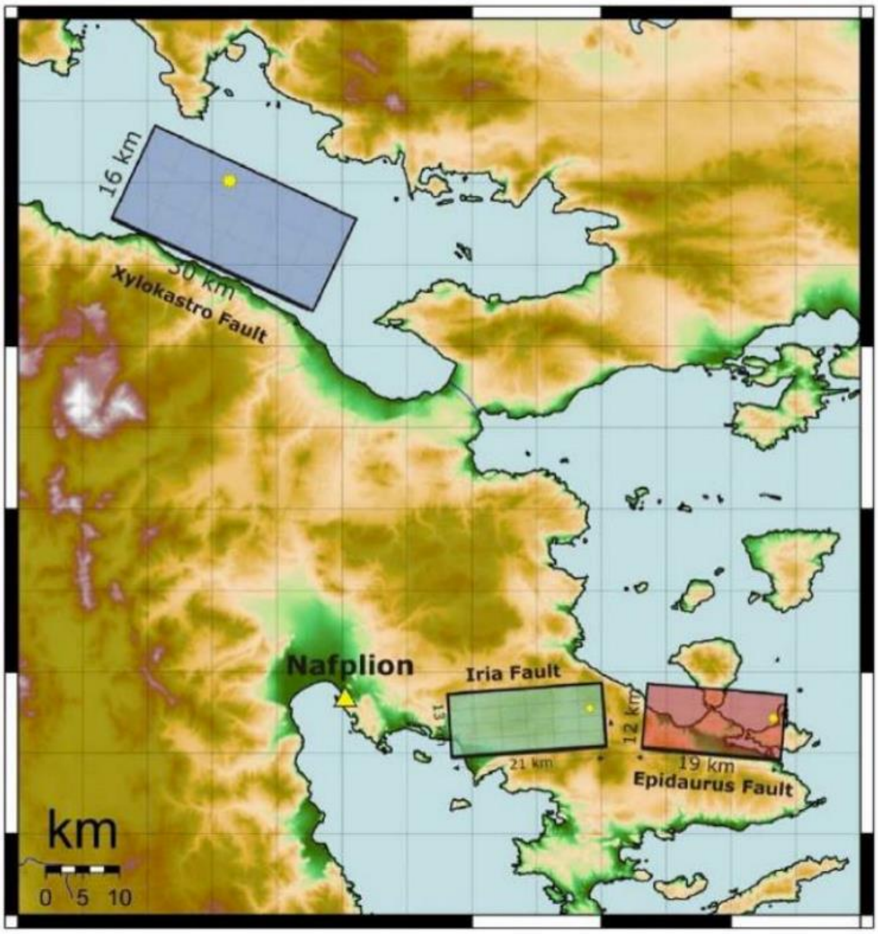

Fig. 1. Seismogenic sources of Argolis (Greece; from Karastathis et al., 2010). The three rectangles represent the simplified surface projection of the seismogenic sources. The thicker side of each rectangle corresponds to the trace of the fault on the surface. The yellow asterisk represents the initial point of rupture.

To assess the base seismic hazard of the Nafplio area, a method based on both a probabilistic approach and a deterministic scenario-based approach was used following two subsequent analysis steps.

First of all, a probabilistic seismic hazard assessment (PSHA) was performed following these basic steps (Reiter, 1990; Baker, 2008): i) identification of all active earthquake sources, ii) calculation of the seismicity rate of each considered source, iii) estimation of a source-to-site model, associated with each source, iv) prediction of the distribution of ground motion parameters as a function of magnitude, distance, etc., v) combination of all the above to calculate the seismic hazard and the associated rates of exceedance. The prediction ground motion model proposed by Danciu and Tselentis (2007) for the Greek region was applied and, finally, the PGA distribution with different return periods was obtained by applying the total probability theorem.

Following, a deterministic seismic hazard assessment (DSHA) was performed using a modified approach based on the results obtained by the PSHA approach. A stochastic simulation based on ground motion methodology (Boore, 1983; Beresnev and Atkinson, 1997; Motazedian and Atkinson, 1997) was applied in a defined magnitude range typical for each identified seismic source to achieve synthetic acceleration time series having PGA values comparable with those computed by the PSHA. In this way, a set of synthetic time histories was obtained for each seismic source for different return periods for the Nafplio area.

4. Local seismic response analysis

4.1. Engineering-geological model

The Argolis peninsula is part of the Dinaric-Hellenic orogenic system, formed by the collision between the Adria Plate and the southern sector of the Eurasia Macroplate (Bortolotti et al., 2013) and it is made up of a succession of NW-verging tecto-sedimentary belts, with a NW-SE trend.

The study area was characterised by two rocky reliefs, the Acronafplia peninsula on the south and the Palamidi hill on the southeast, and by a plain on the north composed by soft-soil deposits and man-made fill materials.

During the field investigations, a geological and geomorphological survey was carried out. Specifically, geological and geotechnical analysis of the outcropping formations in the Acronafplia peninsula and in the Palamidi relief was performed.

A set of 17 previously available boreholes, drilled in the submarine harbour area in front of the commercial Nafplio port, allowed to determine the thickness of recent soft-soil deposits and the depth of the bedrock. The stratigraphy obtained is consistent in the geotechnical investigations.

In order to define a detailed geological model of the subsoil of Nafplio, a more detailed geological map was developed, and some geological sections were created, integrating the literature information, the stratigraphy from boreholes and the stratigraphic contacts observed on site.

The results revealed that Acronafplia peninsula consists of limestone bedrock (Cretaceous), except for the SW side in which conglomerates (Pleistocene) outcrop. The latter are heavily eroded by the marine action on the coast, with the occurrence of relevant rock fall phenomena. Palamidi hill is affected by a NW-verging thrust and it shows an inverted stratigraphic series. The thrust footwall is represented by an anticline composed of intensely fractured limestone (Cretaceous) and clayey-marly flysch (Upper Cretaceous-Eocene). It is also evident the occurrence of a normal fault that lowers the western sector (Acronafplia peninsula). The northern slope of the Palamidi hill is characterised by Pleistocene gravels and breccias, that surround its base, in erosional unconformity with the underlying flysch. Nafplio historical and modern city rise on recent soft soil materials of the coastal plain and man-made fill (Sabatakakis and Koukis, 2010).

Based on the geological model so reconstructed, three main geotechnical units have been distinguished: bedrock, recent soft soil deposits, anthropogenic fill (Fig. 2). Furthermore, to perform future numerical modelling for local seismic response analysis, the characteristic geotechnical parameters were attributed to each geological unit defined in terms of natural weight per unit volume, shear stiffness and damping properties (G/G0 and D% curves) and seismic wave velocity.

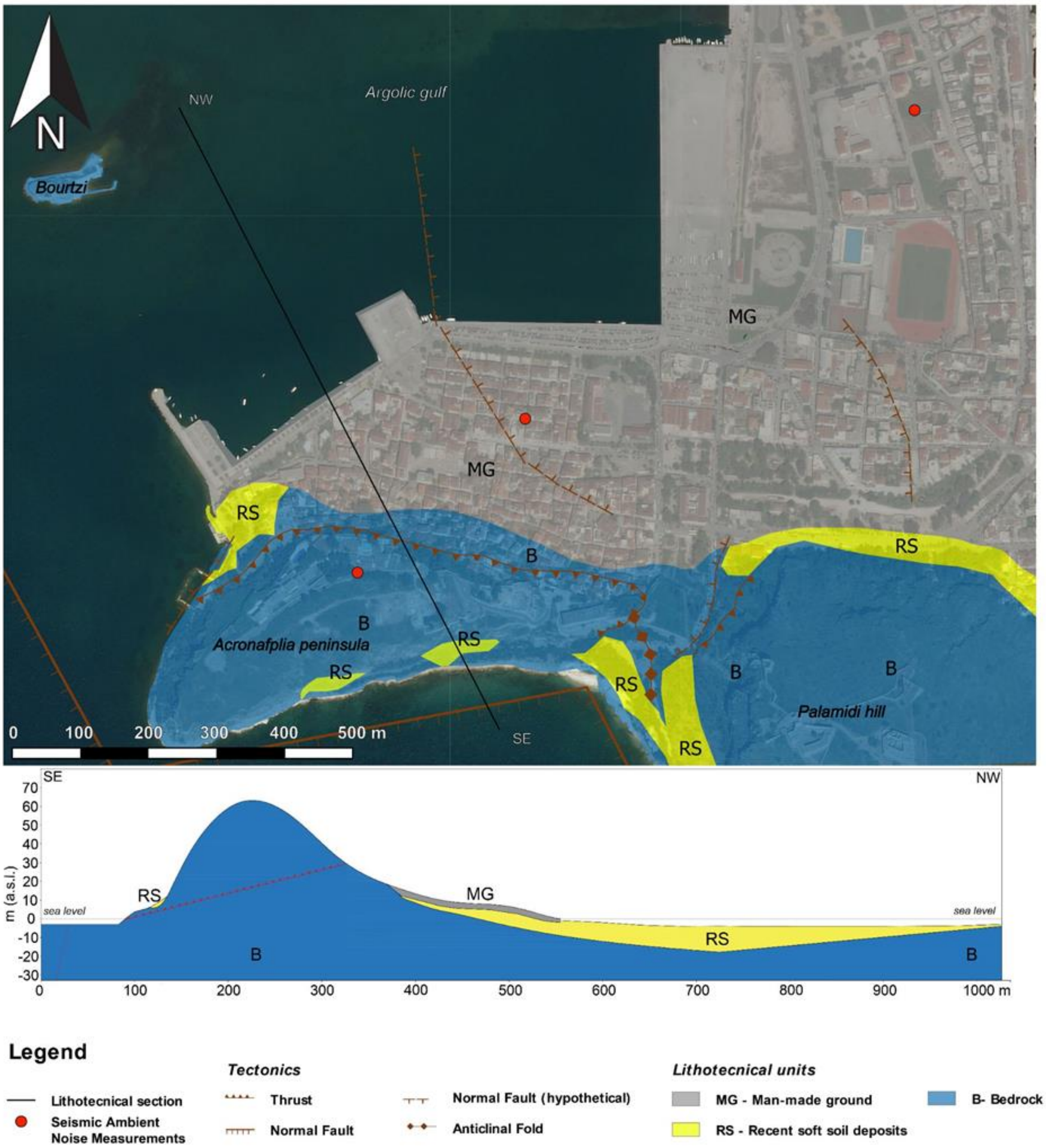

Fig. 2. Engineering-geological map and simplified geotechnical cross-section of Nafplio study area (from Saroglou et al., 2021).

4.2. Seismic ambient noise measurements

Several single-station seismic ambient noise measurements were performed in the historical centre of Nafplio, at the modern town and in the Acronafplia ridge. Seismic ambient noise was recorded for 1 hour in each site using LE-3D/5s 3-component seismometers (0.2 Hz eigenfrequency) by Lennartz Electronic GmbH coupled with REFTEK 130-01 dataloggers and SL06 24-bit digitizers with built-in SS20 three-component velocimetric sensor (2 Hz eigenfrequency) by SARA Electronic Instruments, both set to a sampling frequency of 250 Hz.

These measurements were analysed to derive the fundamental frequency (f_0) of sites characterised by a stratigraphy with a marked impedance contrast, traditionally a soft soil on a stiff bedrock (Bour et al., 1998; Haghshenas et al., 2008), by the Horizontal-to-Vertical Spectral Ratio (HVSR) technique (Nakamura, 1989).

Using Geopsy software (Wathelet et al., 2020), each 1-h record was divided in non-overlapping windows of 40s with 5% cosine taper; the Fast Fourier Transform (FFT) was computed for the three components (North-South, East-West and Up-Down) in each window and the obtained FFT spectra were smoothed by the Konno and Ohmachi (1998) function; the single-window spectra and HVSR ratio were averaged to obtain mean FFT spectra for each component and the HVSR function.

The main outputs from the seismic ambient noise measurements at Nafplio reveal that in the historical centre and in the modern town, built above the recent deposits of the coastal plain, HVSR functions are characterised by marked peaks, with frequency values that vary between 1 and 2 Hz in the modern town area and 2 and 5 Hz in the historical centre. These resonance values can be associated to the lower thickness of the soft soils in the near surface of the historical centre area. At the Acronafplia ridge, instead, HVSR functions do not show any significant peak, indicating that the outcropping limestone acts as seismic bedrock.

4.3. Numerical modelling of the local seismic response

To evaluate the seismic response in the studied area, a two-dimensional numerical modelling (through an equivalent linear analysis at finite elements) for some engineering-geological cross-sections was performed by the LSR2d software (STACEC s.r.l) and using as seismic input a set of recorded earthquakes having spectrum-compatibility with the synthetic time series produced with the seismic hazard analysis representative of different return periods, selected through the ITACA_REXELweb tool (Sgobba et al., 2021).

Firstly, it was possible to obtain the acceleration (horizontal direction) maps which clearly evidence the higher values in the soft soils along the valley edges, where seismic waves are probably subject to diffraction and reflection phenomena by a not-horizontal and superficial bedrock and a lighter increase at the top of reliefs (i.e., Acronafplia hill), probably due to "ridge effect" consisting in the focusing and concentration of the seismic waves (Fig. 3). The amplification functions and the amplification factors (AF), according to the Working Group ICMS (2008) criteria, for several control points, fixed along the cross-sections, were also computed. In particular, these parameters highlight a more intense stratigraphic amplification effect, in the north-northeast of the city centre where the most recent urbanisation was performed on a subsoil characterised by man-made fill and sandy-clay, several metres thick, lying on the geological bedrock which generates significative effects of stratigraphic amplification in good fitting the results from noise measurements. By using the AF values distribution, it will be possible to build amplification maps of the study area which can address the seismic risk mitigation interventions on the existing buildings and/or on the planning of new structures. Finally, the elastic response spectra for the different analysed return periods will be computed for each zone identified having homogeneous seismic response based on the performed numerical modelling results.

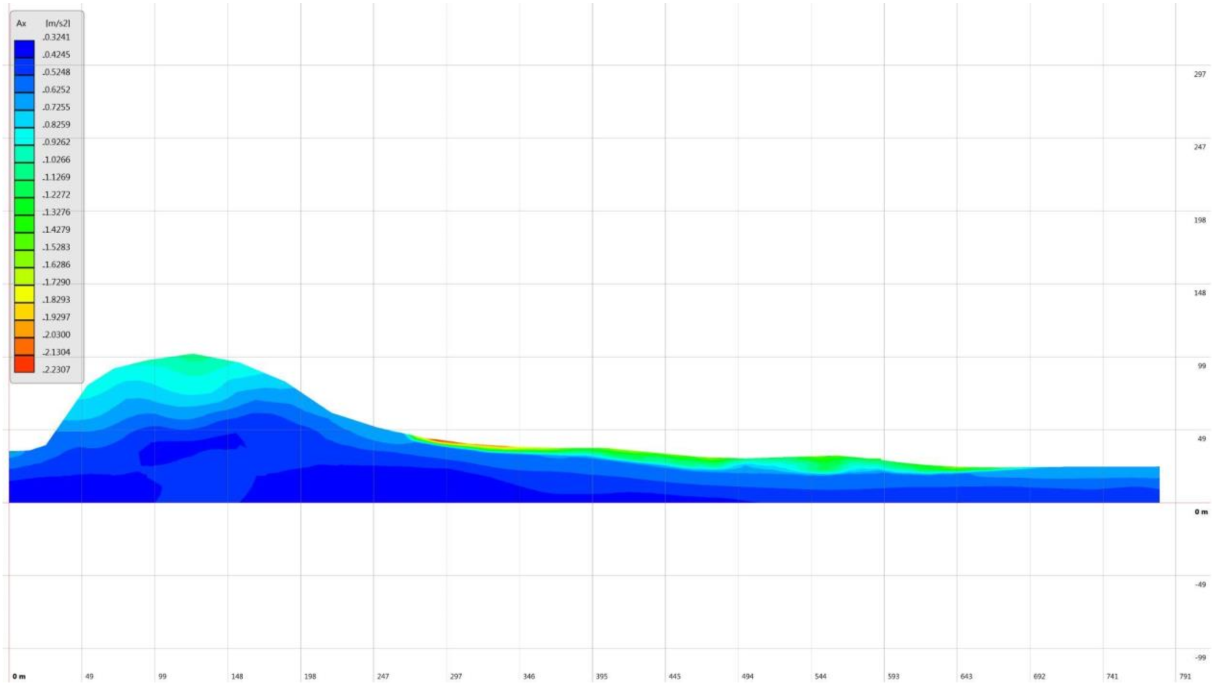

Fig. 3. Example of acceleration values along a cross-section oriented S-N from Acronafplia to Nafplio modern town.

5. Conclusion

Historical centres of old towns in high seismicity areas are widely diffused in the Mediterranean zone. The mitigation of the seismic risk for these resources is therefore a topic of great importance to allow their conservation for future generations.

Local seismic response can induce amplification effects responsible for a more sever action on buildings and old constructions. Therefore, to manage the risk mitigation of such a cultural heritage specific modelling of both engineering-geological and seismic effects are necessary. Such a topic represents the aim of the H2020-RISE project “STABLE” (Structural stABLity risk assEsment; www.stable-project.eu), that concerns the cultural heritage protection in the peri-mediterranean area. The historical city centre of Nafplio (Greece) represented a very interesting test site to analyse the seismic response. The local seismic response was evaluated by combining engineering-geological, geophysical and numerical modelling approaches in order to retrieve a map showing zones with homogeneous seismic response and related elastic response spectra.

Acknowledgements

This study has been developed in the framework of the project PRIN 2017 (Research Projects Of Relevant National Interest), named “URGENT” - Urban Geology and Geohazards: Engineering geology for safer, resilieNt and smart ciTies, and in the framework of the H2020-RISE project “STABLE” (Structural stABLity risk assEsment; www.stable-project.eu), Num. 823966.

References

- Baker, J. W. (2008). An introduction to probabilistic seismic hazard analysis (PSHA). White paper, version, 1, 72
- Beresnev, I. A., Atkinson, G. M. (1997). Modeling finite-fault radiation from the ω n spectrum, Bulletin of the Seismological Society of America, 87(1), 67-84.
- Boore, D. M. (1983). Stochastic Simulation of High-frequency Ground Motions Based on Seismological Models of the Radiated Spectra, Bull. Seismol. Soc. Am. 73, 1865–1894.
- Bortolotti, V., Chiari, M., Marroni, M. et al, (2013). Geodynamic evolution of ophiolites from Albania and Greece (Dinaric-Hellenic belt): one, two, or more oceanic basins? Int J Earth Sci (Geol Rundsch) 102, 783–811, https://doi.org/10.1007/s00531-012-0835-7
- Bour, M., Fouissac, D., Dominique, P., Martin, C. (1998). On the use of microtremor recordings in seismic microzonation, Soil dynamics and earthquake engineering 17(7-8):465-474
- Danciu, L., Tselentis, G. A. (2007). Engineering ground-motion parameters attenuation relationships for Greece, Bulletin of the Seismological Society of America, 97(1B), 162-183.
- Georgiou, C., Galanakis, D. (2010). Neotectonic Study of Urban and Suburban Nafplio Area (Argolida Greece), Bulletin of the Geological Society of Greece, 43: 1428–1437.
- Haghshenas, E., Bard, PY., Theodulidis, N. (2008). Empirical evaluation of microtremor H/V spectral ratio, Bulletin of Earthquake Engineering 6(1):75-108
- Karakaisis, G. F., Papazachos, C. B., Scordilis, E. M. (2010). Seismic sources and main seismic faults in the Aegean and surrounding area, Bulletin of the Geological Society of Greece, 43(4): 2026-2042.
- Konno, K., Ohmachi, T. (1998). Ground-motion characteristics estimated from spectral ratio between horizontal and vertical com-ponents of microtremor, Bull. Seism. Soc. Am., 88, 228-241
- Motazedian, D., Atkinson, G. M., 2005. Stochastic finite-fault modeling based on a dynamic corner frequency. Bulletin of the Seismological Society of America 95, 995-1010.
- Nakamura, Y. (1989). A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface, Railway Technical Research Institute, Quarterly Reports 30(1)
- Papazachos, B., Papazachou, C. (Eds) (2003). The earthquakes of Greece, Ziti Publ. Co., Thessaloniki, Greece
- Reiter, L. (1990). Earthquake hazard analysis. New York, Columbia University Press.
- Sabatakakis, P., Koukis, G. (2010). Aqueous environment and effects on the civil areas: the case of Nafplio, Bulletin of the Geological Society of Greece, XLIII, No 3, p.1508-1519
- Saroglou, C., Bozzano, F., Martino, S., Mouzakiotis, Karastathis, V., Tsirogianni, A., Antonielli, B., Ciampi, P., Fiorucci, M., Iannucci, R., Inciocchi, D., Maniatakis, C., Rivellino, S., Antoniou, A., Papadimitriou, A. (2021). Profiling of the recent deposits of Nafplio coastal plain (Greece) from engineering geological modelling and geophysical surveys, 3rd European Regional Conference of IAEG, 6-10 October 2021, Athens, Greece
- Sextos, A., De Risi, R., Pagliaroli, A., Foti, S., Passeri, F., Ausilio, E., et al (2018). Local site effects and incremental damage of buildings during the 2016 Central Italy earthquake sequence, Earthquake Spectra 34(4):1639-1669
- Sgobba, S., Felicetta, C., Russo, E., D’Amico, M., Lanzano, G., Pacor, F., Luzi, L., Baraschino, R., Baltzopoulos, G., Iervolino, I. (2021) The online graphical user interface of REXELweb for the selection of accelerograms from the engineering strong motion database (ESM). Atti del 39° convegno online GNGTS, 22-24 giugno 2021.
- Wathelet, M., Guillier, B., Roux, P., Cornou, C., Ohrnberger, M. (2018). Rayleigh wave three-component beamforming: signed ellipticity assessment from high-resolution frequency-wavenumber processing of ambient vibration arrays, Geophysical Journal International 215(1): 507-523
- Working Group ICMS (2008). Indirizzi e criteri per la microzonazione sismica – Guidelines for seismic microzonation. Conferenza delle Regioni e delle Province Autonome-Dipartimento della Protezione Civile. English version available at https://www.centromicrozonazionesismica.it/it/download/send/9-guidelines-for-seismic-microzonation/38-guidelines-for-seismic-microzonation