Site effects and risk assessment for the preservation of cultural heritage in the city of Augusta (Italy)

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ABSTRACT

Recent severe earthquakes (e.g. the 2016-2017 Central Italy seismic sequence, the 2020 Greece earthquake and the 2020 Croatia seismic event) show that South-East Mediterranean countries have the highest seismic risk in Europe, because of their high structural vulnerability and significant seismic hazard. In particular, cultural heritage sites suffered the most devastating damage. For this reason, the evaluation of the seismic hazard and risk is a key aspect for the preservation of cultural heritage. In this work, ground response analyses were performed for cultural heritage sites located in the city of Augusta, which is situated on the eastern cost of Sicily (Italy). Eastern Sicily was characterised in the past by destructive earthquakes (e.g. 1169, 1542, 1624, 1693 and 1818). The last significant seismic event (Mw = 5.6) occurred in this area on December 13, 1990, with the epicentre located in the sea offshore the city of Augusta. In the framework of Seismic Microzonation (SM) studies, the city was divided into Seismically Homogeneous Microzones (SHMs), that are expected to have similar effects in case of earthquakes, and the main cultural heritage sites were identified in the SHMs Map. Then, specific site response numerical analyses were performed for each SHM where the cultural heritage sites were located. The methodology applied in this study gives crucial information for the engineers and planners in developing strategies for the preservation of cultural heritage on a large scale.
Keywords: cultural heritage sites, seismic microzonation studies, site effects.

INTRODUCTION

The preservation of cultural heritage is a crucial aspect in South-East Mediterranean countries due to the high seismic hazard and the vulnerable built heritage (Silvestri et al., 2024). Recently, the evaluation of site effects in cultural heritage sites was performed in several countries, e.g. Italy, Greece, Croatia and Egypt (Kappos et al., 2008; da Porto et al., 2012; Stepinac et al., 2021; Cavallaro et al., 2024; Hamed et al., 2024).

Several studies were performed in Italy due to the large variety of the Italian monumental heritage and the complexity of the geotechnical situations (Castelli et al., 2016; Grassi et al., 2021; Grasso & Sammito, 2025). In particular, Eastern Sicily is very rich of historical buildings, built before the emanation of seismic codes, and it is one of the most seismically active areas of Italy (Cavallaro et al., 2017; 2022). For this reason, the conservation of cultural heritage sites is fundamental for most of the Italian cities (Abate et al., 2022).

In this work, the evaluation of the site effects was carried out for cultural heritage sites located in the city of Augusta (Eastern Sicily) with the aim of safeguarding these sites from seismic hazard.

SESMICITY OF THE STUDY AREA

The city of Augusta, located on the eastern coast of Sicily (Italy), lies in a high seismic risk zone. Geologically, the study area is part of the Hyblean Plateau (Figure 1), where the Eurasian and African tectonic plates interact. Indeed, the seismic activity of the area is mainly attributed to tectonic stresses generated by the interaction between the Eurasian and African plates (Cavallaro et al., 2018; Castelli et al., 2021).

The investigated area was affected by significant seismic events in the past, including the 1542, 1693 1848, 1908 and 1990 earthquakes (Locati et al., 2020). The moment magnitude and intensity values felt in the city of Augusta during the aforementioned earthquakes are reported in Table 1, where the moment magnitude of historical earthquakes was evaluated in Rovida et al. (2020, 2022) using the Boxer method (Gasperini et al., 1999; 2010). The interactive seismic hazard map developed by the National Institute of Geophysics and Volcanology (INGV) (Stucchi et al., 2011) in terms of peak ground accelerations (PGA) is showed in Figure 1 for a return period, T_R, of 475 years.

Table 1. *Intensity values of the strongest earthquakes felt in the city of Augusta (Locati et al., 2020; Rovida et al., 2020; 2022).*

Seismic events	Moment magnitude	Intensity values
10/12/1542	6.68 ± 0.24	8
11/01/1693	7.32 ± 0.10	10
11/01/1848	5.51 ± 0.26	8-9
28/12/1908	7.12 ± 0.10	7
13/12/1990	5.61	7-8

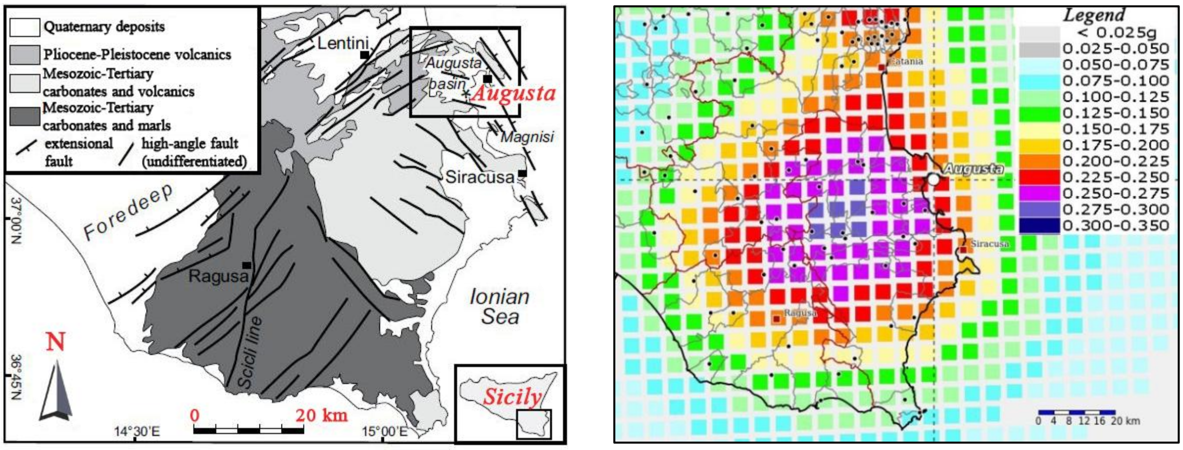

Figure 1. *Geological setting of the investigated area (From Di Martire et al. 2015; modified) (left). Interactive seismic hazard map in terms PGA for T_R of 475 years (From Stucchi et al., 2011; modifed) (right)*

LOCATION OF CULTURAL HERITAGE SITES IN THE SEISMICALLY HOMOGENEOUS MICROZONES (SHM) MAP

Seismic microzonation (SM) studies employ three Levels of detail that progressively increases in complexity to evaluate the seismic ground response and the susceptibility to ground instability phenomena in an area. The main aim of Level I is to create a map of Seismically Homogeneous Microzones (SHMs_Map), which are zones characterized by homogeneous seismic behaviour (Moscatelli et al. 2020; Pergalani et al. 2020). In this work, the main cultural heritage sites, including the *"Madonna Adonai Sanctuary"*, the *"Brucoli Castle"*, the "*Augusta Hangar*" and the *"Swabian Castle of Augusta",* were identified in the SHMs_Map of the city of Augusta developed in the framework of Seismic Microzonation (SM) studies in compliance with the article 11 of Law No. 77 of June 24, 2009 (Figure 2).

The *"Madonna Adonai Sanctuary"* was founded in the first half of the 3rd century in one of the numerous caves of a pre-existing hypogeum. The sanctuary consists of a cave, in front of which, in the 18th century, a masonry structure was built. After the 1990 earthquake, a partial restructuring and consolidation project was undertaken in 2000, and definitive restoration activities were initiated in 2007. The *"Brucoli Castle"* was built in the 15th century to protect the area against turkish and barbary assaults. It suffered damage, notably from the 1693 earthquake, and was used for military and commercial purposes. It was recently renovated and converted into a tourist facility. The "*Augusta Hangar*", built between 1917 and 1920 for military purposes, is a historic reinforced concrete structure for airships. Today, it is a building of historical and technical importance. Restoration work began after its decommissioning in 1991. The *"Swabian Castle of Augusta"* was built in 1232 by order of Federico II to ensure military control of the territory.

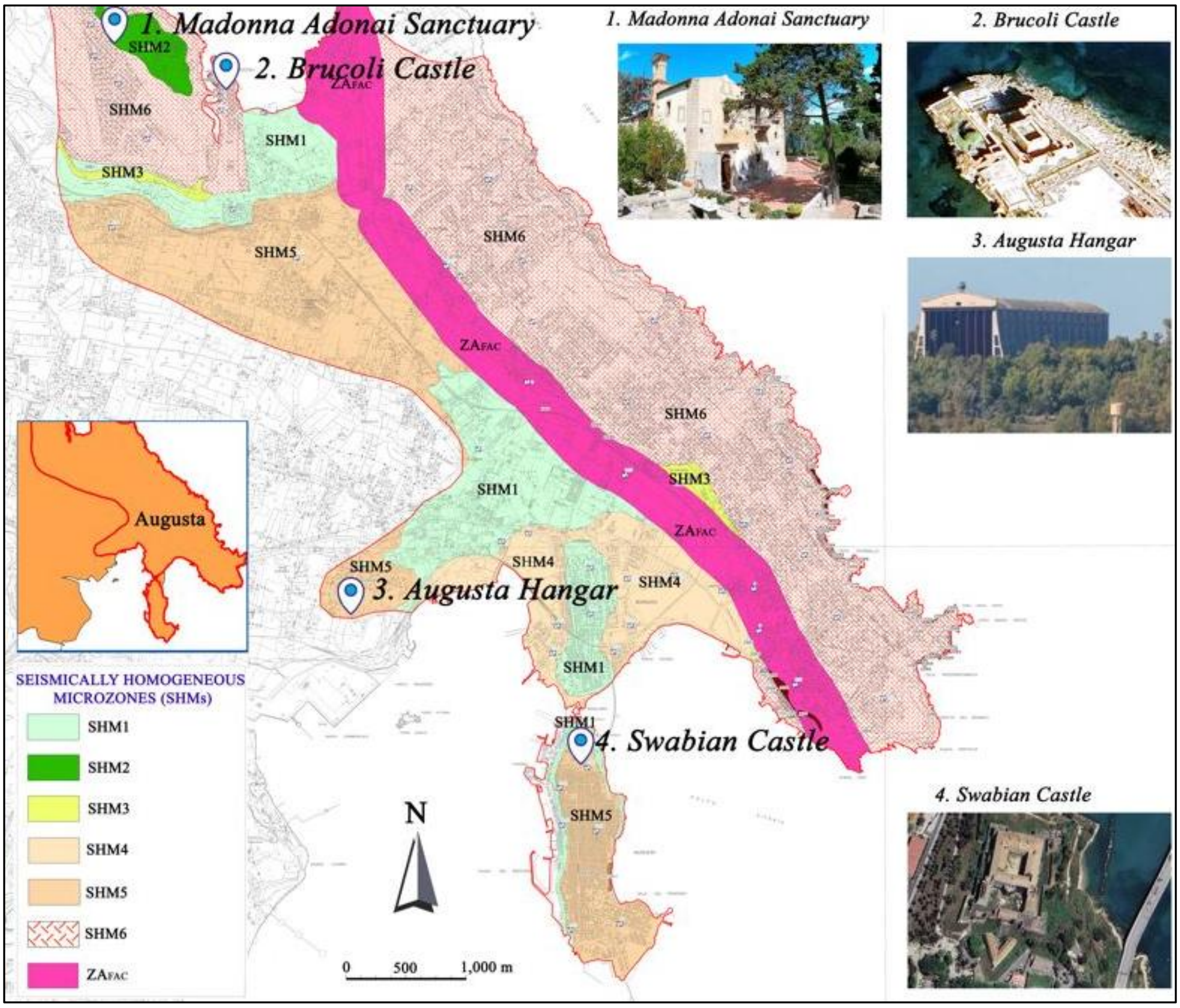

Figure 2. *SHMs_Map of Augusta with the location of the main cultural heritage sites (Photos from Google Maps).*

A total of six SHMs and an Attention zone for active and capable fault, ZA_{FAC}, were detected in the map. In particular, the *"Madonna Adonai Sanctuary"* falls within the SHM2, the *"Brucoli Castle"* is located in the SHM6 and the "*Augusta Hangar*" and the *"Swabian Castle of Augusta"* fall within the SHM5.

The SHM2 consists of an alternation of stratified lithotypes made up of calcarenites (ALS) overlying either a fractured or altered substrate composed of calcarenites and calcirudites (SFLP), or an alternation of fractured or altered lithotypes consisting of calcirudite successions (SFAL). The SHM5 consists of a covering lithoid (LCtm) overlying a cohesive overconsolidated substrate (CO). The SHM6 is composed of calcirudites, calcarenites, and marls, interbedded with scoriaceous products or sandy levels (SFAL) and volcaniclastic products, breccias, and pillow lavas (SFLP).

GEOPHYSICAL AND GEOTECHNICAL DATA

In order to define the geotechnical characteristics for the definition of the subsoil models, in situ and laboratory tests performed in the municipality of Augusta include n. 4 Multichannel Analysis of Surface Waves tests (MASW), n. 2 Down-Hole (DH) tests, n. 2 Dynamic Probe Super Heavy (DPSH) tests, n. 4 Direct Shear tests (DST) and n. 2 Unconsolidated Undrained (UU) triaxial tests.

Shear wave velocity, V_S, profile obtained for the DH test in SHM 6 is displayed in Figure 3, as example, with the linear interpolation used to derive the V_S value from 30 m to the depth of the seismic bedrock (e.g. $z_{bedrock}$=92 m).

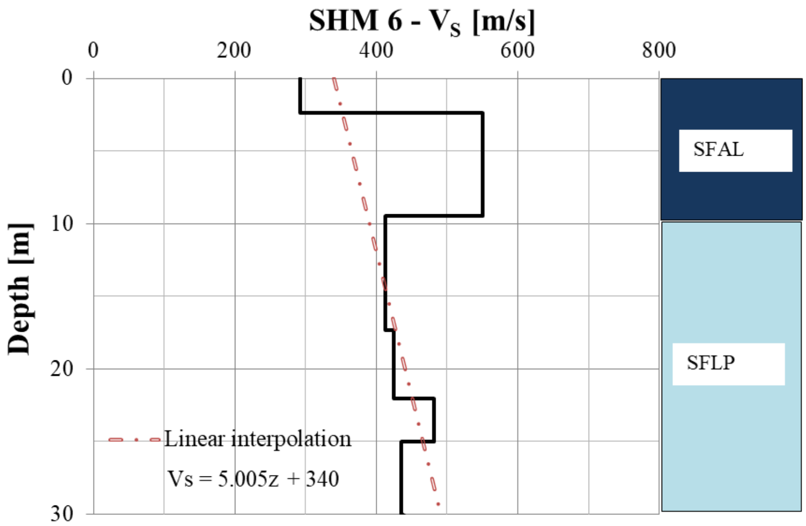

Figure 3. *V_S profile obtained from the DH test in SHM6, where the "Brucoli Castle" is located, with the Geological-Technical (GT) units (SFAL and SFLP).*

The dynamic soil response, crucial for ground response analyses, was described by the normalized shear modulus, G/G_0, and damping ratio, D [%], versus the shear strain, γ[%]. Figure 4 shows the experimental dynamic curves from literature (Cavallaro et al., 2001; Cavallaro and Grasso, 2021; Cavallaro and Maugeri, 2005) used for the ground response analyses for each Geological-Technical (GT) unit encountered in the SHM2, SHM5 and SHM6.

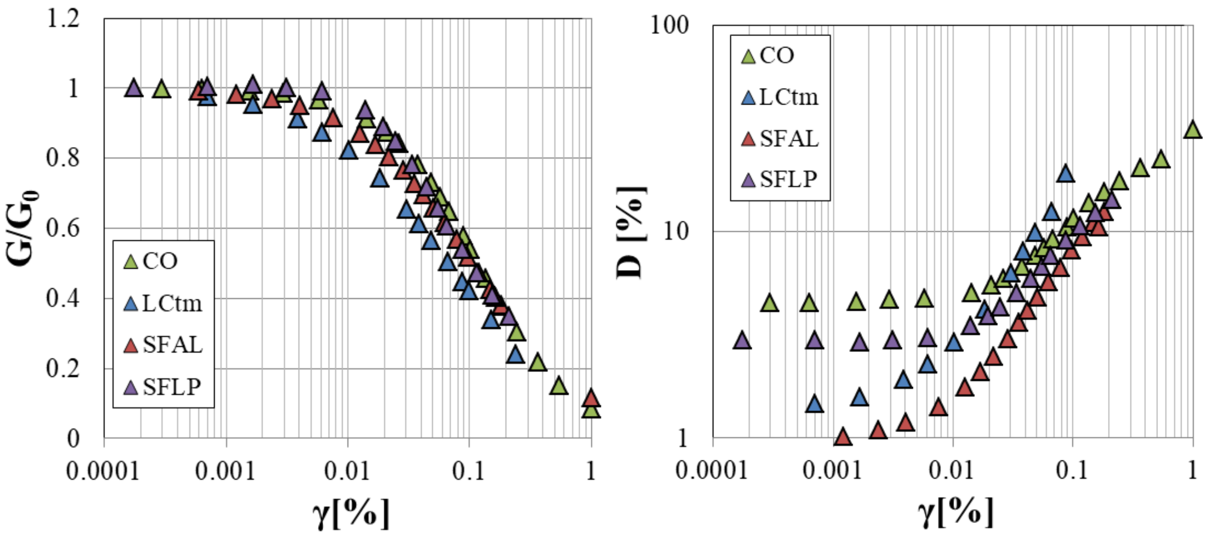

Figure 4. *G/G_0-γ[%] curve (left) and D [%]-γ[%] curve (right) for each GT units.*

SITE RESPONSE NUMERICAL ANALYSES

Selection of accelerograms from the Engineering Strong Motion (ESM) database

The 1-D equivalent linear (EQL) code STRATA (Kottke & Rathje, 2008) was employed for the site response analyses. Geophysical and geotechnical data, previously discussed, were used to define the subsoil models in SHM2, SHM5 and SHM6. The REXELweb tool (Sgobba et al., 2019) was used for the selection of a set of seven ground motion records from the ESM database (Luzi et al., 2020) to be compatible with the target spectrum provided by the Italian seismic code (NTC, 2018) for soil type A and a return period of 475 years.

The magnitude and distance limiting values in which the records fall were guided by the disaggregation of hazard at the investigated site derived from http://esse1gis.mi.ingv.it website (Spallarossa & Barani, 2007) (Figure 5). All input parameters entered in REXELweb tool are showed in Table 2. The compatibility between the set of seven ground motion records and the target spectrum is displayed in Figure 5. The list of selected ground motion records is showed in Table 3 with the magnitude (M_W), the epicentral distance and the peak ground accelerations (PGA).

Table 2. *Input parameters entered in REXELweb*

Target		**Preliminary**		**Matching**	
Target	NTC(18)	**Component**	One horizontal	**Lower tol. [%]**	10
Lat. [°]	37.245	**Soil Type**	A	**Upper tol. [%]**	30
Long. [°]	15.200	**Criterion**	Magnitude-Distance	**T_1 [s]**	0.15
Topography	T1	**M_{min}**	4	**T_2 [s]**	2.00
Nominal life	50 years	**M_{max}**	7.5	**Set size**	7
Functional type	II	**R_{min} [km]**	0	**Adimensional flag**	no
Limit state	SLV	**R_{max} [km]**	40	**Check on PGA**	yes

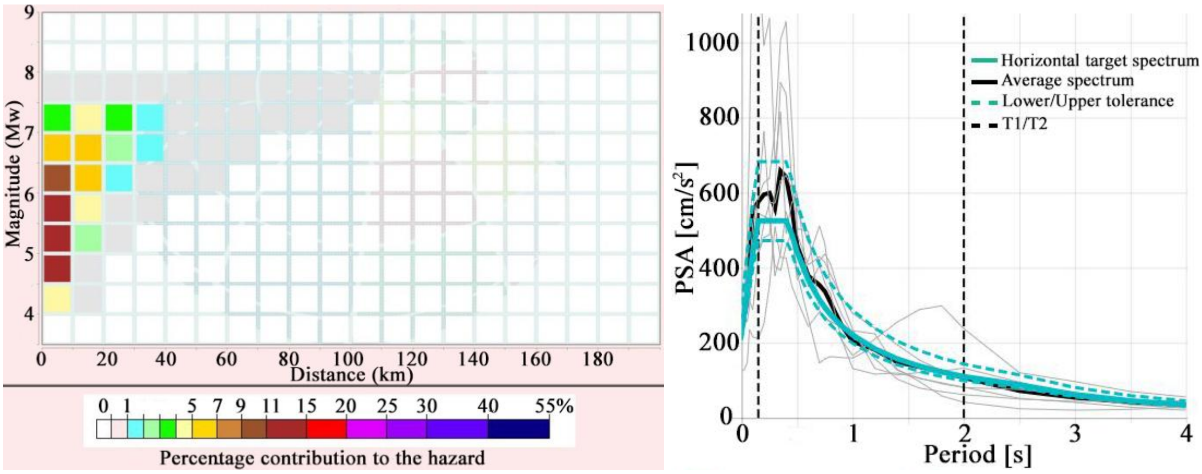

Figure 5. *Disaggregation data from http://esse1gis.mi.ingv for the investigated site (left) and combination of records obtained from REXELweb tool (Sgobba et al. 2019) (right).*

Table 3. *List of the selected ground motion records from the Engineering Strong Motion (ESM) database.*

N.	**Date**	**Earthquake Name**	**Station Name**	**M_W**	**Epicentral distance [km]**	**PGA [g]**
1	2008-05-29	ICELAND	Selfoss-City Hall	6.3	4.3	0.28
2	1976-09-15	FRIULI_3RD-SHOCK	S. Rocco	6.0	15.8	0.16
3	2000-06-21	ICELAND	Selfoss-City Hall	6.5	11.2	0.28
4	2016-10-30	CENTRAL_ITALY	Avendita PG	6.6	11.6	0.20
5	1999-11-12	DUZCE	IRIGM Station No. 487	7.2	28.1	0.34
6	2018-12-26	SICILY ITALY	Santa Venerina	5.0	5.3	0.13
7	2000-06-17	ICELAND	Flagbjarnarholt	6.5	22.7	0.33

Results

Results in terms of maximum accelerations with depth, amplification functions and response spectra are reported in Figures 6-8 for each accelerogram and for SHM5 and SHM6, as examples. Moreover, the average values (red line) were calculated from those obtained by the seven selected accelerograms. The average amplification ratio, R, defined as the ratio between the output and input PGA (Table 3 and Figure 6), is 1.204 and 1.170 for SHM5 and SHM6, respectively. According to the equivalent shear wave velocity, $V_{S,eq}$, and the depth of the seismic bedrock, the NTC(2018) defines five soil types (A, B, C, D and E). In particular, the soil types obtained from the geophysical tests are C (180 m/s ≤ $V_{S,eq}$ < 360 m/s) and B (360 m/s ≤ $V_{S,eq}$ < 800 m/s) for SHM5 and SHM6, respectively. The stratigraphic amplification factors, S_S, provided by the NTC(2018) based on the seismicity and the soil types, are conservative with respect to the site response analyses since they are equal to 1.385 and 1.190 for the SHM5 and SHM6, respectively. The amplification functions (Figure 7), computed as the ratio between the Fourier spectrum at the surface to that of the input motion, show peak frequencies of 1.2 Hz and 1.9Hz for the SHM5 and SHM6, respectively. Finally, the comparison between the elastic response spectra provided by the NTC(2018) for soil type C and B, and the average response spectra obtained from site response analyses by setting a structural damping of 5% is showed in Figure 8.

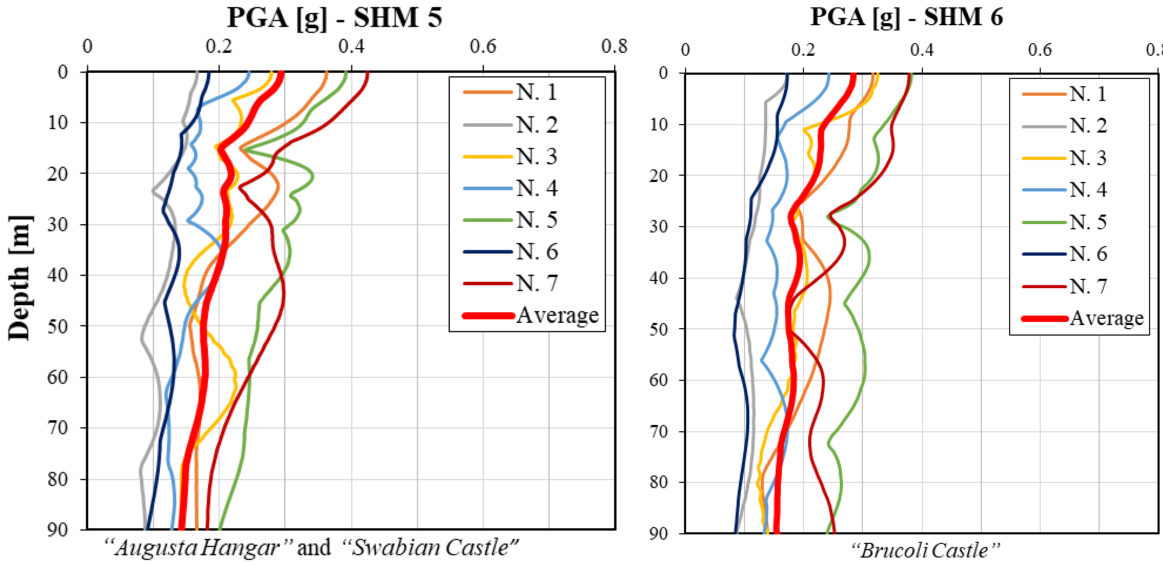

Figure 6. *Maximum accelerations with depth obtained from site response analyses for the SHM5 (“Augusta Hangar” and the “Swabian Castle”) (left) and SHM6 (“Brucoli Castle”) (right).*

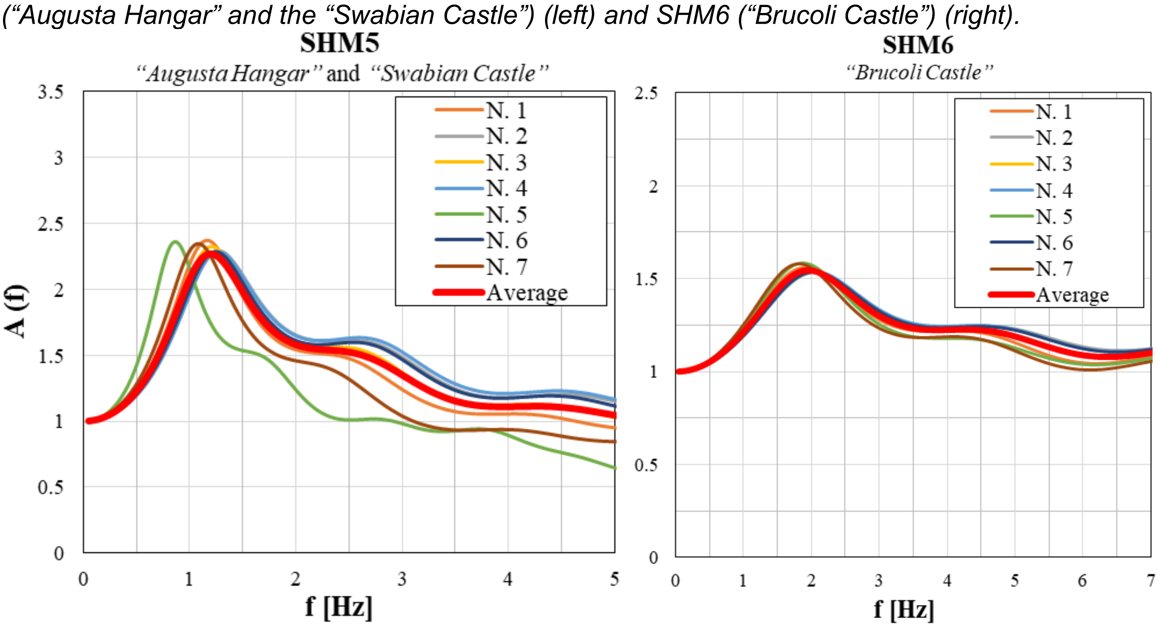

Figure 7. *Amplification functions obtained from site response analyses for the SHM5 (“Augusta Hangar” and the “Swabian Castle”) (left) and SHM6 (“Brucoli Castle”) (right).*

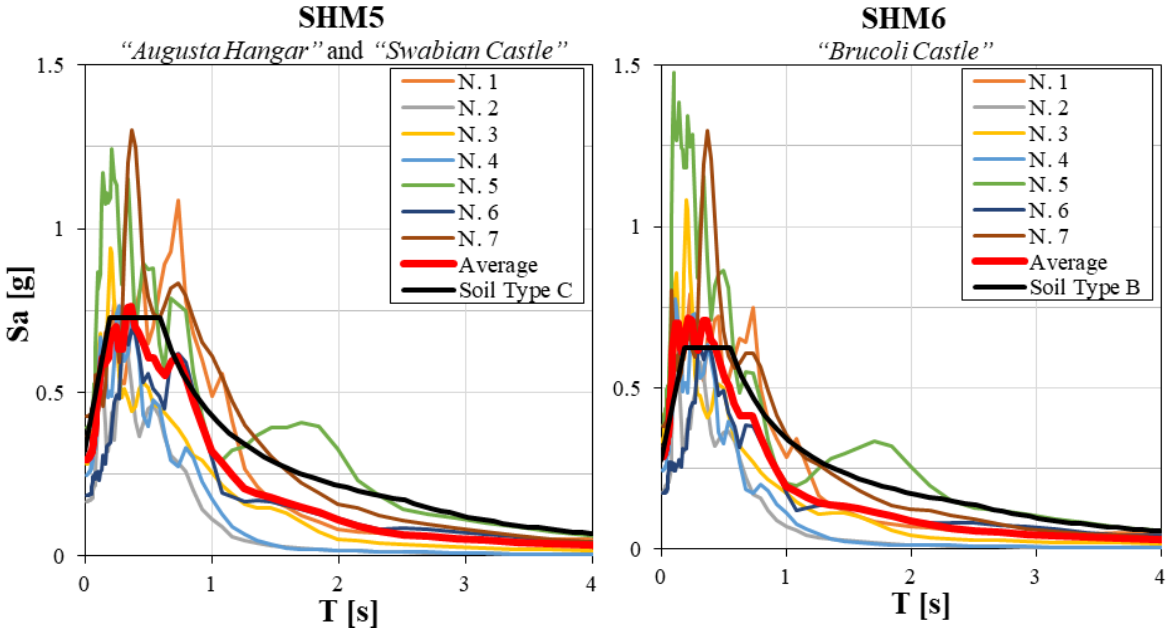

Figure 8. *Comparison between the elastic response spectra provided by the NTC(2018) and the same obtained from site response analyses for the SHM5 ("Augusta Hangar" and the "Swabian Castle") (left) and SHM6 ("Brucoli Castle") (right).*

CONCLUSIONS

The preservation of monuments and historic sites is a crucial aspect of geotechnical engineering. This topic has gained increased importance in South-East Mediterranean countries characterized by high structural vulnerability and seismic hazard.

In this work, the main cultural heritage sites were identified in the Seismically Homogeneous Microzones (SHM) Map of city of Augusta (Eastern Sicily). A set of seven ground motion records was selected from the the Engineering Strong Motion (ESM) database to be used for the site response analyses. Subsoil models were defined from geophysical and geotechnical data performed in the investigated area. Site effects were assessed for each SHM where the cultural heritage sites were located. Results of this study provide valuable information for the preservation of historical buildings and for the planning of the seismic improvement interventions on a large scale.

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