TOPOGRAPHIC EFFECTS IN AMATRICE SUGGESTED FROM THE SISERHMAP PREDICTIVE MODEL, SEISMIC DATA AND DAMAGE

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ABSTRACT

Amatrice is considered as the "symbol" village of the destructive action induced by the 6.0 and 6.5 magnitude earthquakes, which struck Central Italy on August 24th and October 30th 2016. The village, site to 10km from epicentre, paid the highest price in terms of human lives, injuries, widespread collapses and damage to buildings. Our first field surveys in the Red Zone ascertained that the building collapses or damage was widespread, and involved different building typologies, in different areas, and included new buildings too.

We performed a preliminary analysis using the topographic module of SiSeRHMap. The results of this analysis indicated a substantial amplification over most of the hill, with greater values located at the NW end of the promontory and along the top of the steepest slope, where amplification values reached up to approximately 2.0 in the frequency range 2-5 Hz that includes the typical fundamental vibration modes of most buildings.

In order to precisely define the effective role of the topographic site effect, two sets of two seismic stations were installed at four critical points in the Red Zone, in two different periods during the seismic sequence. The SSR results, in accordance with those of the HVSR analysis, showed a relevant amplification at the crest station, more than a factor of four taking into consideration the median values. In addition, the directional analysis showed an amplification at 2-3Hz along the transversal axis of the relief, but further amplifications were also recorded at higher frequencies.

Keywords: Amatrice Hill; Site amplification; SiSeRHMap model; Seismic damage; Spectral analysis

1. INTRODUCTION

The Amatrice urban area was severely hit, in terms of human life and damage, by the August 24th earthquake, $M_w=6.0$, that involved a large area in central Italy. The severity and the different distribution of the damage, also in relation to the building typology, provides important insight into the relevant role covered by seismic site effects (Zimmaro and Stewart, 2016 and Maufroy et al., 2018). Among these effects, the topographic effect, that occurs in the presence of a substantial changing of the topographic surface, seems to be called into question by the topographic shape of the Amatrice

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hilly plateau, mainly at the top of its prominent sector. In this sector, historical buildings were located, but recently built buildings were also present. Today, this sector falls into the "Red Zone" as designated by the authorities, and hence it is circumscribed and checked, given the severity and spread of damage (figure 1a).

Taking advantage of the long period of the seismic sequence, our objective was to study the effective role of the topographic effect on ground motion. Therefore, we applied experimental SSR and HVSR analyses, in relation to the possibility to predict the observed amplification by using the new generation of heuristics calibrated numerical methods. These methods, based on an approximated modelling, permit a rapid estimation of the 3D topographic effect using only morphometric data (e.g. using the curvature parameter), such as the Frequency-Scaled Curvature (FSC) introduced by Mouflouy et al. (2012). We also used another GIS-based model, SiSeRHMap, introduced by Grelle et al. (2016), that permits to take into account the seismic topographic effect and the seismic stratigraphic effect. SiSeRHMap is the acronym of: Simulation of Seismic Response by using a Hybrid Model. This model merges the stratigraphic and topographic effects in accordance with the "serial-parallel" model (Grelle et al., 2017). Its main features are defined as follows:

i) the model is defined hybrid due to the fact that it computes the seismic response using a physically based approach, producing a 1D solution on some assigned cases for training the metamodel. This is a non-physical emulator model that uses trained approximation functions that are capable of developing frequency dependent maps regarding the stratigraphic seismic response, as well as the topographic amplification, which is defined in terms of the topographic aggravation factor, as defined by Assimaki et al. (2005);

ii) it gives complex tri-dimensional solutions using an easy computation process that reproduces the underground layered soil using a GIS file (Gis Cubic Model), (Grelle et al., 2014);

iii) the one-dimensional solution is performed by a non linear equivalent model with the ability to find the non linear regression function that fits the dynamic degradation data of materials;

iv) the training of the metamodel is performed by a specific evolutionary algorithm that is part of the group of algorithms, which are similar to the genetic algorithms;

v) the topographic aggravation factor (TAF) is a non linear frequency dependent function which is used as a spectral amplification factor of the 1D seismic response. In this phase, the input data, such as for example DEM, slope and curvature, are defined in the GIS environment. The topographic model is a complex model based on the shape of the reliefs and their stiffness. Other specific information can be found in Grelle et al. (2016), and Grelle et al. (2017). The model was validated on: a) the Albino plateau area (France); b) the Narni hill (Italy); c) the East mountain area (Utah, USA); and d) Port au Prince (Haiti).

In this paper we illustrate our work in progress on the seismic site effect that occurred in Amatrice, focusing on the topographic effect. Hence, SiSeRHMap is used here solely in relation to an evaluation of the topographic effects. A more complete version of the code, in order to associate both the stratigraphic and the topographic effect, will be applied in a forthcoming work.

2. BACKGROUND

2.1 Geology and Morphology of the Area

Amatrice is a village in the Apennines of Central Italy. This area is a tectonically active zone, undergoing post-orogenic Quaternary extension, as expressed at the surface by a set of NNW–trending normal faults (Michele et al., 2016; Pizzi and Galadini, 2009). It is located along the Apennine sector extending across the Sibillini thrust, NNE-trending. This sector is one of the most important tectonic alignments of the Central-Northern Apennines, which was reactivated in an extensional fashion by the August 24, 2016 mainshock (Bonini et al., 2016). The village rises up on a hilly plateau with an altitude between 900 and 1000 meters, at the confluence of the Tronto and Castellano rivers. This plateau is bordered to the east by the Laga Mountains, and to the north-east by the Sibillini mountains. The geological setting (figure 1b) consists in a substratum composed of pelitic-arenaceous lithofacies belonging to the formation of the Laga Mountains (Festa, 2005). These rocks are formed by blocks
and thin layers in the upper part, with interposed marly-arenaceous lenses, and by blocks and thicker layers in the lowest part (named “m2” in the Geological Map of Italy, APAT, 1955). The substratum is covered by colluviums or old alluvium deposits in the gentle-slopes/flat-zone or in the valley (named “s2” and “q2” in the Geological Map of Italy, APAT, 1955), (Pagliaroli, 2016).

In order to define the subsoil structure, we performed geophysical surveys at the top and at the base of the relief. These consisted of n. 6 MASW (Multichannel Analysis of Surface Waves) performed with linear array of 24 geophone extended for 36 or 48 meters and n.13 HVSR (Horizontal to Vertical Spectral Ratio) triaxial single-station measurements. Both the MASW and HVSR data were jointly processed, in order to have an adequate detailed knowledge at the near surface, as well as to characterize the deeper soils. In this preliminary phase of our work on the Topographic effect in Amatrice, the contribution of the meta-data regarding the results circa specific lithological settings and the dynamic features of the terrains, has had a marginal role in the analysis as is possible to ascertain below. However, the general trend shown by the Vs subsoil profiles (figure 1c) highlights two relevant Vs changes that increase at approximately depths of 20-25 meters and 50-60 meters. The details on the nature of the terrain and the analysis will be reported in a more organic work that will also include the role of the seismic stratigraphic effect in a rigorous global analysis that we are developing and that will be object of the next paper.

The most damaged zone was the historical quarter of Amatrice, lying on a prominent relief elongated Northwest – Southeast, bounded by a steep slope (slope angles about 30°) to the North and West, and by a gentle slope (slope angles about 15°) to the South. The relief is approximately 50-70 meters in height from the valley, 200-400 meters wide and approximately 2 kilometers long, including the NW prominent part elongated over approximately 500 meters. This latter part is the urban historical centre, and is mainly occupied by old buildings. It was immediately declared as the “Red Zone” due to the extensive damage that occurred within this area.

![Figure 1](image.jpg)

Figure 1. Some background features of Amatrice: a) damage distribution after the event of August 24th 2016 in the urban area; source: Copernicus Emergency Management Service; b) geological map from the Italian National Geological Maps 1.100.000 – ISPRA; c) best fit profile (black lines) by MASW and HVSR combined inversions and their mean (red line)
2.2 Preliminary view on the damage

Features and distribution of damage are an important and relevant diagnostic tool in order to ascertain and study the site effect in zones affected by earthquakes (Mucciarelli et al., 2011; Wang et al. 2016). In the majority of cases, the data required for an adequate interpretation must be in relation to the building typology, construction year, geometry and reinforcement interventions. However, some particular trend evidence on damage or collapses can be highlighted in a preliminary way by the possible local differences manifested by the seismic response (figure 1a). The recurrent building typology that had extensive severe damage and collapses regarded two-storey and three-storey houses realized with rubble masonry. Along the top of the steep slope in the northern, north-western sectors and in some parts of the middle hilly plateau, severe damage and collapses occurred in more recent buildings realized in reinforced concrete and brick. The oldest structures regarding medieval bell towers remained standing with only minor damage at the top, highlighting an affinity between damage and spectral amplitudes of the ground vibration. The sites of our mobile stations (figure 1a) were individuated in relation to the logistic condition and also taking into account the distribution of damage. Specifically, taking into consideration that the T1299 station is at the base of the hill in the North-West valley where very little damage occurred, the installation locations were as follows: i) SUOR, on the prominent promontory where a convent collapsed, ii) ROMA, at the edge of a local steep-slope to the north of the hill where the “Hotel Roma” collapsed, iii) MONU, in the central part of the hill and at approximately the middle of the flat top of the hill where there is a small monument, and iv) SCOI, in a sector to the South of the hill where there is a tourist structure, “Lo Scoiattolo”, that had been only slightly damaged by the 2016 mainshock, but whose foundation collapsed during the strong seismic sequence of January 18th 2017.

3. PREDICTION ANALYSIS

A numerical analysis with the topographic module of SiSeRHMap was performed using the morphometric input maps developed by a resolution in altitude of 5 meters. In addition, the input maps (DTM, slope and curvature) were given in a computation with a spatial resolution of 30 meters and returned in post-processing with a spatial resolution of 2 meters by using a calibrated smoothed Gaussian spatial distribution. The analysed area was extended to comprise the entire hilly plateau, that included the urban area and the valley zones, in order to cover the entire area subject to the installation of the seismic stations. The multi-spectral maps were computed in a frequency band from 1 Hz to 10 Hz with 1Hz intervals, in addition to an additional map at 0.5 Hz, and another map at a very high frequency (50 Hz) that is associated to the infinite frequency (vibration period referred to zero seconds). This last one is used by metamodel for the PGA scaling in referencing to the stratigraphic response. The shear wave velocity was attributed to the equivalent uniform relief (equivalent stiffness) of the whole hill. A computational data-inversion was performed using in combination MASW and HVSR measurements. This data, added to the stratigraphic logs from the bore-holes, permitted obtaining a sufficient and detailed modelling of the underground structure in the “Red-zone”. The results illustrate that the supporting structure of the relief is a lower stiff rock that is most likely composed of sandstone and siltstone levels, with different stiffnesses for the most part; in this material, with thicknesses of 40-60 meters, the Vs range is of 600-800 m/s. As known from literature, this geological formation is covered by soft deposits resulting from an old alluvial deposition and/or colluvial resulting from the alteration of the bedrock; in this material the Vs range is of 250-400 m/s, with thicknesses of 8-20 meters. In the preliminary computation, we assumed an equivalent velocity of the relief of 680 m/s, resulting from the average travel time of the shear wave from the base to the top of the hill in the Red Zone sector. However, it is important to note that in this work the analysis is limited only to defining the topographic effect isolated by the global seismic response; the stratigraphic effect may assume a relevant role in the final computation of the seismic response. This differential approach can be performed due to the nature of the SiSeRHMap model (similar to a serial parallel model). However, the use of the entire computational capability of the model will be the focus of future work in the short-term.

With regards to the Red-zone, the multispectral maps (figure 2) illustrate that the Topographic
Aggravation Factor values (TAF), defined as the ratio between the predicted 3D acceleration spectral response and its corresponding 1D, have a different distribution in relation to frequency, and thus to the wavelength, assumed in the computation. At a relatively high frequency, 8-10 Hz, the greater values, up to 2.2, are distributed along the promontory front involving the arc that comprises the hospital of Amatrice, up to the convent where the SUOR station was installed. Relevant TAF values, approximately 1.4 are distributed at the border of the hilly-plateau too. In this zone, the TAF values tend to have a greater value up to 2.0 in the frequency range of 3-5 Hz, with an increase of values corresponding to the sector on the top of the hill with a changing slope. At a low frequency, 1.0-2.0 Hz, the greater values extend up to the central part of the hilly plateau. This migration of the amplification versus the low frequency is correlated with the geometry of the hill (width/height), due to the fact that its transversal dimension mostly coincides with the half-wavelength of the seismic motion; the range of this latter is 350-250 meters that matches the width median values that refer to the top of the hilly plateau. In addition, agreement also occurs with the topographic fundamental frequency defined in accordance with $\text{Vs}/0.2H$ taking into consideration the height of the hill, $H$, of 70-80m. However, the analysis defines that a greater inclusion in the topographic effect, of the central hilly areas where the hill sector is wider, occurs at frequencies less than one, but the TAF values are very low in that spectral interval. Based on this feature, it is possible to associate the greater TAF values, in each specific point, in accordance (fitting) with the half-wavelength enveloping the part of relief in which the point is centred, rather than considering the TAF given by the enveloping of the entire hilly relief for all points. This attitudinal effect and as a consequence, the detection ability of SiSeRHMap, is greatly highlighted by the typical geometry of the hill plateau.

Figure 2. Some multispectral maps of the Topographic Aggravation Factor (TAF) resulting from SiSeRHMap, the complete map set regard a spectral computation from 0.5 to 10 Hz.

The spectra obtained by extraction from the multispectral maps of the TAF values at the seismic station sites (figure 2), highlight substantial non-amplification for the sites T1299 and SC01 at the base of the hill. The greatest amplification is illustrated by the SUOR station with a peak around 3 Hz.
and a value up to 1.9, while for the ROMA site the amplification values increase to 3-3.5 Hz and continue also at the greater frequency with a value around 1.6. At the MONU site, an evident peak is showed at 2.0 Hz, reaching a value over 1.4.

4.EXPERIMENTAL ANALYSIS

4.1 Method and instrumentation

We processed and analysed the seismic events that were part of the long seismic sequence that occurred in Central Italy during the period 2016-2017, with the two biggest mainshocks on August 24th and October 30th 2016 (Table 1). We collected seismic data from a local station, T1299, belonging to the Italian strong-motion network (RAN) and furthermore from four mobile seismic stations, denominated SUOR, SCOI, MONU, ROMA, belonging to the Unisannio network. These stations were installed in two different time periods in the year 2017: Round 1 (SUOR, SCOI) from January 1th to March 18th, and Round 2 (MONU, ROMA) from May 12th to August 10th. The stations, MONU, ROMA and SUOR were installed on the plateau where Pleistocene alluviums (q2) outcrop. Station SCOI was installed at the base of the plateau, where the bedrock (m2) is present, and is covered by a thin layer of colluvial deposits (figure 1). In order to highlight the possible influence of the source mechanism, radiation pattern, or the directional effects, using the largest data acquired in SUOR, a splitting of the aftershock events was performed taking into account the direction of the sources in relation to the Amatrice urban area. The sources have been divided into two directional clusters: the Apennines (NW-SE) and the anti-Apennines (NE-SW) mountain chain directions. These clusterings concord with the canalization effects due to regional and local tectonic structures that are usually involved in Apennine earthquakes.

These mobile stations were continuously operating over different time periods, as shown in Table 1, due to the fact that they had different standbys owing to the unfavourable weather conditions that could have inhibited the solar power recharge. Each station was equipped with Nanometric instrumentation: a Centaur 24 bit digital recorder, and a triaxial broadband Trillium compact seismometer, with a flat frequency response from 0.0083 to 100 Hz; the sample rate was 100 sps. We acquired consecutive one-hour-long time series, as MiniSEED files, subsequently converted into SAC format using the Seisgram2k software (http://alomax.free.fr/seisgram/SeisGram2K.html). We decided to analyse only seismic waveforms regarding earthquakes with a magnitude equal to or greater than 2.5. We manually inspected the traces to select the events, and also to check the quality of the seismic traces in terms of signal-to-noise ratio. Subsequently, we applied to the selected time windows the following procedure, using the SAC software (http://ds.iris.edu/ds/nodes/dmc/software/downloads/SAC): i) removing the mean; ii) tapering with a 5% Hanning window; iii) 2nd order Butterworth band-pass filtering in the 0.3-35 Hz frequency band; conversion from counts to velocity units (mm/s).

<table>
<thead>
<tr>
<th>Station</th>
<th>Round</th>
<th>2.5&lt;=M&lt;3.0</th>
<th>3&lt;=M&lt;3.5</th>
<th>3.5&lt;=M&lt;=4.0</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1299</td>
<td>1</td>
<td>65</td>
<td>21</td>
<td>4</td>
<td>90</td>
</tr>
<tr>
<td>SCOI</td>
<td>1</td>
<td>14</td>
<td>3</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>SUOR</td>
<td>1</td>
<td>61</td>
<td>21</td>
<td>3</td>
<td>85</td>
</tr>
<tr>
<td>SUOR-App</td>
<td>1</td>
<td>41</td>
<td>13</td>
<td>0</td>
<td>54</td>
</tr>
<tr>
<td>SUOR-Ant-</td>
<td>1</td>
<td>20</td>
<td>8</td>
<td>3</td>
<td>31</td>
</tr>
<tr>
<td>T1299</td>
<td>2</td>
<td>30</td>
<td>9</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>ROMA</td>
<td>2</td>
<td>25</td>
<td>6</td>
<td>4</td>
<td>35</td>
</tr>
<tr>
<td>MONU</td>
<td>2</td>
<td>27</td>
<td>9</td>
<td>5</td>
<td>41</td>
</tr>
</tbody>
</table>
The data recorded by the T1299 station (http://ismd.mi.ingv.it/stazione.php?sta=T1299) display the characteristics shown in Table 1. The station was equipped with a Kinemetrics Episensor accelerometer, with an extended bandwidth from DC to 200 Hz. The data were sampled to 200 sps. We collected the earthquake waveforms from the EIDA (European Integrated Data Archive) catalogue, and we applied an analogue procedure to the selected time windows, in the same way as was applied to the Unisannio network. Finally, to uniform all the data set to the same units and also to the same sampling, the accelerometric data was resampled at 100 Hz and converted to velocity units (mm/s).

We chose the installation sites of the mobile stations (figure 1) based on the necessity to investigate the seismic response in sectors with specific morphometric features, illustrated in paragraph 2.2.

4.2 Data analysis and results

The results of the experimental data regard the spectral ratio analysis (figure 3) on earthquake and noise recordings (figure 4) and their azimuthal directional analysis (figure 5). In particular, we performed the Standard Spectral Ratio (SSR) analysis, assuming the T1299 station as a reference station, and a Horizontal-to-Vertical Spectral Ratio (HVSR) analysis, both for the earthquake, and for the noise recording data. The processing also consisted in a polarization analysis by computing the azimuthal distribution of the spectral amplification.

4.2.1 SSR analysis

The standard spectral ratio (figure 3) processing consisted in a preliminary treatment of the signal by using the tapering Hanning function, and the subsequent smoothing of the spectral forms by using the Konno and Ohmachi (1998) function, assuming b=40. The data were statistically analysed in terms of the median and respective 16 and 84 percentile.

With regards to the general trend, all the stations highlight substantial amplifications in relation to T1299 in the range of 1-10 Hz for each component. Greater amplitudes occurred on the horizontal components, while only marked peaks occurred in the vertical component around 10-15 Hz, with values for the stations at the top of the hill (8-12 amplified) greater than those observed at the SCOI station at the base of the hill (4 amplified).

With regards to the events recorded in round 1, they refer to the SUOR station located in the Red zone and to the SCOI station located in the open valley; while those recorded in round 2, refer to the two other stations, ROMA and MONU, sited at the top of the hill.

- SUOR: this station, located at the prominence of the hill, shows two notable amplification peaks around 3-3.5 Hz and 9-10 Hz with a substantial difference between the NS and EW components. The directivity analysis shows a double directionality of the amplification with a maximum amplification, approximately 6, at a high frequency (9-10 Hz), which is centred along the direction around 120°-300°N showing a concordance with the longitudinal or transversal elongation of the Amatrice hill. Instead, at a lower frequency (3-3.5 Hz), a maximum greater than 7 is centred on the transversal direction of the Amatrice hill.

- ROMA: This station manifested the highest amplification, reaching peak values around 9. There was a substantial difference in the two horizontal spectra: an amplification within a large frequency interval (2-9 Hz) was observed in the NS component; this effect lessened in the EW component where two peaks at around 7 Hz and 10 Hz, were observed. For this station, a minor peak of 3 at nearly 6-7 Hz in the vertical component, was also observed. The directivity analysis showed a substantial univocal azimuthal trend with an amplification that reached a maximum in the frequency distribution in the 2-7 Hz frequency band. A clear peak around 4.5-6.0Hz, over 9, with a directionality having an azimuth of 335°-0°N with a maximum about 20°-200°N (5.49Hz) was also observed, in agreement with the transversal direction of the hill.

- MONU: this station showed maximum amplification values at around 2 Hz and 10 Hz, this latter being only on the EW component and the smallest among all the stations located at the top of the hill.
In this case too, the directional amplification around 20°-200°N (2.00Hz) is in agreement with the transversal direction of the hill for the peaks at a low frequency by assuming the maximum values over 5.

With regards to the frequency interval, a non-clear trend was manifested in the vicinity of the E-W direction on about 3.00 Hz. This latter manifestation is clearly in discordance with the trend observed in the spectral amplification for the other stations located at the top of the hill.

- The SCOI station showed a high-frequency (8-10 Hz) amplification, with a substantial equal distribution of the amplification along the two orthogonal components. In fact, the directivity analysis manifested a weak directionality of the amplification at a high frequency, 8-10 Hz, with a value of 8,
and a substantial absence of amplification peaks at the lowest frequency down to 4 Hz. In this

4.2.2 HVSR by earthquakes and noise

We computed the HVSR by merging the NW and EW spectral components with the geometric mean (figure 4). Subsequently, in a similar way to that of the SSR analysis, the spectral ratios were statistically analysed in terms of the median and respective 16 and 84 percentile. This analysis substantially confirmed the same trend already highlighted by applying the SSR analysis to each station. However, where the SSR analysis highlighted significant differences between the spectral shapes of the NS and EW components, as in the case of the SUOR station, the HVSR method provided a more smoothed curve. The directivity effect closing to north is observed around 3 Hz by the SSR analysis at the SUOR station persists in the HVSR azimuthal plot. An azimuthal directional trend of the amplification results in according with SSR analysis is shown also for ROMA e MONU stations. In addition, due to the fact that the HVSR method works with single-station measurements, we were able to extend it also to the T1299 station. We plotted the HVSRs for the T1299 station in the last column of figure 4. The different curves refer to the different set of data considered in the SSR analysis for each Unisannio station. It is encouraging to observe how the HVSR estimates obtained at the T1299 station are almost flat. These results confirmed the validity of our choice to use T1299 as a reference station.

![Figure 4. Results from the SSR and HVSR analysis using recordings of both the aftershocks a) and noise b).](image)

The last step in our analysis was to compute the HVSR functions on noise recordings. Therefore, we manually selected for each station and for each component, six 10-minute-long time windows, avoiding disturbances or transients. Before calculating the spectra, we applied the same automatic procedure, as used for the earthquake waveforms. The HVSR estimates were computed on 20, 48-sec-long time sub-windows of noise signals. These curves show a clear similarity with the HVSR
computed on earthquakes, generally with lower amplitude. The polar diagrams generally confirmed that which had already observed from the directivity analysis performed on earthquakes.

Figure 5. Directional analysis regarding SSR, HVSR-aftershock and HVSR-noise. In the central biggest polar diagrams are reported the maximum values in relation to the transversal and longitudinal disposition of the Amatrice’s hill.

5. DISCUSSIONS AND CONCLUSIONS

Taking into consideration the preliminary results from the analytical and experimental approaches, it
has been possible to offer a considerable insight into the role of the topographic effect in the Amatrice hill. Despite the fact that the Red Zone at the top of the hill was covered by old/historical buildings and to a lesser degree by more recent buildings, damage appeared more severe when compared to similar structures present in other zones (e.g. at the base of the hill). This damage distribution seems to be in agreement with the results obtained by the topographic module of SiSeRHMap (figure 6) highlighting the amplifications in terms of TAF with values around 1.5-2.0 at frequencies greater than 3 Hz on the promontory (where the SUOR station was installed) and on the border of the hill (where the ROMA station was installed). Instead, for the frequency range from 3 Hz down to 1 Hz, results showed that the central part of the hill was the only part involved, reaching an amplification up to 1.5 at 2 Hz, with decreasing values in the passage to lower frequencies. The slight damage observed for the two medieval towers with a fundamental frequency lower than 2 Hz, supports the minor amplification that occurred in this frequency band.

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Figure 6. Comparison among the average TAFs in the frequency 1 Hz - 4 Hz resulting from SiSeRHMap, the SSR directional analysis and the damage. The blue lines indicate the hill transversal direction while the dashed blue lines indicate the hill longitudinal direction.

The experimental results from the SSR and HVSR data showed relevant amplifications for the stations installed at top of the hill (up to 6), with the same notable directionality effect, that appears in coherence with the geometry of the elongated shape of the hill. In particular, a directional amplification near to the NorthEst-SouthernWest direction is shared by all the stations at the top of the hill, in accordance with the transversal direction of the elongated hill; instead a non-directional amplification (for SCOI) or a non-amplification (for T1299) characterized the two stations at the base of the hill. Regarding this latter, the very slight damage to homes built at the turn of the century or perhaps before, sited in proximity of the station, together with a flat horizontal-to-vertical spectral ratio (HVSR), indicates that the T1299 station is the most adequate reference station. Specifically, from the experimental results, the amplification observed on the Amatrice hill strongly varies in the 2-10 Hz frequency band, and is influenced by the location of the measurement site on the hill. This is corroborated by the fact that the SUOR station, which is located at the prominence of the hill, shows amplification effects with strong directivity along two different directions, at two different frequencies: the effect at a lower frequency, around 3 Hz, has a directional trend that is transversal to the elongation of the Amatrice hill. Another amplification effect at a higher frequency, is prevalent along the longitudinal elongation of the hill. This latter effect seems to be mostly influenced by the azimuths of the earthquake epicentres in relation to the hill. In fact, when we separated the spectral
ratios regarding the azimuth of earthquake sources, we observed that the amplification computed at a high frequency for earthquakes that aligned along the Apennine thrust, was higher than that observed for the anti-Apennine sources. This result was also supported by the HVSR measurements.

5. References


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