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Geological and geophysical characterization of the "Duomo di Orvieto" area, Umbria Region, Central Italy

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ABSTRACT: A multidisciplinary approach based on the integration of in situ geophysical and geological techniques was applied to investigate the Orvieto Cathedral (Umbria Region, Central Italy) and the subsurface. In particular, the electrical resistivity tomography and the horizontal to vertical spectral ratio analysis of single station ambient vibrations measurements were used. This paper reports the results obtained with the joint analysis of the in situ geophysical investigations, geological field survey and borehole data. The joint analysis of different data allowed us (1) to image the geological setting, (2) to highlight some resonance frequencies of the monumental building, and (3) to estimate the resonance frequency of the site.

1 INTRODUCTION

In recent years, the geophysical methods (e.g. seismic, magnetic, electrical and electromagnetic, etc.) are increasingly used to investigate the subsurface without having to engage in invasive investigations such as boreholes and probes. In many instances, geophysical techniques enhance the reliability and speed, and also reduce the overall costs of the investigation and the risk of missing target features. Among the available geophysical techniques, the electrical resistivity tomography (ERT) and the horizontal to vertical spectral ratio method (HVSR) applied to single station ambient vibrations (AMV) measurements have been widely applied to provide valuable information in seismic microzonation (Moscatelli et al. 2014), seismotectonic and geomorphological studies (Balasco et al. 2011), civil engineering applications (Mucciarelli et al. 2011) to characterize the seismogenic fault systems (Galli et al. 2014), to reconstruct the geometry and the mechanical-dynamical properties of the superficial litho-stratigraphic units (Hailemikael et al. 2017), to delineate landslide body (Perrone et al. 2014) and to study coseismic liquefaction phenomena (Giocoli et al. 2014).

In this study, the Orvieto Cathedral in Umbria Region, Central Italy, and the underling subsurface structure were investigated by the joint application of ERT and HVSR by single-station ambient AMV measurements in order to provide preliminary information useful for the assessment of the safety level of the Cathedral under future earthquakes.

2 GEOLOGICAL SETTING

The geological setting of Orvieto is the result of neotectonic and volcanic events taking place in the Quaternary period. The stratigraphic sequence of the study area is characterized, from bottom to top, by the Cenozoic shales, marls and sandstones of the Umbro-Tuscan units (CU) covered by the Middle Pliocene marine clays (MC), followed by a Lower Pleistocene sequence in fluvial-lacustrine facies (sands, gravels, diatomites and pumices) of limited

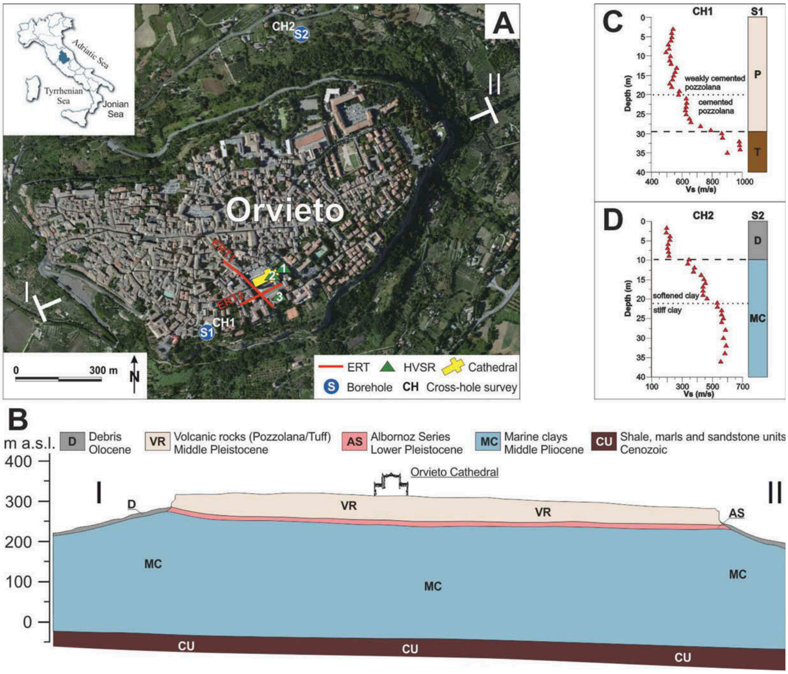

Figure 1. A) Satellite map of the Orvieto town showing the locations of the boreholes (S1, S2) with cross-hole (CH1, CH2) and of the Orvieto Cathedral. B) Geological schematic cross-section of Orvieto. C) Borehole log S1 with shear wave velocity (Vs) profile from cross-hole survey CH1 (modified by Muzzi et al. 2001). P - pozzolana. T - Tuff. D) Borehole log S2 with shear wave velocity profile from cross-hole survey CH2 (modified by Muzzi et al. 2001). D - Debris. MC - marine clays.

thickness known as Albornoz Series (AS), and finally by the Middle Pleistocene volcanic rocks (VR) (Figure 1).

The medieval town of Orvieto sits on the volcanic rocks, which constitute a tabular volcanic mesa (Orvieto mesa) about 1500 m long and 700 m wide. The Orvieto mesa is an erosion relict situated at the edge of the broad Alfina plateau produced by the volcanic activity of the Apparato Vulsino roughly 315000 years ago (Cencetti et al. 2005). Two distinct facies constitute the Orvieto mesa: the first one has a more marked stony appearance (tuff) with sub-vertical fissures from cooling and a reddish-yellow color and the second one (pozzolana) can be traced to a loose mass, blackish-grey in color and without evident fissuring. The Orvieto mesa is bounded by a distinct escarpment with a height from a few to tens of meters. Slopes bounding the volcanic escarpment are very steep (> 70°), locally vertical. At the interface between the volcanic rocks and the underlying MC a sharp break in slope from subvertical to about 12° is observed. The Orvieto area has been constantly affected by landslide phenomena. Landslides occur in the volcanic rocks and in the underlying MC. Several types of landslides were documented. A further cause of instability is the collapse of vaults of the numerous man-made caves in the volcanic mesa. The analysis of archival data revealed that some rock falls and severe building damages are related to historic earthquakes. As documented by historical sources, Orvieto suffered the effects of both far-field and near-field earthquakes.

In this work, geological investigations together with electrical resistivity tomography (ERT) and horizontal-to-vertical spectral ratio by single-station ambient vibrations recordings (HVSR-AMV) were performed to provide preliminary information useful for the assessment of the safety level of the Orvieto Cathedral under future earthquakes. In particular, two ERT and three HVSR-AMV (Figure 1) were carried out in order to (1) image the geological setting, (2) evaluate the main resonance frequencies of the monumental building, and (3) estimate the resonance frequency of the site. The ERT and HVSR results were supported by geological field survey and data obtained by two geognostic wells and two cross-hole surveys (Muzzi et al. 2001) reported in Figure 1 as S1, S2 and CH1, CH2.

3 ELECTRICAL RESISTIVITY TOMOGRAPHY

Two ERT surveys (ERT1 and ERT2) were performed to investigate the subsurface in the Orvieto Cathedral square. Electrical resistivity data was collected with a Syscal R2 (Iris Instruments) resistivity meter, coupled to a multielectrode acquisition system (37 or 48 electrodes) with constant spacing (a = 5 m) between adjacent electrodes. The length of the ERT ranged from 180 - 235 m. Different array configurations (e.g., Dipole-Dipole, Wenner-Schlumberger, and Wenner) and different combination of dipole length (1a, 2a, etc.) and "n" number of depth levels ($n < 7$) were used, obtaining investigation depths of about 35 m. The data analysis was carried out using the RES2DINV software (Loke 2001). The obtained 2D electrical resistivity models are shown in Figure 2. The ERT show an absolute error of 8.5 % and a resistivity values range from 13 to more than 2361 Ωm.

The two ERT cross each other at 90° and at the intersection show the same electrical resistivity distribution (Figures 1 and 2). This highlights the good quality of the electrical resistivity data, as ERT1 and ERT2 were acquired and processed independently.

On the basis of both geological and borehole data (Figure 1), it was possible to calibrate the electrical resistivity models and to directly correlate the electrical resistivity values with the subsurface lithologies.

Both ERT1 and ERT2 show a resistivity pattern characterized by two plane-parallel electrical resistivity layers. In agreement with geological and borehole data, the surficial layer (thickness < 20-25 m) of lower electrical resistivity values (< 250 Ωm) is related to the pozzolana, whereas the lower layer (below 305 m a.s.l.) of higher electrical resistivity values (> 250 Ωm) can be attributed to the tuff, as found in the borehole S1 (Figure 1). The most outstanding feature of the tuff layer is certainly the relatively low resistivity zone ($\rho < 150$ Ωm) between 100 and 140 m in ERT1 and between 70 and 10 m in ERT2. This is due to different physical (electrical) properties of the same lithotype (tuff), rather than to the presence of different lithologies. In particular, it can be attributed to the highly fractured tuff. The very high electrical resistivity sectors (> 2300 Ωm) inside the pozzolana layer are associated to the man-made caves or to the anthropic structures.

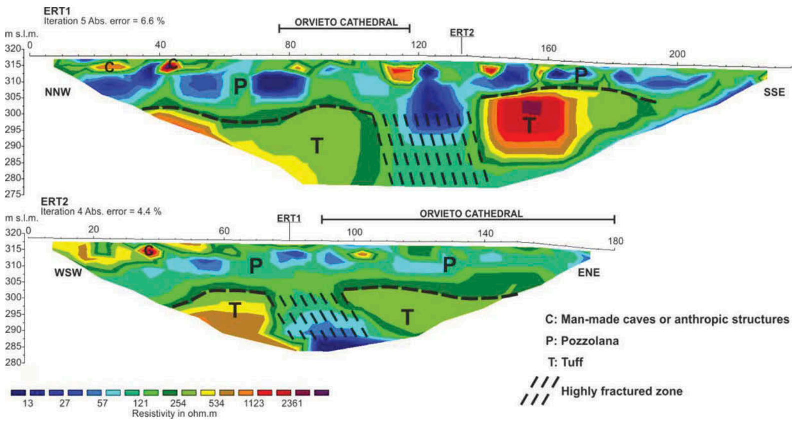

Figure 2. ERT1 and ERT2 carried out across the Orvieto Cathedral square (see Figure 1 for the location of ERT).

4 HORIZONTAL TO VERTICAL SPECTRAL RATIO BY SINGLE-STATION AMBIENT VIBRATIONS MEASUREMENTS

The dynamic behavior of the complex building was already studied in a previous experimental campaign (Clemente & Buffarini, 1998). Measurements were carried out between October 6th and 15th, 1997. Eight velocimetric SS-1 Kinematrics sensors were deployed in 19 different configurations. A resonance frequency at 2.5 Hz was present in almost all the spectra relative to the sensors in the transversal direction of the nave. Records of the nave walls showed also resonance frequencies at 1.1 and 1.5 Hz. These could be related to anti-symmetric and symmetric modes of the walls, respectively.

In June 2013, three single-station ambient vibrations (AMV) measurements were performed to obtain a fast estimate of the resonance frequency of the Cathedral and of the underling subsurface. In particular, the HVSR 1 measure was performed in the free field 5 m outside the Cathedral, the HVSR 2 measure was carried out at the foundation level of the Cathedral, and the HVSR 3 measure was carried out at about 60 m away from the Cathedral in a cave 15 m below the ground floor of Villa Mercede building. The Figure 1 shows the location of the single-station AMV measurements. All the measurements were performed using a SARA 24 bit SL06 data-logger connected with a triaxial SS20 geophone (2 Hz nominal eigen-frequency). It has been demonstrated that short-period sensors ensure reliable measurements far below the nominal eigen-frequency (Strollo et al. 2008). In all cases, the data were acquired for a minimum recording length of 30 min and sampling rate was fixed to 200 sps. In particular, for the measure located at the foundation level of the Cathedral (HVSR 2) and in the cave 15 m below the ground floor of Villa Mercede housing (HVSR 3), the recordings were synchronous and acquired for 2 hours during night-time between 02:00 and 04:00 a.m..

To calculate HVSR curves, each record was processed to remove the mean value and linear trend. Subsequently, the signals were divided in time windows of 60 s length allowing 50 % overlap between windows. Only stationary time windows were selected for the analysis by applying an anti-triggering algorithm to avoid strong transients. For each selected window, the signals were 5 % cosine tapered and converted to the frequency domain. The spectra were smoothed using the Konno–Omachi window with parameter b value set to 40 (Konno & Omachi, 1998). The horizontal spectrum of ground motion was calculated as the quadratic average of the smoothed spectra of the north–south (NS) and west–east (WE) components and then divided to the vertical spectrum to obtain the HVSR curve for each time window. The final HVSR function was calculated as the average HVSR curve for all the time windows.

We analysed the HVSR results in the frequency range 0.2–15 Hz and interpreted them according to the SESAME project criteria (SESAME, 2004) (Figure 3).

The HVSR results show a significant peak, with average amplitude between 4 and 9, at the frequency 0.45 Hz and secondary maxima between 3 and 5 in the range 1 - 1.50 Hz (Figure 3). The reliability of the HVSR peaks was evaluated by analyzing the shape of the spectral components of motion. The 0.45 Hz peak is a stable and consistent feature in all HVSR curves (HVSR 1, 2 and 3). In addition, the 0.45 Hz HVSR peak is due to a local minimum of the vertical component with an "eye shape" in the spectra plot (Figure 3). This 'eye shape' is always the clear signature of a HVSR peak with stratigraphic origin (Castellaro & Mulargia, 2009). This observation, together with the large mean amplitude of the 0.45 Hz HVSR peak above 4, allow us to interpret the 0.45 Hz HVSR peak as the subsurface fundamental frequency in the Orvieto Cathedral area.

The interpretation of the HVSR peaks in the range 1-1.5 Hz was mainly based on the analysis of the HVSR 1 and 2 carried out 5 m outside and inside the Cathedral, respectively. By analyzing the shape of the average spectra of the three components of motion in the frequency range 1-1.5 Hz, it is possible to note that the shape is not characterized by an "eye shape" pattern but by the presence of three individual spectral peaks with different amplitudes (source effect). Thus, the HVSR peak in the frequency range 1-1.5 Hz was associated to the resonance frequency of the Cathedral, in agreement with Clemente & Buffarini (1998). The effect of the Orvieto Cathedral is not present in the spectra recorded 15 m below the ground level for measure 3 (Figure 3, right-bottom panel), suggesting that the structural vibration of

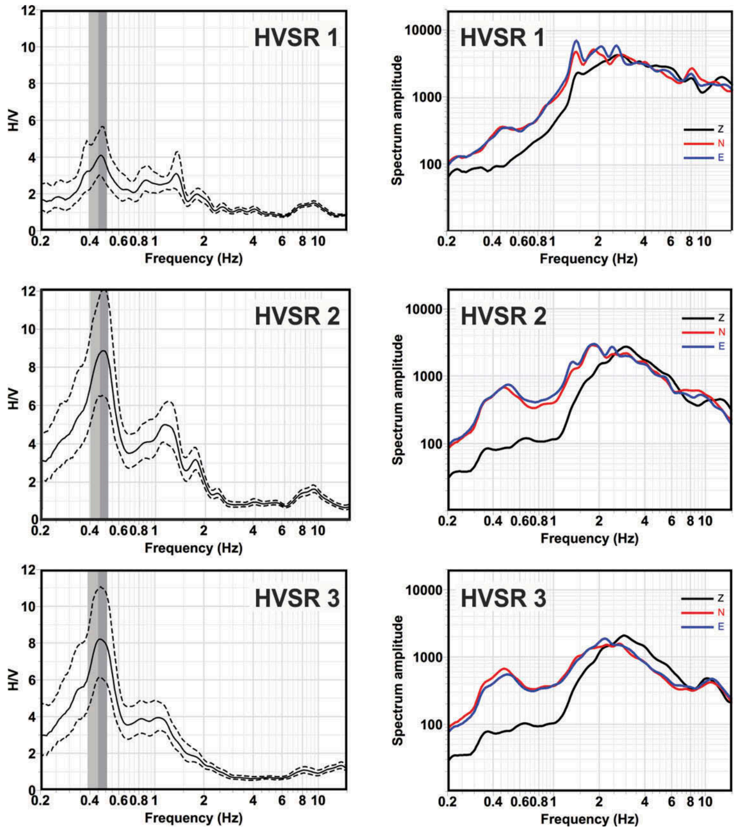

Figure 3. Average HVSR (solid black curves) obtained for measurement performed in the free field 5 m outside the Cathedral (HVSR 1), inside the Cathedral at the foundation level (HVSR 2), and 60 m away from the Cathedral in a cave 15 m below the ground floor of Villa Mercede building (HVSR 3) (see Figure 1 for measurement locations); dashed lines represent the average ± 1 st. dev.. The vertical gray bars show the uncertainty in the estimation of the resonance frequency. Right panels: average spectra computed for the three components of motion.

the Cathedral strongly affects the AMV wavefield at close distance and at the ground surface (HVSR 1 and 2).

The spectra of the three components of motion also show the higher amplitude of the Z component with respect to the horizontals, which causes the HVSR amplitude to become lower than one in the 2.5-7 Hz band. This may be due to the velocity inversion between T and the underlying less rigid AS/MC and/or to the shallow velocity inversion by the presence of a large cavity network in the volcanic rocks of the Orvieto mesa (Castellaro & Mulargia, 2009).

5 1-D NUMERICAL MODEL

To evaluate the reliability of the estimated fundamental frequency in the Orvieto Cathedral area through HVSR method (i.e. 0.45 Hz), we validated our observations against independent information about the subsurface properties of the study area. In particular, we numerically simulated the free-field HVSR function by its direct 1D forward calculation using the HVinv code (García-Jerez et al. 2016). This code allows for the calculation of synthetic HVSR curves at the free surface of 1D horizontally stratified multilayered models in which media are isotropic and elastic. In particular, the subsurface structure is considered made of horizontally

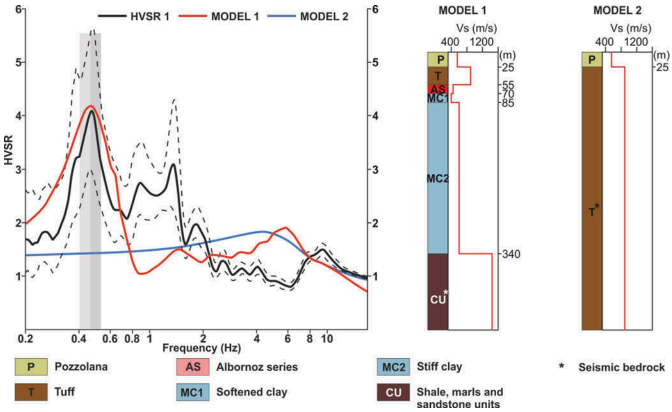

Figure 4. Comparison between the theoretical HVSR calculated from 1-D model 1 (bleu curve) and model 2 (red curve), and the HVSR 1 obtained in free-field outsite the Orvieto Cathedral; the vertical gray bars show the uncertainty in the estimation of the resonance frequency thorough HVSR method.

stratified uniform layers over an elastic half-space (i.e. seismic bedrock). Each layer is characterized by the following parameters: thickness "h", density "ρ", P-wave velocity "Vp" and S-wave velocity "Vs". At Orvieto Cathedral the subsurface structure includes, from top to bottom:

- 25 m of pozzolana, P (ρ = 1390 Kg/m^3; Vs = 560 m/s; Vp = 950 m/s);
- 30 m of tuff, T (ρ = 1300 Kg/m^3; Vs = 900 m/s; Vp = 1700 m/s);
- 15 m of Albornoz series, AS (ρ = 1730 Kg/m^3; Vs = 450 m/s; Vp = 780 m/s);
- 15 m of softened clay, MC1 (ρ = 2010 Kg/m^3; Vs = 400 m/s; Vp = 1300 m/s
- 200-450 m of stiff clay, MC2 (ρ = 2180 Kg/m^3; Vs = 600 m/s; Vp = 1700 m/s);
- shale, marls and sandstone units, CU (ρ = 2500 Kg/m^3; Vs = 1450 m/s; Vp = 2500 m/s).

The constant value of the parameters (h, ρ, Vp and Vs) for each layer was well established from our geological and ERT investigations and from previous geotechnical and geophysical studies carried out in the Orvieto area (Muzzi et al. 2001). In detail, the thickness of P unit was evaluated by the ERT1 and ERT2 (Figure 2), whereas the thicknesses of T and AS units were derived our field geological investigation. As regard the thickness of MC, gravimetric investigation carried out by Di Filippo et al. 1991 showed at least 200 m thick MC near the Orvieto mesa. In addition, geological information (Jacobacci et al., 1970) suggest that all Pliocene succession (i.e. MC) has a maximum thickness of about 400-450 m and lies directly on CU.

The theoretical HVSR curves were obtained for different models constituted of 5 homogeneous elastic layers, corresponding to P, T, AS, MC1 and MC2 units, overlaying an elastic half-space identified as CU (seismic bedrock). Given that the major uncertainty concern the thickness of MC2, we simulated the theoretical HVSR curve for different models changing only the MC2 thickness. The best result was obtained for the model 1 in Figure 4. In addition, considering that the European and Italian building regulations, Eurocode 8 (ENV, 1998) and NTC18 (2018), rely on the identification of a soil category to account for site effects in the estimation of the expected earthquake ground-motion level and that the identification of the soil category is based on the average shear wave velocity of the upper 30 m ($V_{s,30}$) to discriminate soil categories, we decided to define the theoretical HVSR of a further model (model 2, Figure 4). The difference between models is that the model 1 is representative of the whole subsurface down to bedrock depth (about 340 m) (Figure 1B), whereas the model 2 is limited to the shallower 30 m and the half-space is considered as the top of the T layer.

The results in terms of theoretical HVSR of model 1 and 2 are compared with the reference observation obtained in free-field (HVSR 1) in Figure 4.

The Figure 4 shows a good agreement between the empirically estimated f_0 value and the fundamental peak of the theoretical HVSR of model 1. This observation supports the interpretation of the low frequency resonance at 0.45 Hz in the Orvieto Cathedral area as due to the thick stratigraphic succession down to bedrock depth at about 340 m below the ground surface.

As expected, the theoretical HVSR calculated on the basis of model 2 shows a broader shape with maximum value of 1.5 around 5 Hz (red curve in Figure 4), which cannot reproduce the peak frequency at 0.45 Hz. This comparison confirms that f_0 estimation by HVSR is a valuable tool for the determination of the site frequency response, as suggested by several studies (Luzi et al. 2011).

6 CONCLUSION

In this study, a multidisciplinary approach based on the integration of in situ geophysical and geological techniques was applied to investigate the Orvieto Cathedral (Umbria Region, Central Italy) and the subsurface. In particular, we focus our attention on two geophysical techniques, the electrical resistivity tomography (ERT) and the horizontal-to-vertical spectral ratio by single-station ambient vibration recordings (HVSR-AMV). The joint analysis of different data allowed us (1) to image the geological setting, (2) to highlight some resonance frequencies of the Orvieto Cathedral, and (3) to estimate the resonance frequency of the site.

ERT1 and ERT2 were carried out across the Orvieto Cathedral square. The two ERT investigations put into evidence two plane-parallel electrical resistivity layers. In agreement with borehole data and our geological observation (Figure 1), the surficial layer (thickness ~25 m) of lower electrical resistivity values (< 250 Ωm) is related to P, whereas the lower layer of higher electrical resistivity values (> 250 Ωm) is attributed to T (Figure 2).

The HVSR results show significant peaks, with amplitude between 3 and 9 units, at the frequency 0.45 and in the range 1 - 1.50 Hz (Figure 3). The "eye shape" highlighted by the shape analysis of the spectral components of motion, together with the result of the 1-D numerical analysis (model 1), allow us to interpret the 0.45 Hz HVSR peak as the subsurface fundamental frequency in the Orvieto Cathedral area. In particular, we suggest that the resonant peak at 0.45 Hz is related to the sharp contrast (2.8) in seismic impedance (ρ * Vs) at the MC/CU boundary. The interpretation of the HVSR peak in the range 1-1.5 Hz was mainly based on the analysis of the HVSR 1 and 2 carried out inside and 5 m outside the Cathedral, respectively. By analyzing the shape of the average spectra of the three components of motion in the frequency range 1-1.5 Hz, it is possible to note that the shape is not characterized by an "eye shape" pattern but by the presence of three individual spectral peaks with different amplitudes (source effect). Thus, the HVSR peak in the frequency range 1-1.5 Hz was associated to the resonance frequency of the Cathedral, in agreement with Clemente & Buffarini (1998). The effect of the Orvieto Cathedral is not present in the spectra recorded 15 m below the ground level for measure 3 (Figure 3, right-bottom panel), suggesting that the structural vibration of the Cathedral strongly affects the AMV wavefield at close distance (HVSR 1 and 2). It is worth noting that the fundamental frequency of the Cathedral is far from the first mode of vibration of the subsurface (0.45 Hz). This is very beneficial for the seismic safety of the Cathedral. The assessment of the seismic vulnerability of the monumental building may benefit from a detailed study if the site-structure interaction taking into account our results.

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