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Ambient Vibrations Measurements and 1D Site Response Modelling as a Tool for Soil and Building Properties Investigation

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Abstract: The safety of historic buildings heritage is an important task that becomes more substantial when the buildings are directed to educational purposes. The present study aims at evaluating the dynamic features of the *Benedettini* complex, an historic monastery located in downtown Catania, which is at present the headquarters of the humanistic studies department of the University of Catania. Both the building's complex response to a seismic input and the soil-to-structure interaction were investigated using ambient noise recordings. The results point out a multiple dynamic behaviour of the monastery structure that shows several oscillation modes, whereas the identification of a single natural frequency can be observed in some sites where the structure can more freely oscillate. This observation is also confirmed by the variability of computed damping values that appear linked to the different rigidity of the structure, as a function of the either the longitudinal or transversal orientation of the investigated structural elements. Moreover, the comparison between the building's fundamental period and spectral ratios frequencies, which were obtained from free field ambient noise measurements located outside the monastery, outline the presence of potential resonance effects between the site and structure during a seismic event. Numerical modelling of the local seismic response confirms the obtained experimental site frequencies, setting into evidence that higher amplification factors are reached in the same frequency range characterizing the building.

Keywords: spectral ratio; ambient noise; seismic site response; soil-to-structure interaction; fundamental periods

1. Introduction

Cultural heritage safeguarding has become increasingly important in recent times due to its economic and social significance. The downtown area of a city is usually the most vulnerable part, since several historic buildings are mostly located there. These valuable constructions often undergo reduced structural capacity due to deterioration phenomena and damages suffered in the past. Geophysical surveys are normally adopted as a tool for cultural heritage restoration and protection plans [1–5]. Moreover, cultural heritage buildings were typically built without considering seismic actions, and therefore are potentially susceptible to earthquake damage. It is, indeed, well known that the level of building damage and its distribution during an earthquake is due to the combined effect of local site response, based on subsurface ground conditions, and the dynamic features of the structure itself.

Seismic site effects are caused by significant contrasts in the seismic wave impedance of different lithotypes and/or the irregular geometry of the surface, resulting from the presence of canyons, valleys, or hills [6–8]. These effects imply variations in the amplitude and frequency content of seismic waves that ultimately need to be taken into account on the grounds that they affect earthquake hazard estimates. In the frequency domain, they can be estimated through several spectral ratio methods, which effectively reveal how near surface geological structures modify the spectral content of seismic waves. The most common technique for the local seismic response estimation is the standard spectral ratio (SSR), which compares earthquake recordings at two sites. One of these is a "reference site", which is usually located on solid bedrock, and considered to be devoid of significant site effects [9]. Another widespread technique that does not need a reference station is based on the horizontal-to-vertical spectral ratio (HVSR) using noise recordings (i.e., microseismic or ambient vibrations). This method was originally introduced by Nakamura [10] to characterise the transfer function of subsurface geological units. It has become widely used over the past two decades, since it has been shown to provide a reliable estimate of the predominant frequency of ground motion response at the surface of soft soil deposits [11–14]. This method applied to horizontal shear wave recordings by Lermo and Chavez-Garcia (1993) was shown to be consistent with results obtained using the SSR technique, especially in the frequency range around the fundamental frequency. In recent years, many authors have also successfully tested the reliability of HVSR in estimating local effects linked to the presence of different morphological conditions, landslides, faults, etc. [15–20]. Moreover, being a non-invasive technique, it can be used in cultural heritage sites [21–23].

The period (T) and the damping (D) of a building play an important role regarding the amplitude and duration of a seismic action. The period of a building can be assumed to be similar to that of a damped harmonic oscillator, having a mass M and a rigidity K:

$$T = 2\pi\sqrt{\frac{M}{K}} \tag{1}$$

Building height, structural typology, damage state, and regularity/irregularity in plan and elevation can also significantly influence such parameters. In order to assess T, several numerical methods, such as for instance the finite element method or the boundary element method, are widely used.

Empirical relationships provided by seismic codes [24], correlating T with the height (H) in meters, represent another way to determine the building period:

$$T = C_t H^a \tag{2}$$

where C_t and a are parameters that are linked to the type of structures. These relationships often are not able to define an accurate T value of studied buildings. For this reason, in order to estimate the building's dynamic properties, many researchers frequently adopt experimental techniques based either on the use of forced vibrations [25,26] or earthquake inputs [27,28], as well as on ambient vibrations [29,30]. Among the experimental techniques, the ambient vibrations method became widely used very quickly, since it was easy and quite inexpensive. However, it is important to remember that a comparison between the T estimated on undamaged buildings by using the ambient vibrations are 10–30% lower than periods estimated using more energetic seismic inputs [31,32].

In the present study, we used ambient vibrations processed through HVSR techniques in order to evaluate the seismic site effects in the *Benedettini* complex, which is located in the Catania (Italy) urban area (Figure 1a,b). In addition, the spectral ratios between the ambient vibrations Fourier spectra of horizontal components (HHSR), which are evaluated at the base and the different building levels, were used to determine the dynamical properties of this structure. These kinds of studies are important in investigating the possible soil-to-structure resonance effects that can arise when the fundamental frequency of a building shares the same range as that observed in the foundation soil [33–35].

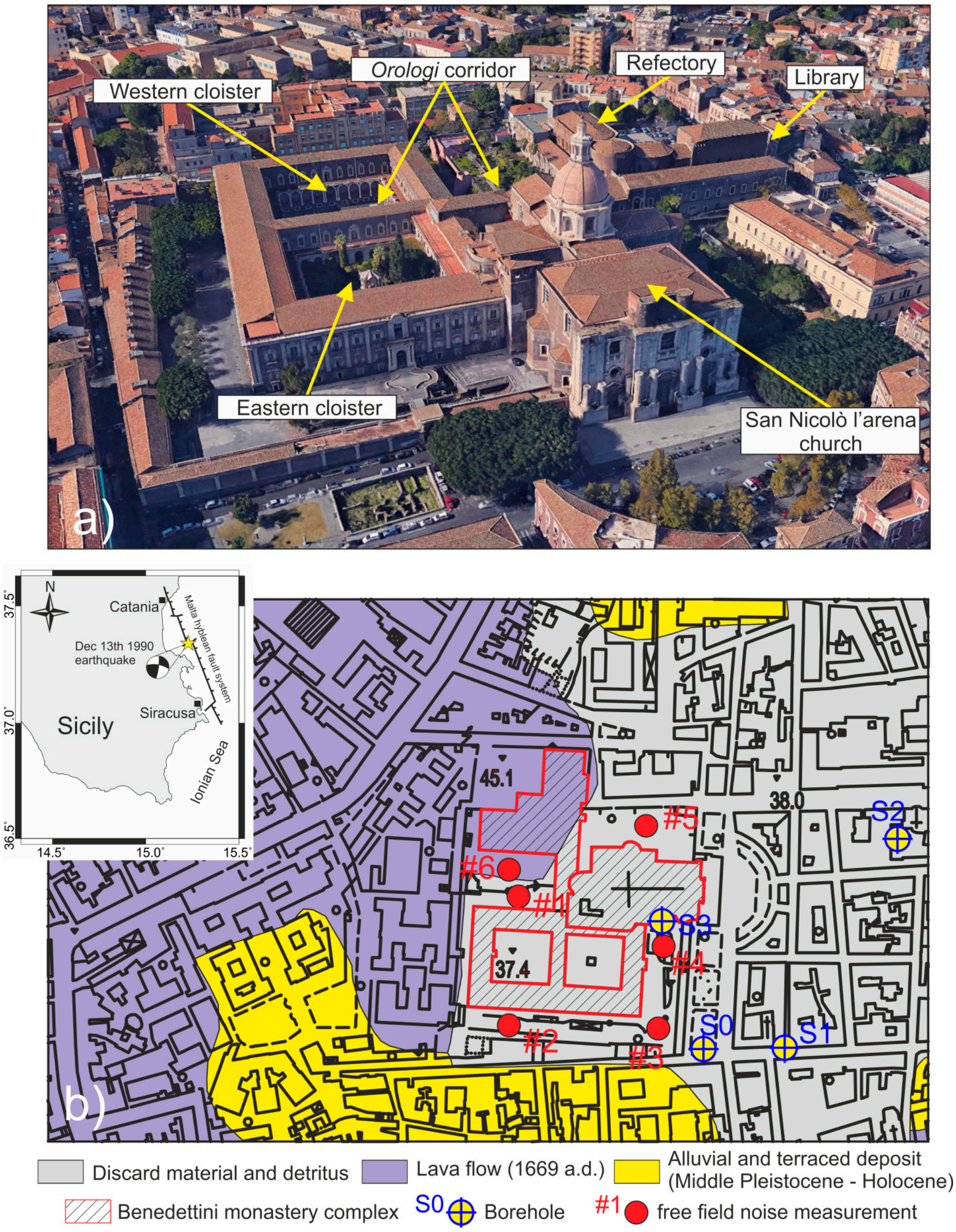


Figure 1. Aerial view (**a**) and lithological sketch (**b**) of the investigated area. The inset shows the location and focal mechanism of the 1990 M5.7 earthquake.

2. Benedettini Complex History

The *Benedettini* monastery complex is located in downtown Catania, which is one of the higher seismic hazard Italian cities. The seismic history of Eastern Sicily has been characterised by large events with a moment magnitude ranging from 6.2 to 7.3 [36,37].

The construction of the Monastery complex began in 1558. However, its original structure was modified by two natural calamities that struck the city of Catania, which had a key role in its future development. Following the Etnean eruption of 1669 and the 1693 M7.0 earthquake, the monastery was harshly destroyed and then rebuilt, becoming a tally example of the addition of different architectural historical periods. Originally, the monastery had a square floor plan with an inner cloister called the "marble cloister" (now renamed Western cloister). The original church that was attached to it, at present named San Nicolò l'Arena, was destroyed by the 1669 lava flow. The shape of the area surrounding the *Benedettini* monastery was fully modified after the eruption, since part of the complex was surrounded by a 12-m thick lava flow. The reconstruction of the church started in 1687, and continued until 1693, when a powerful earthquake almost destroyed the monastery. It was rebuilt and grew larger, with respect to its original plan, in 1702 when the eastern cloister was added to the western one, together with an additional area, aimed at the library and the refectory, on the northern side. The construction work on the church of San Nicolò l'Arena was resumed, but its façade remained incomplete. From 1868, the monastery was reused for civil purposes—mostly for schools and an astrophysics laboratory, including a laboratory of meteorology and geodynamics—with deep and sometimes irreversible changes to its structure. Most of the frescos were cancelled, the corridors were divided, and other divisions were added to create offices, training rooms, and toilets. Notwithstanding, it was recognised as a national monument immediately after the Italian Unification. During 1977, in as part of a renaissance project of downtown Catania, the municipality donated the monastery to the University of Catania, which used it as the location of their Humanities department. Furthermore, in 2002, UNESCO (United Nations Educational, Scientific and Cultural Organization) included the monastery in the World Heritage List, as a site that was representative of the late Baroque of southeastern Sicily.

Subsequently to the M5.7 earthquake that struck southeastern Sicily in 1990 [38,39], some structural elements of the San Nicolò l'Arena Church and the eastern cloister were damaged, and several vertical cracks were detected. The extensive investigation on the masonry structure that was performed pointed out the presence of two different construction typologies. Namely, a solid stonework that was built by large and regular blocks, filled with rubble masonry, and made with rather strong mortar; and a highly inhomogeneous stone masonry bounded by a cover (about 300-mm thick) that was made with tile fragments and stones having rather weak mortar, and was locally called *incoccio* [40,41]. Often, the two architectural typologies are present in the same structural elements, with the second one mainly used as a repair technique. Eventually, in recent times, the masonry structure was modified by implanting reinforced concrete elements. It can therefore be easily inferred that such a structural mixture deeply affects the seismic behaviour of the whole structure.

3. Geologic Setting

The present geologic features of the Catania area (Figure 1b) are the result of tectonic uplift, sea level changes, and lava flows originating from Etna eruptions. The area shows a complex setting with lateral heterogeneities at a local scale, due to the presence of volcanic and sedimentary units [42]. The sedimentary substratum of the urban area is formed by a sequence of Quaternary clays, up to 600 m thick, overlain by several tens of meters of sands, which extensively outcrop in the southwestern boundary of the city, and within some areas protected from lava invasions. Sands are also included inside the clay horizons as thin layers that become predominant proceeding upwards in the succession, and gradually switch to sandy clays. Sands, conglomerates, and silty clays that are several meters thick also lie in discordance on the clayey basement, and mostly outcrop in the southern part of Catania. The city area is characterised by a series of predominantly flat marine terraces, which were covered by several meters of lava flows in prehistoric and historic times. Such processes are the result of the late Quaternary dynamics [42] in which the terraces represent marine deposits of the transitional environment, resulting from changes in the sea level that occurred during the Quaternary glaciations. The lava flows are the most extended lithotype outcropping in the urban area, covering almost the entire city substratum and deeply changing the original morphology. Borehole data have highlighted the heterogeneous nature of this formation, which is characterised by alternating compact and scoriaceous levels that are extremely variable in thickness [43,44]. Moreover, the presence of pyroclastic levels is observed in the sedimentary sequence of sand and sandy clays. Finally, in the historic core of the city, the upper stratigraphic horizon consists of several meters of rubble, which largely resulted from the destruction of buildings caused by the 1693 earthquake.

A detailed lithological sequence of the investigated area was settled through boreholes information (see locations in Figure 1b) coming from the microzoning studies of Catania [45] and a geotechnical characterisation of the monastery subsoil performed by Grasso et al. [46]. The area is characterised by the presence, at a depth of about 40 m, of a Quaternary clay bedrock overlaid by a l0–15-m thick historic (~693 BC) basaltic lava [42]. This lava formation is covered, respectively in the northern and in the southern area of the monastery, by 5–10 m of the 1669 fractured lavas, and by 15–20 m of terraced deposits (fine sand). Finally, detritus with a thickness of about 5–10 m cover all of the monastery area (Figure 2).

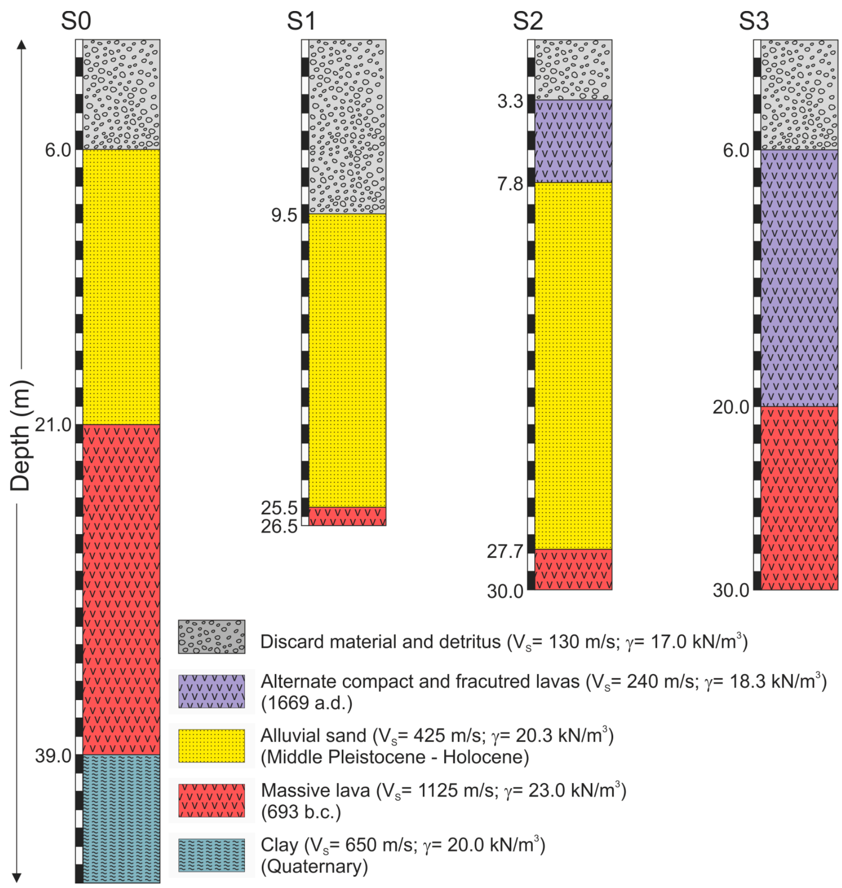


Figure 2. Litho-stratigraphic sequences from boreholes data (see Figure 1b for the location).

4. Methodology

4.1. Ambient Vibration Measurements

Ambient noise measurements were performed in all of the monastery areas owned by the University of Catania, which therefore did not include the buildings held by the Catania municipality (San Nicolò l'Arena church and the public library). Three-component velocimeters (Tromino), sampling the signal at a frequency of 128 Hz, were used. Inside the building, 21 sites were chosen near the main structural elements (Figure 3), and ambient vibrations were recorded for 20 min on the same vertical axes at different levels of the construction. On the whole, 50 measurements were performed in the western and eastern cloisters, deploying the measurements in each floor (basement, ground, first, second, and attic floors). Similarly, 17 measurements were allocated to each floor (ground, first, second, and roof floors) of the refectory. Furthermore, six sites were selected in the free field outside of the building, as remote as possible from the surrounding structures (see location in Figure 1b). The velocimeters, both inside and outside the structure, were settled with the north–south component oriented transversally to the 214-m long *orologi* corridor, which crosses the entire monastery and represents its maximum length (see Figure 3).

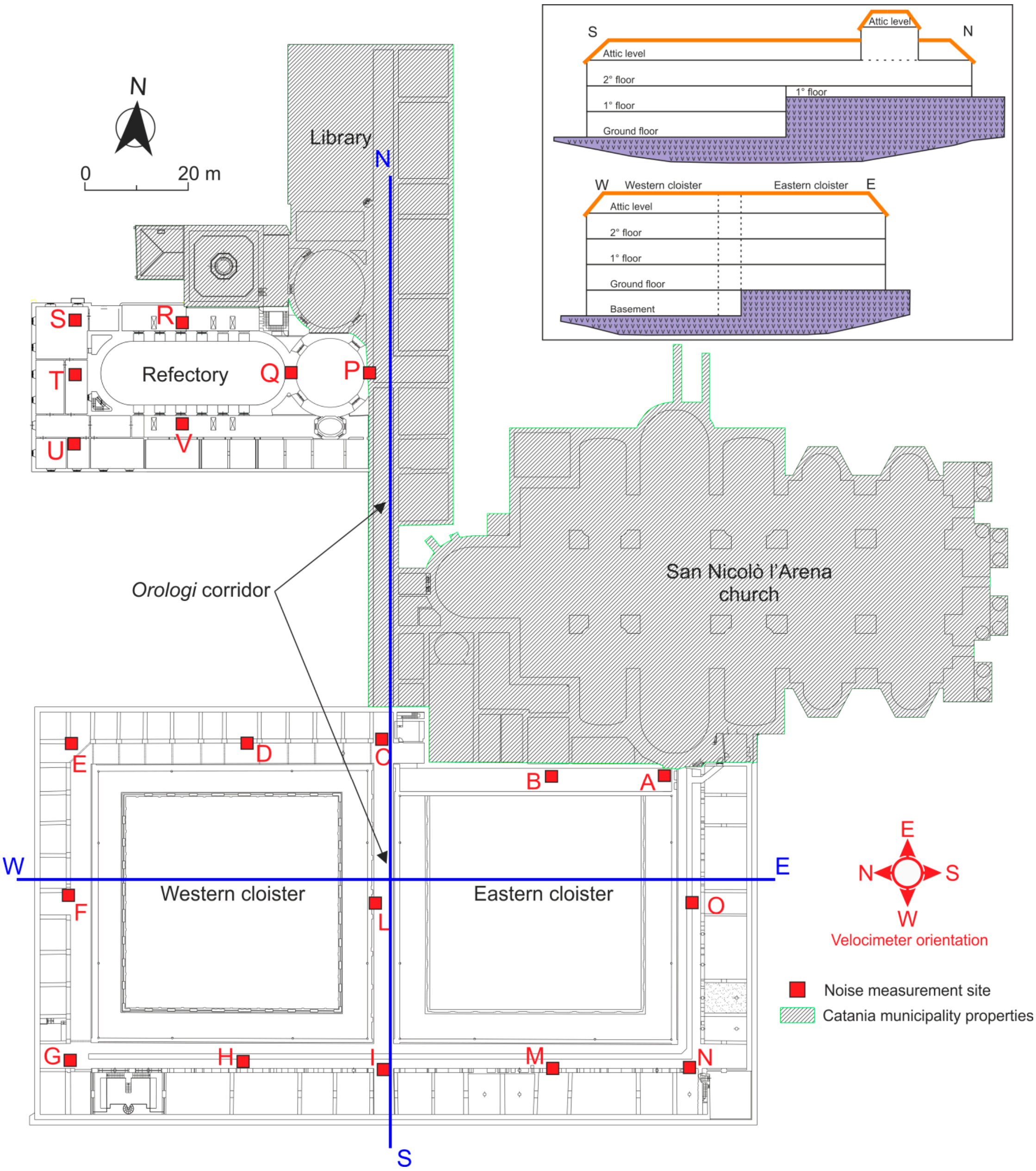


Figure 3. *Benedettini* monastery layout with the location of noise recording sites. The inset shows the north–south (NS) and east–west (EW) simplified sketches pointing out the different levels and number of floors existing in the *Benedettini* complex.

The data processing procedure consists in subdividing the recorded signal in time windows of 20 s, selecting the most stationary part, and not including transients associated to very close sources. Fourier spectra were then calculated in the frequency band 0.5–20.0 Hz, and smoothed using a Konno and Ohmachi [47] filter with b = 40. Hence, the spectral ratios between the ambient vibrations Fourier spectrum of horizontal components, which were recorded on the various building floors, and the same components as sampled in the free field, were computed (Figures 4–7). The resulting function, named HHSR (horizontal-to-horizontal spectral ratio), is then the system transfer function, which was obtained through a simple deconvolution method based on the spectral ratio between the output (the recording at the different building levels) and input signals (ground motion at the base) [48,49]. Site #1 (see Figure 1b for the location) was used as the reference site.

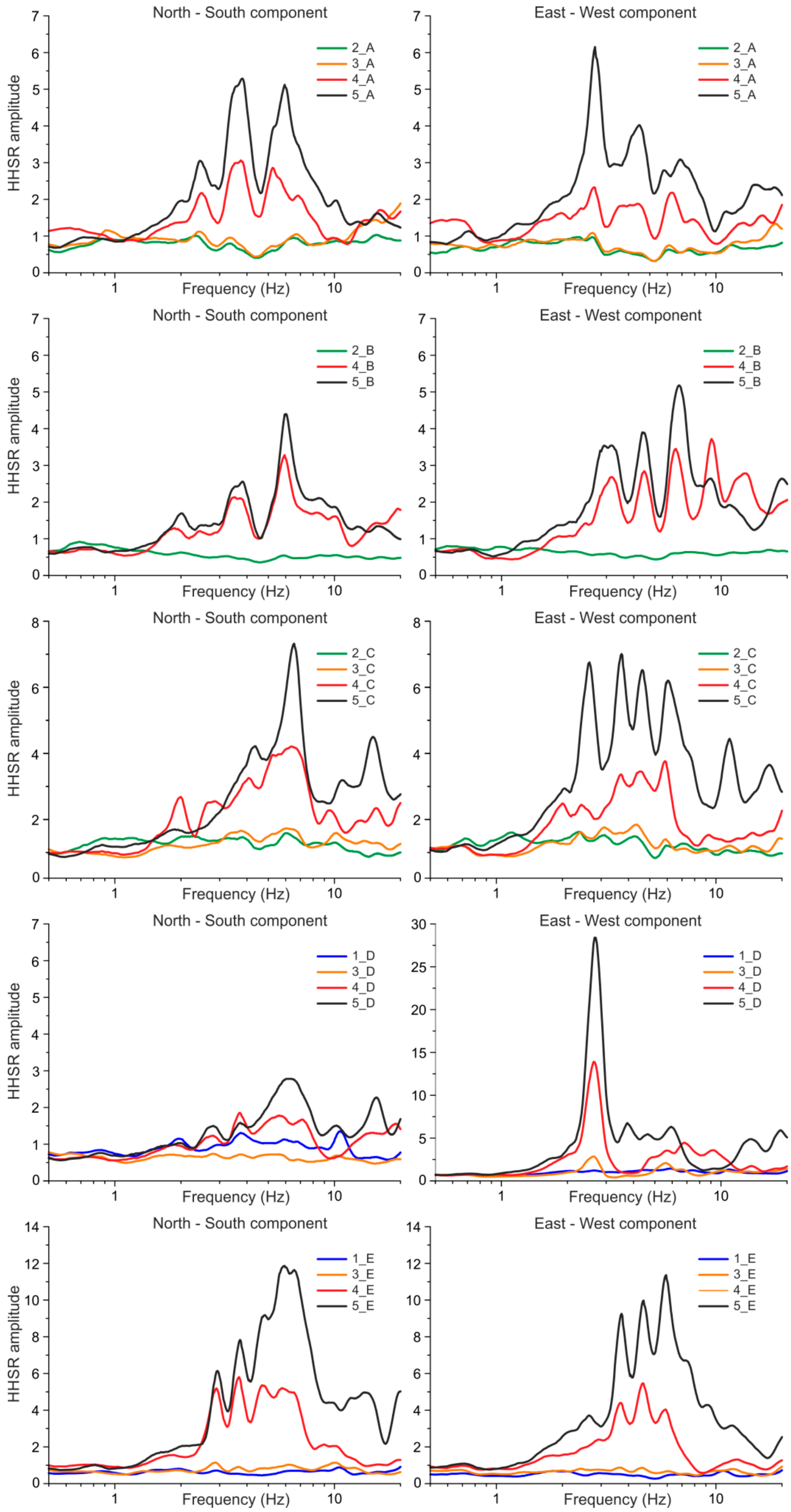


Figure 4. Horizontal-to-horizontal spectral ratio (HHSR) plots obtained from noise recordings performed at floors one (basement) to five (roof) for the sites A, B, C, D, and E.

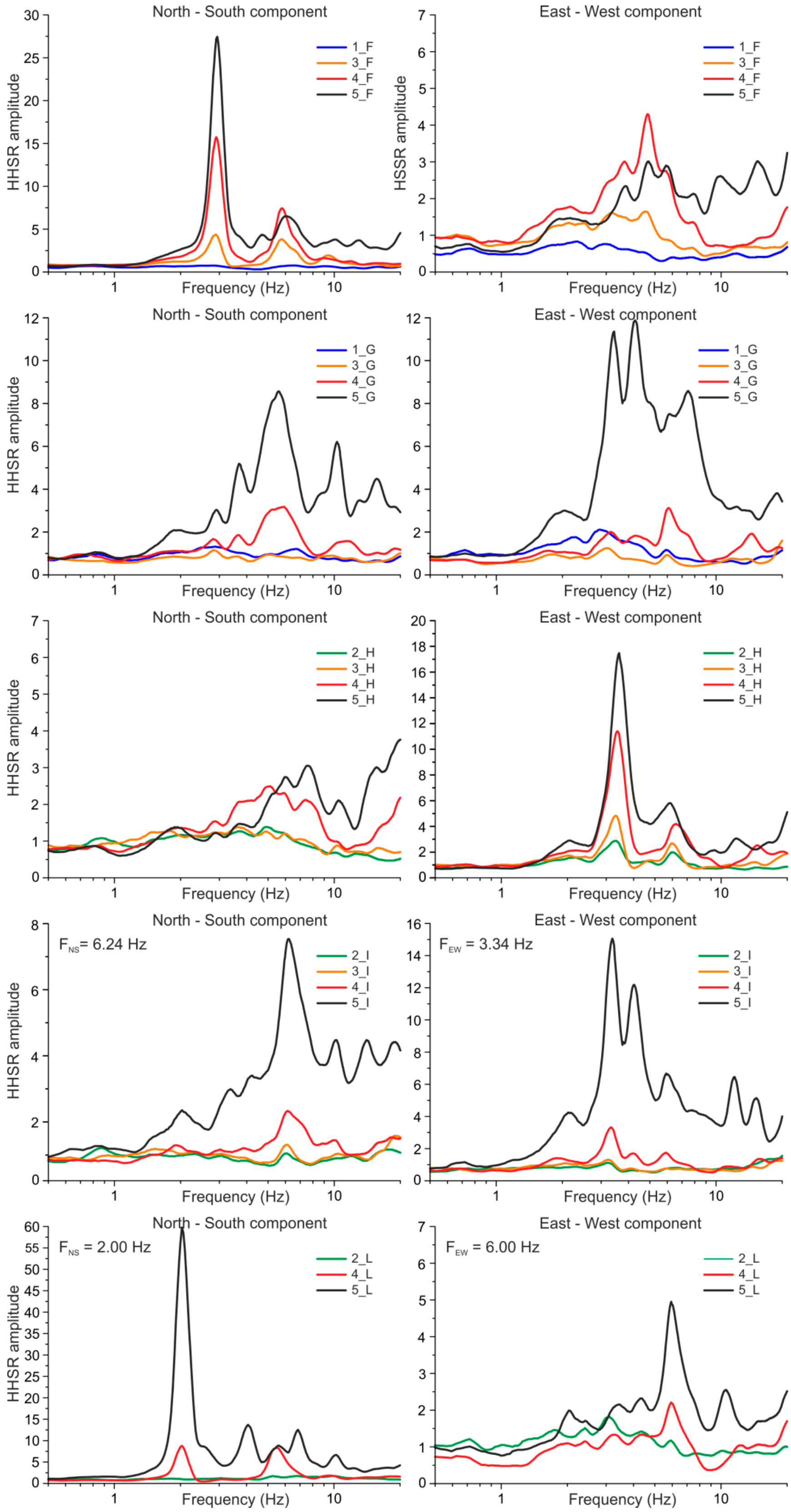


Figure 5. HHSR plots obtained from noise recordings performed at floors one (basement) to five (roof) for the sites F, G, H, I, and L.

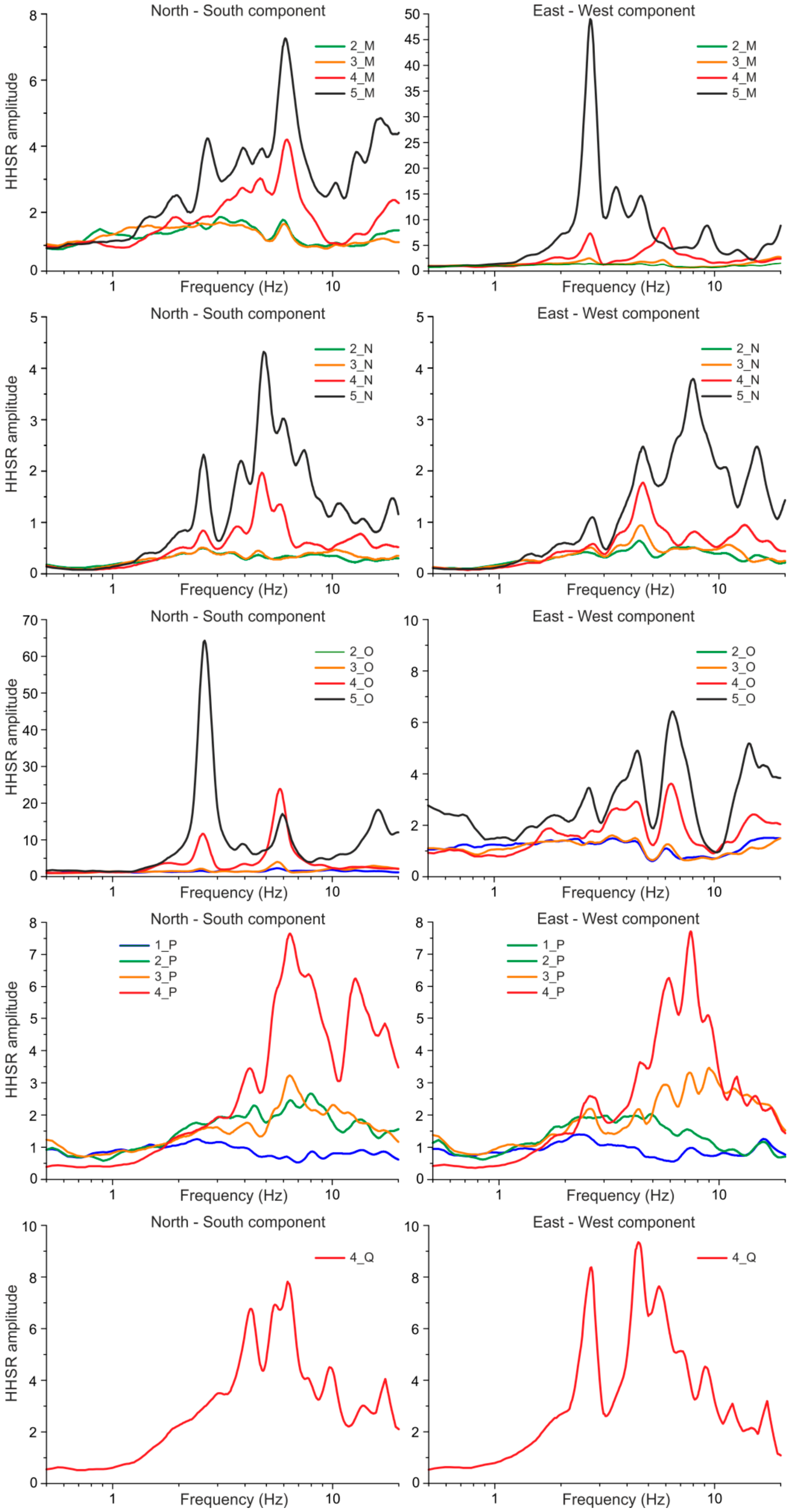


Figure 6. HHSR plots obtained from noise recordings performed at floors one (basement) to five (roof) for the sites M, N, O, P, and Q.

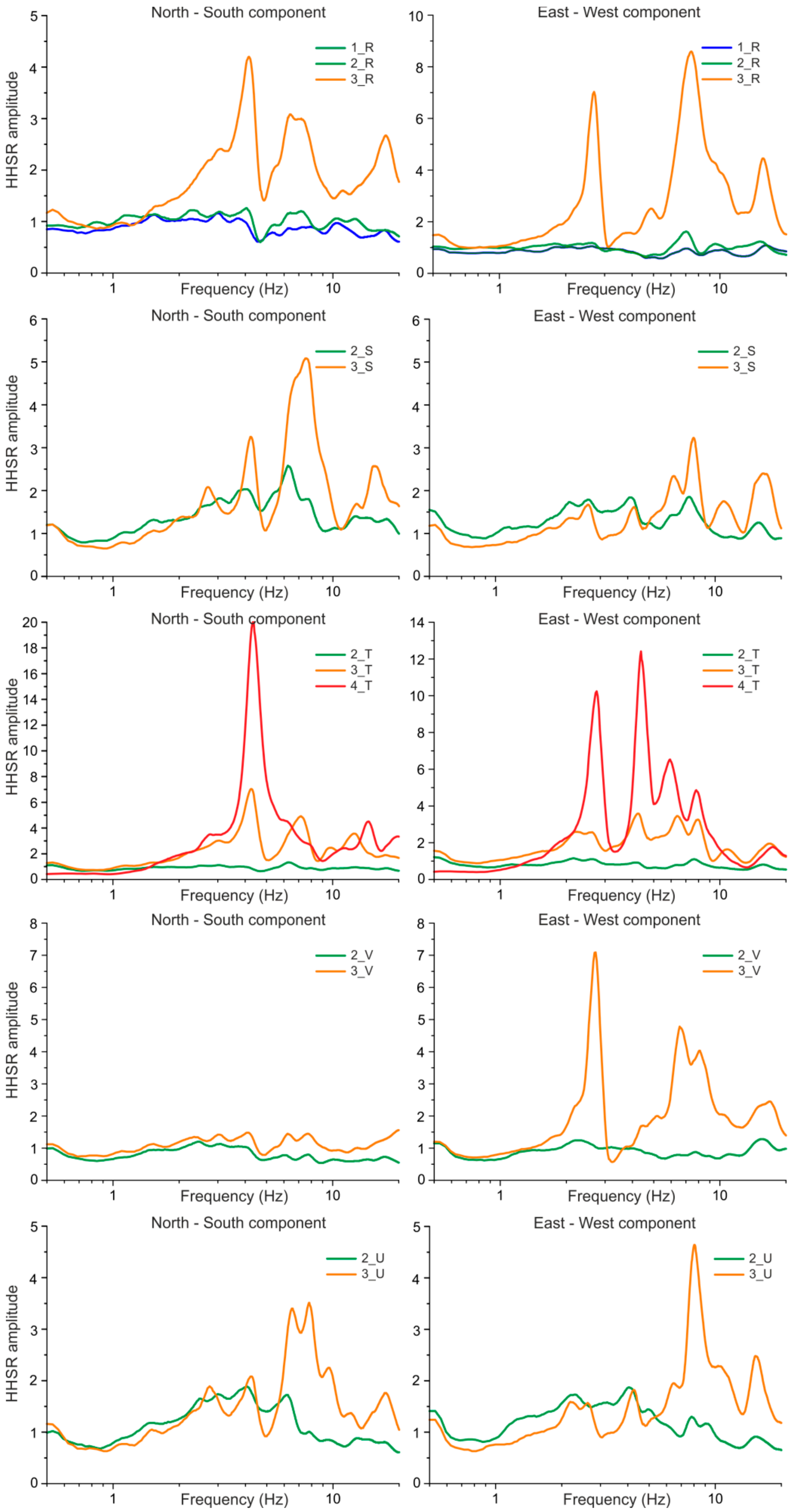


Figure 7. HHSR plots obtained from noise recordings performed at floors one (basement) to five (roof) for the sites R, S, T, U, and V.

The HVSR technique was instead applied to the recording sites located outside the building, computing the Fourier spectra (FFT) through the above described procedure. In this case, the ratio of the geometric averaged horizontal-to-vertical frequency spectrum is used to determine the fundamental site resonance frequency (Figure 8). Following the criteria suggested by SESAME [50], only the HVSR peaks reaching an amplitude that was greater than two units were considered as significant. The comparison between building and site frequencies was then used as a tool to put into evidence the potential presence of resonance between site and structure during a seismic event. It has to be remembered that the presence of lava flows at the surface could imply the existence of possible velocity inversions with the underlying soft sediments, which could give rise to a HVSR amplitude lower than one unit [51–53]. Panzera et al. [44] tested the influence of lava thickness on the HVSR amplitude, in the frequency range 1.0–10.0 Hz. The authors observed that the amplitude of the spectral ratio peaks decayed, reaching values lower than one, when massive lava with a thickness higher than 20 m overlaid sedimentary terrains. In the *Benedettini* monastery area, compact lavas did not outcrop, but the geologic sequence was made by 20–30 m of detritus, fractured lavas, and/or terraced deposits with lower shear wave velocities (see Figure 2).

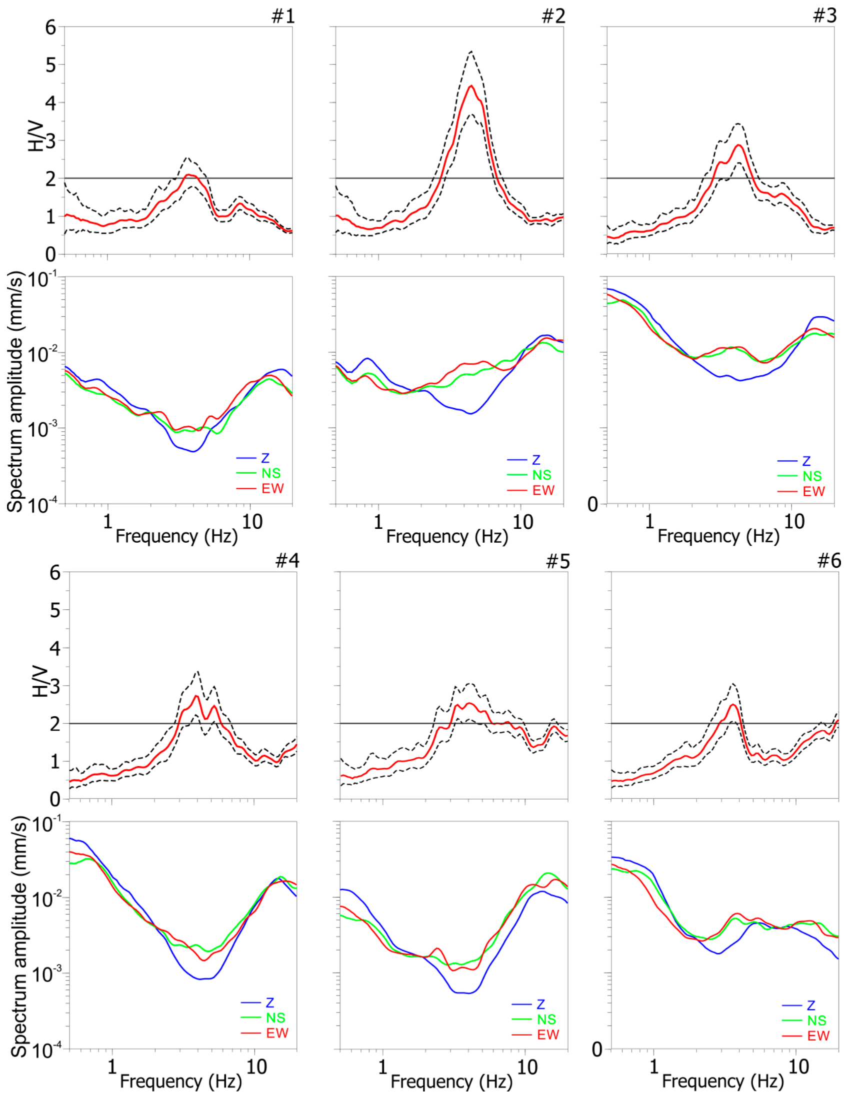


Figure 8. HVSR plots and corresponding Fourier spectra obtained from ambient noise recordings performed outside the *Benedettini* monastery (see Figure 1b for the locations).

The amplitude and duration of a building's shaking due to an earthquake is also related to its damping. In the present study, we adopted the Random Decrement Method (RDM) [54], which is one of the most used methodologies for assessing the damping on structures. A building can be assumed as a single degree of freedom oscillator whose motion equation is:

$$m\ddot{x} + c\dot{x} + kx = f(t) \tag{3}$$

where, $f(t)$ is the externally applied force as a function of time; m, c, and k are respectively the mass, the damping coefficient, and the stiffness of the system; x is the displacement, and $\dot{x}$ and $\ddot{x}$ are the velocity and the acceleration. The basic assumption of the RDM is that the input is the sum of a random signal and an impulse response function, as described by Equation (3). Then, by averaging several time windows (N) with the same initial conditions (initial displacement to be zero), the random component tends to disappear, while the response of the structure is enhanced. This procedure provides an estimate of the system free-vibration decay, $\delta(\tau)$, which can be obtained as:

$$\delta(\tau) = \frac{1}{N}\sum_{i=1}^{N} s(t_i + \tau) \tag{4}$$

where s is the ambient vibration window of duration τ, and t_i is the time verifying the initial conditions, in which ambient vibrations remain stationary, and the impulse response of the structure is revealed. In the present study, we estimated the damping values using ambient noise records, and through the RDM technique [55], which was implemented in Geopsy (http://www.geopsy.org/). The use of the RDM requires that the mode under analysis is well detectable [56]. Then, considering the Benedettini monastery as a complex structure characterised by several oscillation modes, we applied this technique only on measurement sites showing well separated modes. In particular, the RDM was applied on the first mode of vibration, which usually has the largest contribution to the structure's motion [57]. In order to properly apply the RDM on the chosen frequency, the signal was processed using a band pass butterworth filter with an order of 3 in a range of ±10% around the fundamental mode, and taking into account windows containing 20 times the considered period. Figure 9 shows examples of the computation performed for some selected locations in the topmost part of the studied structures.

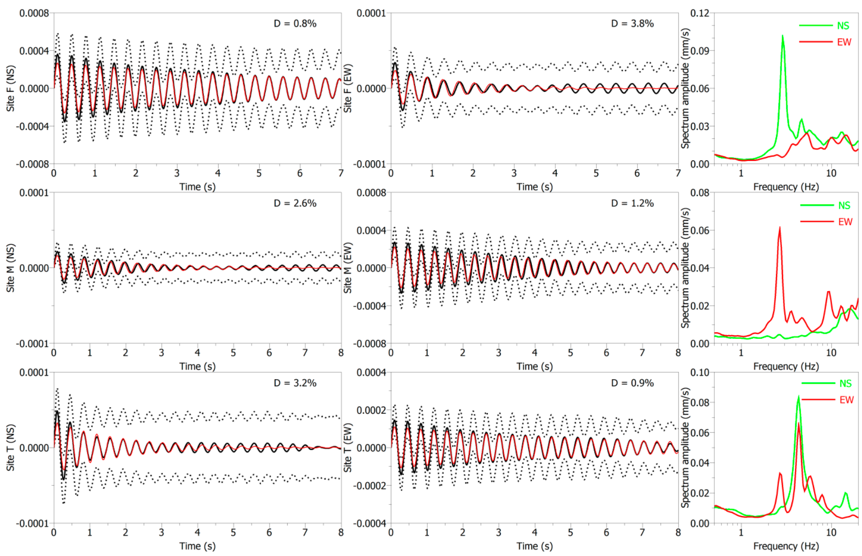
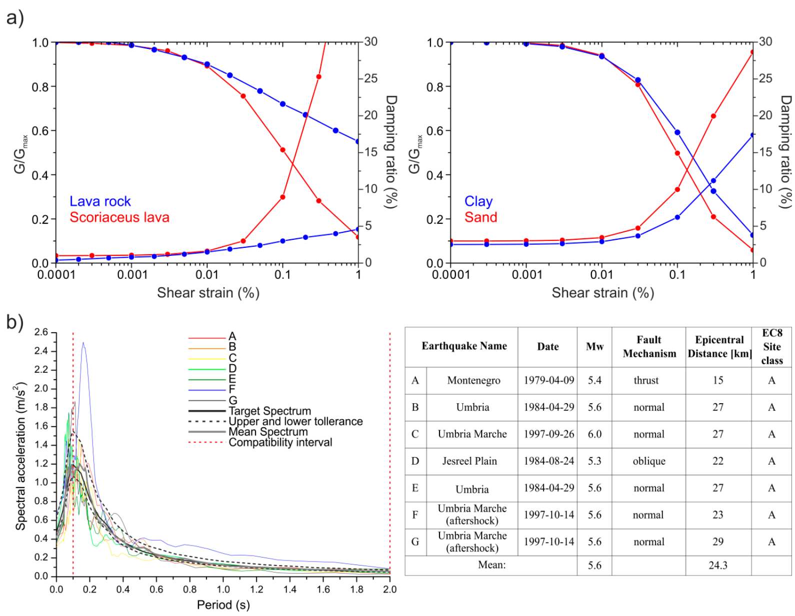


Figure 9. Examples of damping curves obtained using the random decrement method (RDM) and corresponding Fourier spectra (FFT) for selected sites. The continuous black line corresponds to the mean of the random decrement, the dashed lines correspond to the standard deviation, and the solid red line corresponds to the fitted exponentially decreasing function.

4.2. Modelling 1D Amplification Function

The scientific community agrees on the reliability of the fundamental frequency peak achieved through HVSR, whereas it has frequently questioned the existence of a simple direct correlation between HVSR amplitude values and the actual site amplification [13,58]. Catania is characterised by alternating outcrops of sediments and basaltic lavas, with the presence of possible lateral and vertical heterogeneities, but several authors [43,44,59] used one-dimensional (1D) modelling to reproduce the seismic site effects on the outcropping lithology, with sound results. For this reason, having no earthquake recordings for the investigated site, a numerical modelling was carried out using the code STRATA (https://nees.org/resources/strata). It computes the seismic site response of a 1D soil column using the equivalent-linear (EQL) approach or the frequency-dependent equivalent linear (F-EQL) analysis. The F-EQL approach was chosen in this study to overcome the limitations of EQL analysis in predicting site amplification at high frequencies when the induced strains are large [60]. The analysis is performed considering a horizontally polarised shear wave vertically propagating through horizontal layers. This code requires a geologic profile specifying the unit of weight (KN/m^3), the thickness (m), and the shear wave velocity (m/s) for each layer down to the bedrock. In particular, the bedrock was considered an elastic half-space with a unit of weight 20 kN/m^3 and 2% damping. Moreover, for the F-EQL response analysis, other key geotechnical parameters required include the normalised shear modulus decay $G(\gamma)/G_{max}$ and the damping versus strain curves $D(\gamma)$ for each layer. The input stratigraphic sequence (see Figure 2) was modelled using the elastic parameters of the main geological formations, as characterised in the CNR-GNDT (Consiglio Nazionale della Ricerche—Gruppo Nazionale Difesa dai Terremoti) "Catania Project" [61]. The used experimental curves of the $G(\gamma)/G_{max}$ and the $D(\gamma)$ are shown in Figure 10a. They were taken from Carrubba and Maugeri [62] for cohesive soils (clay) and from Cavallaro et al. [63] for weathered lava and non-cohesive soils (sand). These curves were obtained by performing the resonant column test (RCT) on specimens collected in Catania urban area. As regards the compact lava, strain-dependent damping and shear modulus degradation curves were taken from Seed and Idriss [64], according to Bessason and Kaynia [65], which estimated site amplification in lava rock on soft sediment sites.



	Earthquake Name	Date	Mw	Fault Mechanism	Epicentral Distance [km]	EC8 Site class
A	Montenegro	1979-04-09	5.4	thrust	15	A
B	Umbria	1984-04-29	5.6	normal	27	A
C	Umbria Marche	1997-09-26	6.0	normal	27	A
D	Jesreel Plain	1984-08-24	5.3	oblique	22	A
E	Umbria	1984-04-29	5.6	normal	27	A
F	Umbria Marche (aftershock)	1997-10-14	5.6	normal	23	A
G	Umbria Marche (aftershock)	1997-10-14	5.6	normal	29	A
Mean:			5.6		24.3	

Figure 10. (**a**) Shear modulus (G) and damping factor (D) dependent on shear strain (γ) used in this study; (**b**) compatible combination of the acceleration response spectra (5% damping) found for the considered earthquake scenario.

As a reference earthquake, we choose the M5.7 earthquake that struck southeastern Sicily in 1990, producing slight damage to the structural elements of the Church of San Nicolò l'Arena and in the eastern cloister. This strike slip event, located on Malta–Hyblean escarpment about 25–30 km from the city of Catania (see the epicentre location in the inset map of Figure 1b), can be considered as a moderate scenario for Catania [59]. The magnitude (M_W), the hypocentre distance, and the focal mechanism stand for the input of the Cauzzi et al. [66] attenuation law in order to define the target spectrum. The ground motion model, considering a strike slip mechanism and a Eurocode 8 [24] site class A, is defined by the following relationship:

$$Log_{10}Y = f_M + f_R + f_{SS} \tag{5}$$

where the terms f_M and f_R are:

$$f_M = c_1 + m_1 M_W + m_2 M_w^2 \tag{6}$$

$$f_R = (r_1 + r_2 M_W) Log_{10}(R_{RUP} + r_3) \tag{7}$$

in which c_1, m_1, m_2, r_1, r_2, r_3, and f_{SS} (strike slip fault mechanism) are numerical coefficients determined by the authors through regression analyses. The R_{RUP} is the rupture distance, which for the magnitude minor or equal to 5.7, the authors considered equivalent to the hypocentre distance [66]. This ground motion prediction equation is defined for the 5% damping displacement response spectrum (*DRS*) in cm, considering the period (*T*) range 0.01–10 s. This relationship is also defined for the peak ground acceleration (*PGA*) in cm/s^2 and for the peak ground velocity (PGV) in cm/s. Pseudo-spectral acceleration (*PSA*) values can therefore be computed from *DRS* by using the formula:

$$PSA(T;5\%) = DRS(T;5\%)\frac{4\pi}{T^2} \tag{8}$$

The dataset used to calibrate such an attenuation model encloses more than 3600 accelerometer records from 98 global earthquakes with moment magnitudes ranging from 4.5 to 7.9. The *PSA* obtained for the chosen reference earthquake was then used to select seven strong motion accelerograms from the European strong motion database (ESD) [67] through the REXEL software [68] (Figure 10b). In the first step, the code selects the records contained in the ESD that fall into the magnitude and distance bins specified by the user for a specific site class. Afterwards, the user specifies the period range and the tolerance limits within which the average spectrum of the N selected accelerograms should be included. The search is in this case performed by selecting $N = 7$ records that match the design spectrum in the period interval 0.1–2.0 s, considering a 30% (upper) and a 10% (lower) tolerance. Figure 10b shows the results of the performed analysis.

The STRATA code provides, among the outputs, the mean acceleration response spectra (Sa) at the chosen critical damping, the mean amplification function, which was obtained as the ratio between Sa at the surface and at the bedrock, and the peak ground acceleration profile (Figure 11).

5. Discussion and Concluding Remarks

This study aims at investigating the dynamic properties of the *Benedettini* monastery structure. In order to inspect possible soil-to-structure resonance effects, the natural frequencies experimentally obtained for the different portions of the complex building were compared with the ones measured in the free field area close to the monastery. As previously specified, the San Nicolò l'Arena church and the public library were excluded from this study, since they are not easily accessible due to being owned by the Catania municipality. However, their dynamic properties were studied by Valente and Zigone [69].

The HHSR results set into evidence the complex dynamic behaviour of the monastery structure. It can indeed be observed that most of the spectral ratios do not enable the identification of a single natural frequency, but they do show several oscillation modes (see Figures 4–7) in the frequency range of 2.0–10.0 Hz. These results can be interpreted as a consequence of several factors, such as the structural complexity of the whole edifice (masonry building with the presence of reinforced concrete elements), the irregular plan shape, and the presence of adjacent structures. Local modes near the measurement points can indeed be ascribed to the floor tiling, floating floors, piping, and the out-of-plane movements of detached walls and stairwells that are detached from the frame of the building. In the monastery, all of these elements are present as a consequence of the changes made over the years to adapt the structure to different uses. However, in some places of this complex building, where the influence of the above listed elements is lower (e.g., sites D, F, H, L, M, O, and T in Figure 3), the presence of dominant fundamental frequencies can easily be detected in the HHSRs. In such cases, pronounced dominant peaks are observed in the frequency interval 2.0–5.0 Hz (Figures 4–7), emphasizing that, besides the lack of homogeneity of the complex plan, the role played by the different heights of the various portions of the building is not negligible (see inset in Figure 3).

The decay of the building shaking amplitude due to a seismic input was estimated through the RDM, which allows the quantification of the building damping. Although the damping values obtained through a weak motion input (ambient noise) must be handled with caution, significant information can be gained. Most seismic codes assume a 5% constant value of damping without correlating it with the fundamental period of the structure. In a recent study, Salameh et al. [70] demonstrated that the damping is related to the soil foundation and the building geometry. In our study, it also appeared evident that the variability was linked to the different rigidity of this complex structure as a function of the longitudinal or transversal orientation of its structural elements. The examples in Figure 9 set into evidence damping values that changed between 1–5%, varying when measurements were performed in either the north–south (NS) or east–west (EW) oriented parts of the structure.

The HVSR outside the monastery (Figure 8) allowed us to determine the predominant frequencies of the soil. The spectral ratios depicted significant peaks, with amplitudes between two and five units, in the frequency range of 3.0–6.0 Hz. The influence of the 1669 AD lava layer on the spectral ratio amplitude was also quite evident. The highest spectral ratio amplitudes were indeed observed in site #2 (see Figures 1 and 8), where such a lava layer was not present, and a decrease in amplitude was observed as the thickness of the lava increased (see #1, #3, and #6 in Figures 1 and 8). At sites #4 and #5 (see Figures 1 and 8), where the 1669 AD lava overlaid the 693 BC lava, the HVSRs showed a broadband distribution of frequencies, due to the existence of alternating compact and scoriaceous layers having different velocities. The monastery was then built on several stratigraphic sequences showing different HVSR patterns. The reliability of the observed HVSR peaks was tested by inspecting the shape of the Fourier spectra (FFT). As described by Castellaro and Mulargia [52], the existence of a geologic discontinuity was identified in the Fourier spectra by the presence of an "eye-shaped" feature, with a local minimum of the vertical component. Conversely, the presence of three individual spectral peaks is usually related to disturbances such as those induced by nearby structures. The FFT spectra related to HVSRs clearly showed the presence of the "eye-shaped" features, therefore excluding the influence of disturbances (Figure 8). It is also important to point out that the comparison between the buildings and the site frequencies put into evidence the existence of potential site-to-structure resonance during a seismic event. This can explain the moderate damage observed in the San Nicolò l'Arena church and in the eastern cloister as a consequence of the M5.7 1990 earthquake.

Numerical modelling of the borehole stratigraphies (see the location in Figure 2) was carried out using the code STRATA, in order to evaluate the 1990 earthquake ground shaking. The results, which were obtained in terms of the acceleration response spectra at 2% and 5% damping, point out that the highest spectral acceleration peaks fell in the range of the monastery main oscillation periods, with maximum *PSA* values between 0.3 g and 0.6 g. The amplification functions showed a shape similar to that of HVSRs, reaching amplification values between 2.5 and 4.0 (Figure 11). The peak ground acceleration profiles (Figure 11) highlighted that the main amplification effects took place at a depth lower than 10 m. This can be related to the presence of a discard material and a detritus layer originating from the ruins of past earthquakes.

Finally, we tried to use the PGA values obtained at the surface to estimate a mean Mercalli–Cancani–Sieberg macroseismic intensity (I_{MCS}) for the area. The scientific literature reports several relationships correlating I_{MCS} and PGA, such as that proposed by Locati et al. [71]:

$$I_{MCS} = -0.64 + 3.58 LogPGA(cm/s^2) \quad (9)$$

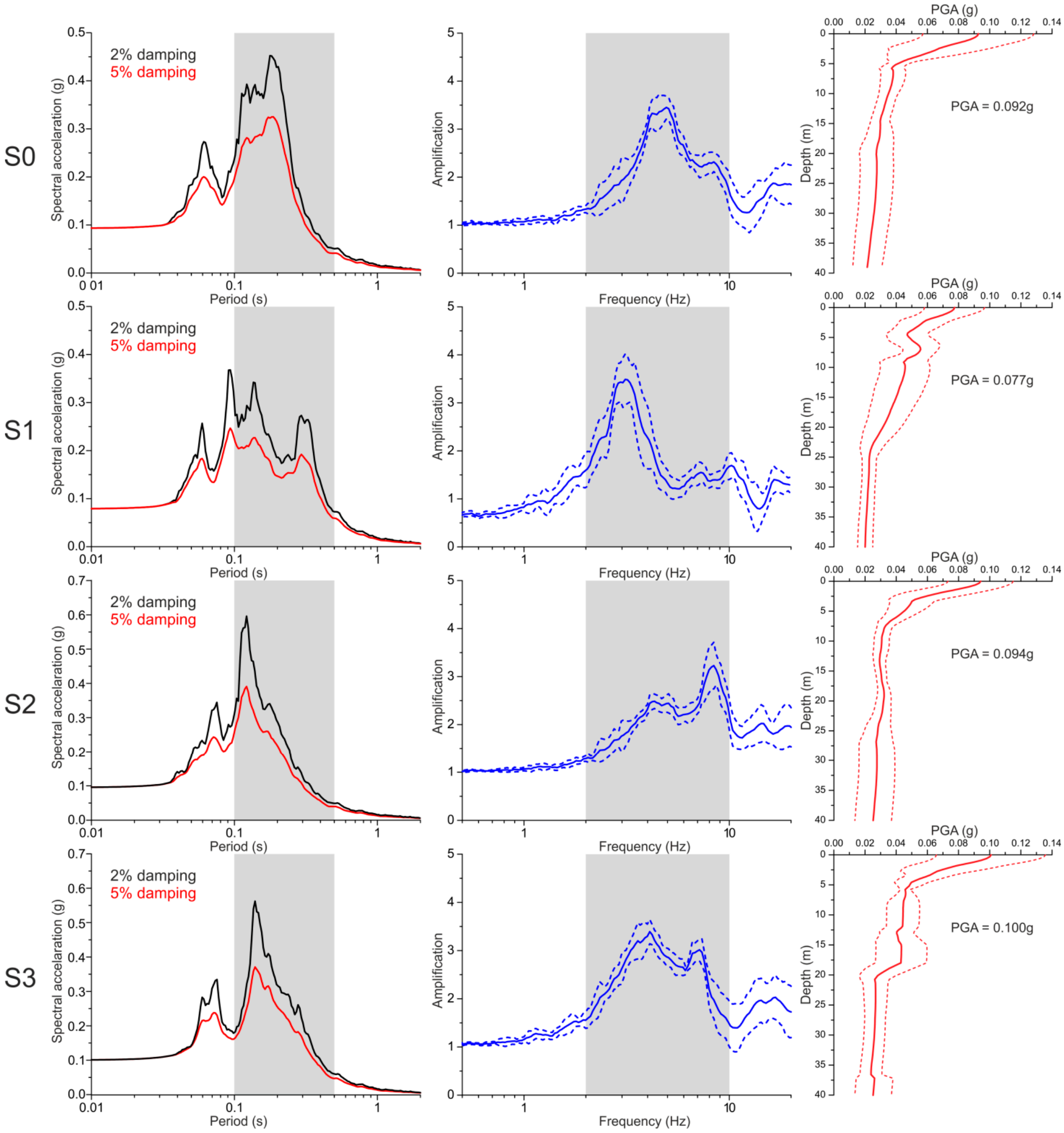


Figure 11. Acceleration spectra, amplification function, and peak ground acceleration profile obtained from the one-dimensional (1D) modelling performed through the code STRATA.

It was then possible to estimate an I_{MCS} value of about VI–VII for the study area, which is sufficient to explain the observed damage to the monastery.

The approach followed in the present study highlights how the structural complexity and the local seismic response play an important role in building damage. Through a detailed ambient vibration survey and a 1D site response modelling, it was possible to highlight the main soil and structure properties. These findings can therefore represent useful clues for further numerical modelling, and to finalise additional engineering investigations aiming at reducing the seismic risk.

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