Urban seismic stations: soil-structure interaction assessment by spectral ratio analyses

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Abstract

In this work we present and discuss the results of ambient seismic noise analyses computed at 4 sites where seismic stations, managed by the INGV (*Italian Institute for Geophysics and Vulcanology*) and the DPC (*Italian Department of Civil Protection*), are installed inside buildings. The experiments were performed considering different types of installation: sensor located at the bottom of a school, directly installed on rock (case 1); sensor located at the bottom of a medieval fortress, built on an isolate hill, directly installed on rock (case 2); sensor installed on the foundations of a medieval fortress, built on an isolate hill (case 3); sensor installed on the foundations of a school, built on allluvial deposits (case 4). Since recent works proposed the use of spectral ratio techniques to study the dynamic characterization of buildings, ambient seismic-noise measurements were performed for each site close to the stations (at the base of the structures), at the top of the structures and outside the buildings. In order to check the source of vibrations both horizontal to vertical spectral ratio (HVNR) and standard spectral ratio (SSR) techniques were applied. For all stations the results from ambient seismic noise were compared, to those obtained from earthquakes (HVSR). In order to detect preferential directions of amplification, for each site average HVNRs and HVSRs were computed considering one azimuth for each set of 5°.

We obtain different results for different types of installation: in case 1 and 2, where the sensors are directly installed on rock, the vibrations of the structure do not affect the noise measures performed close to the stations, which show flat HVNR in the whole frequency range: in both cases the eigenfrequency of the building is given by the HVNR calculated from the measures performed at the top of the structure. In case 3 and 4, where the sensors are installed on the foundations of the considered structures, both the amplification peaks between 5 and 9 Hz (case 3) and between 5.5 and 7 Hz (case 4) include the contribution of the free oscillations of the buildings. In particular, in case 4, HVNRs performed outside building highlight possible soil-structure resonance effects in case of an earthquake.

Keywords: site effect, soil-structure interaction, spectral ratio techniques

Introduction

In the last years the estimation of seismic site response of inhabited areas and the dependence of soil vibrations on structures represented a focal point in many studies concerning earthquake engineering and engineering seismology. Northern Italy is an area where a dense population as well as a high number of industrial facilities are present; thereby a reliable site response assessment, biased in some cases by the vibrations of buildings, plays a fundamental role for seismic hazard analyses (e.g. estimation of empirical ground motion prediction equations, earthquake scenarios, probabilistic seismic hazard analyses, microzonation studies).

In this framework many papers studied the soil-structure interaction (e.g. Facke et al., 2006; Mucciarelli and Gallipoli 2006; Parolai et al., 2005; Mucciarelli et al., 2004; 2003; Gallipoli et al., 2003; Wolf and Song, 2002; Trifunac and Todorovska, 2000) highlithing that, in case of microtremor surveys performed in urban areas (e.g. Massa et al., 2008; Gallipoli et al., 2004; Mucciarelli and Monachesi, 1998; 1999), the free oscillations of a structure might bias the estimation of the fundamental frequency of the soil and at the same time the seismic response of particular lithologies might obscure the eigenfrequencies of vibration of a building.

A correct understanding of the sources of the soil resonance amplification peak becomes relevant from an economical point of view if the frequencies of vibration of the buildings fall into the range where soil amplification is expected: in this case damage might increase during an earthquake due to possible soil-structure resonance effects.

Even though Northern Italy is characterized by a low seismicity rate, some areas, such as the Eastern Alps, are able to produce energetic events (up to Mw 6.5 for the 06th May 1976 Friuli earthquake; Gruppo di Lavoro CPTI, 2004). The results reported in the seismic hazard map of Italy (Gruppo di lavoro, 2004, PCM 3519 of the 28th April 2006) show that Northern Italy is characterized by predictable horizontal acceleration peaks up to 0.3 g for 475 yrs return period: this estimation becomes relevant due to the great number of cities and villages with historical districts characterized by buildings with an high degree of vulnerability.

The remarks reported in this paper are based on the results of empirical analyses computed considering ambient seismic noise recorded in correspondence of 4 strong-motion station (table 1), 3 managed by the INGV (http://rais.mi.ingv.it) and 1 managed by the DPC (figure 1). In the last years, several studies shown that horizontal to vertical spectral ratios analyses from seismic ambiet noise can be an effective tools also in estimating the frequency of vibration of buildings (e.g. Parolai et al., 2005). In this work we considered seismic stations installed inside structures (recent buildings and medieval fortress) that are built on sites characterized by different geological (rock and soft soils) and morfological (alluvial plain and isolated hills) setting. It is worth noting that, even if the considered stations are located at the bottom of the structures, the analyses were computed considering sensors installed both on foundations (case 3 and 4) and directly on rock (case 1 and 2). The results of HVNR calculated from seismc noise recorded close to the stations were compared with those obtained by the same technique applied on microtremors recorded at the top of the structures. Finally, for the stations where earthquake recordings were available (figure 1) the results of HVNR were strengthened by HVSR.

Data set and methods

The ambient seismic noise was recorded for each site using sensors Lennartz LE3D-5sec (flat response in velocity between 0.2 and 40 Hz) coupled with a Reftek 130/01-24 bit data logger. The measurements were done both at the bottom of the structures (close to the strong-motion station) and at the higher floors. Where possible, measurements located outside and far from the structures were also performed. For each measure about 30 minutes of ambient seismic noise were recorded at the sampling rate of 100 Hz.

In order to obtain HVNR (Nakamura, 1989), first the mean, the linear trend and the instrumental response were removed, also, a band-pass Butterworth 4 poles filter between 0.2 and 25 Hz was applied. Each component of the recorded signals was windowed in time series of 120 s length (cosine taper 5%) and the horizontal components were rotated between 0° and 175° with step of 5°. The power spectral density (PSD) were calculated for each component and then smoothed using the Konno and Ohmachi (1998) window (b=20). Finally, for each considered azimuth average HVNRs were computed calculating for each time window the spectral ratio between the spectrum of the radial component and the spectrum of the vertical one.

In case of synchronized measurements performed at the top and at the bottom of the structures, also the SSR (Borcherdt, 1970) method was applied. This method has benn often used in ambient noise testing of buildings (Ivanovic et al., 2000; Parolai et al., 2005). The data processing was the same described for the HVNR.

For the strong-motion stations with available earthquake recordings, also HVSR (Lermo and Chavez-Garcia, 1993) were computed in order to check the reliability of HVNR calculated at the bottom of the structures. The data processing, as described for the ambient seismic noise, was applied to earthquakes considering different portion of signal: 5 s and 15 s of S waves, starting 0.5 s before the S-waves picking, and 20 s of coda were selected. The beginning of coda was selected by following the 2TS criterion (Rautian and Khalturin, 1978). Also in this case, for each analysed phase, average HVSRs were calculated and then a directional analysis (step of 5°) has been performed as previous described for HVNR.

Spectral ratio analysis

Bagolino station

The strong-motion station of Bagolino (BAG8, 45.82N 10.46E), managed by the INGV, is installed on rock that outcrops in the cavity under the basement of a primary school. The structure is characterized by pillar foundations that directly dip into the rock (figure2, top left panel). The school is a two-stories reinforced concrete (RC) structure built on a soft slope composed by lithological units characterized by the presence of limestone and dolomite. On a map view the school is characterized by a square-shaped with side-lenghts of about 40m and height of about 10 m.

Ambient noise measurements were performed both close to the accelerometer is installed on rock and at the highest floor of the building, in correspondence of the side where the station is located. The results of ambient seismic noise measurement performed very close to the strong-motion station are reported in figure 3. In general the spectral ratio analyses show a flat response in the whole frequency range. Average HVNRs show a slight variability of the amplification factor with direction (up to 2) only for frequencies higher than 2.5 Hz. The polar plot shows that preferential directions of amplification (however negligeble) are observed between 120° N and 150° N in particular for frequencies between 4 and 8 Hz.

The measure performed on the top of the school (inset in the left panel of figure 3) shows for both horizontal components maximum amplification peaks between 6 and 7 Hz, correlated to the vibrations of the structure.

Average HVSRs were also calculated considering 30 earthquakes recorded at BAG8 from June 2006, characterized by $1.6 < Ml < 4.3$ and hypocentral distances up to 190 km. As shown in figure 4, the average HVSRs calculated considering the analysed portion of signal (5 and 15 s of S-phase and 20 s of coda) are in good agreement and confirm HVNR results. Even for the earthquakes, slight amplifications are observed between 120° N and 150° N, in particular for frequencies between 4 and 8 Hz. In general for Bagolino-case it is possible to state that the strong-motion recordings appear to be not affected by the free oscillation of the structure. The orientation of the portion of the school where noise-measures have been computed (azimuth of about 30°N) might be responsable for the slight azimuthal dependence observed in the frequency range 5-8 Hz.

Aulla station

The strong-motion station of Aulla (AUL, 44.20N 9.97E), managed by the DPC, is installed in the cellar of an ancient medieval fortress; also in this case the sensor is directly installed on rock. The fortress is a masonry structure built on an isolated hill, characterized by serpentine rock (figure 2, top right panel). On a map view the structure is characterized by a square-shaped with side-lenghts of about 50m. In correspondence of the corners 4 square-shaped tower, with side of about 10m, are present. The hill is oriented in a NW-SE direction, with azimuth of about 150°-160° N.

Two synchronized ambient noise measurements were performed both near the accelerometer (bottom of the structure) and at the top of the tower. The results are reported in figure 5: average HVNRs at the bottom are characterized by no significant resonance peaks. The measure performed on the tower highlights average HVNRs characterized by amplification factor up to 4 in the frequency range between 8 and 12 Hz: in this case it is possible to suppose that the peaks are due to the vibrations of the structure. As highlighted in the polar plot both measures are characterized by preferential direction of amplification for different frequencies: at the bottom of the structure around 1, 3 and 9 Hz in the 110°-120°N direction and for measure in the tower around 10 Hz in the 30°-60°N direction. For both measures a narrow peak with slight amplification (about 3) is detected around 1 Hz: in this case since in the surronunding of the hill industrial facilities are present, the source of the peak at 1 Hz might be anthropic. As demonstrated by Marzorati and Bindi (2006) the whole area of North Italy is characterized by a man-made background seismic noise that represents the dominant sources of high-frequency noise (> 1Hz), generated from the coupling of traffic and machinery energy into the earth. This hypothesis is supported by the results obtained from the noise-measure performed at the base of the hill, where the peak around 1 Hz is still present (inset in the top panel of figure 5).

SSR performed considering the measures at the top and at the bottom of the fortress (using the bottom as reference) better highlights the frequencies of vibration of the structure around 10 Hz (figure 6). In general, also in this case (sensor directly installed on rock), the results of the noise-measure at the bottom appear to be not affected by the free oscillations of the structure. This case becomes relevant if compared to that of Asolo station (next paragraph), characterized by the same geological and morphological setting, but by a different type of installation.

For this site only two earthquakes were available for HVSR: the 23th december, Ml 5.1 and 4.7 Parma earthquakes (15:24:21 and 21:58:25 respectively), both characterized by an epicentral distance of about 50 km and by a perpendicular propagation path with respect to the elongation of the Aulla hill. For both earthquakes amplification peaks in the range 2-3 Hz are detected; in particular for peaks between 2.5 and 3 Hz a preferential direction of amplification between 70° and 80° (perpendicular to the elongation of the hill) is observable (figure 7).

In the case of the mainshock, considering also a relevant difference in the observed-PGA (8.28 cm/s^2 for the NS component and 21.66 cm/s^2 for the EW), it is possible to suppose an influence of the topography on the recordings.

Asolo station

The strong-motion station of Asolo (ASO7, 45.80N 11.91E), managed by the INGV, is located at the bottom of an ancient medieval fortress, but contrary to AUL, the sensor is directly placed on the foundations. The fortress is a masonry structure built on an isolated hill, characterized by hard sandstone (figure 2, bottom left panel). On a map view the structure is characterized by a rectangular-shaped with side-lenghts of about 50 m and 30 m respectively. The fortress is characterized by elongation on the NE-SW direction, very similar to the orientation of the hill (azimuth of about 45°N). Close to the NE corner of the fortress is present a tower, where the strong-motion station is installed.

Ambient noise measurements were performed both at the bottom of the tower (close to the accelerometer) and at the the top of it. In order to check the influence of the hill a further measure was performed few meter outside the fortress.

The results are reported in figure 8: average HVNRs at the bottom are characterized by 2 peaks with amplification factor up to 3 for frequencies spanning about from 5 to 6 Hz and from 8 to 9 Hz. The peak between 5 and 6 Hz shows an higher variability with respect to different directions. The measure performed on the top of the tower shows HVNRs characterized by amplification factors spanning from 10 to 15 at the same frequencies excited by the measure performed at the bottom. Also in this case the first peaks appear to be more sensitive to different directions. No amplification is observed for the measure performed in the middle of the slope of the hill (inset in the top panel of figure 8).

For both measures, the polar plots show for the peaks between 5 and 6 Hz a preferential direction of amplification around 150° N, whereas for the peak between 8 and 9 Hz a preferential direction of amplification around 90° N is observed.

Average HVSRs were also calculated considering 25 earthquakes recorded at ASO7 from August 2006, characterized by 2.3 < Ml < 4.3 and hypocentral distances up to 250 km. The results expressed both in cartesian and in polar coordinates, shown in figure 9 (for the three analysed windows), are in good agreement with those obtained from noise.

In this case the spectral ratio analysis, permormed considering both microtremors and earthquakes, is able to highligth that the sensor installed at the bottom of the fortress (directly placed on the foundations) appear to be sensitive to the vibrations of the structure. The preferential direction of amplification observed at about 150°N, for frequencies between 5 and 6 Hz, might represent the mean mode of vibration of the structure. At the same time, the amplification at about 90°N for frequencies between 8 and 9 Hz might represent an higher mode. In this case, since the structure is oriented NE-SW, like the hill, it is not possible to exclude a further contribution of the topography on the preferential direction of amplification.

Vobarno station

The strong-motion station of Vobarno (VOBA, 45.64N 10.50E) managed by the INGV, is located at the bottom of a primary school, but on the contrary of BAG8, the sensor is directly installed on the foundations (plate foundation). The school, a two-stories RC structure, is built on lithological units characterized by alluvial deposits (figure 2, bottom right panel).

On a map view the school is characterized by an irregular shape with a preferential elongation in the NE-SW direction. The major and minor dimensions of the structure are about 65 m and 30 m, respectively, the height is about 10 m.

Ambient noise measurements were performed both near the accelerometer (bottom of the structure) and at the highest floor of the building, in correspondence of the side where the station is

located. The results are reported in figure 10: average HVNRs at the bottom are characterized by a main peak of amplification with factor up to 4 for the frequency of about 6 Hz. This peak shows a variability of amplification of about 1 with respect different directions. The measure performed on the highest floor of the school shows average HVNRs characterized by peaks, with amplication factor up to 7.5, at 6 Hz and 7 Hz: the latest appears to be more sensitive (factor up to 5) to different directions.
In order to estimate a reliable seismic site response, two further measures were performed; one few meter outside the school and the other about 1 km NW of the structure (both performed on alluvial deposits). These results are reported in figure 11: average HVNRs show for both measures amplication for frequencies between 6 and 7 Hz, with factor up to 3 (for the measure closer to the school) and 7, respectively. In Particular for the measure performed 1 km far from the school, it is possible to detect preferential directions of amplification spanning between 90°N and 170°N (highest amplification).
SSR calculated considering the 2 measures performed inside the structure (using the bottom as a reference) are showed in figure 12: in this case the peak with higher amplification factor (up to 90) might be due to the resonance phenomenon between soil response and one mode of vibration of the structure. Also in this case it is possible to observe (in particular for frequencies between 6 and 7 Hz) preferential direction of amplification between 90°N and 180°N.
Average HVSRs were also calculated considering 17 earthquakes recorded at VOBA from July 2006, characterized by $1.3 < Ml < 4.3$ and hypocentral distances up to 180 km. As shown in figure 13, the results expressed both in cartesian and in polar coordinates (for the three analysed windows) are in good agreement with those obtained from noise: it is possible to observe the presence of a peak, with amplification up to 4, at the frequency of about 6 Hz. The polar plot highlights also in this case a preferential direction of amplification between 90° N and 170° N.
The analysis computed both on microtremors and earthquakes lead to suppose that the sensor placed on the foundation of the school might be sensitive to the vibrations of the structure. Taking into account that for HVNR, HVSR and SSR the preferential zone of amplification range between 90°N and 180°N, and the school have the major elongation in the transversal direction, an hypothesis is that the polar plots reported in figure from 10 to 13 show the main mode of vibration of the structure. It is worth noting that, also considering the results reported in figure 11, for Vobarno the amplification peaks between 5.5 and 7 Hz share the effects due to the alluvial deposits and the free oscillation of the school, with the consequance of increase potential damage in case of an earthquake.

Discussions and conclusions

In this paper a set of microtremor measurements, performed close to 4 strong-motion stations installed inside buildings, are presented and discussed. The analyses were performed considering different types of structures (medieval fortress and recent buildings), installations (sensor installed on rock and on the foundations), geological (hard rock and soft soil) and morphological settings (isolated hills and alluvial plain). For all stations the HVNR were strengthened by HVSR results.

The main remark of the paper is that in, the presented cases,, the reliability of the recordings is biased only where the sensor is directly connected to the foundations of a building. In similar settings, like those of ASO7 and VOBA, the seismic site response might be hidden by the vibrations of the structures: in both cases there is an agreement between the resonance frequencies and the direction of amplification obtained by the measurements performed at the bottom and at the top of the structures. Possible differences between results at the top and at the bottom might be due to the complexity of vibration of the structure. For both ASO7 and VOBA the observed preferential direction of amplification might be partially due to the vibration of the structure with respect their shape.

In order to confirm our hypothesis the spectrograms related to the events that produced the highest PGA values for ASO7 and VOBA stations (up to 35 cm/s^2 for VOBA) were calculated.

Figure 14 (top panels) shows the spectrogram calculated for the 28^{th} December 2006, Ml 3.6, earthquake, recorded 46 km NE of ASO7. The spectrogram was calculated considering the radial component characterized by the highest amplification (factor 6 for 140° N direction).

It is possible to observe the frequencies between 5 and 8 Hz assume the highest value (about -60 dB) in correspondence of the S-phase arrival. It is worth noting that this range of frequencies are excited both before the P-waves first arrival and after the coda, even though with lower values. This evidence means that, where sensor is directly installed on the foundations, as well as for the noise measurements, also in case of an earthquake the records of ASO7 might be biased by the frequencies of vibrations of the fortress.

Figure 14 (bottom panels) shows the spectrogram calculated for the 14^{th} July 2008, Ml 3.5, earthquake recorded 6 km North of VOBA. The spectrogram was calculated considering the radial component characterized by the highest amplification (factor 10 for 135° N direction).

The frequencies around 5.5 Hz assume the highest value (about -60 dB) in correspondence of the S-phase arrival. Also in this case it is worth noting that, again after the coda, the frequencies around 5.5 Hz continue to be excited; this phenomenon is less evident in the pre-event. As well as for ASO7, also at VOBA, where the sensor is directly installed on the foundations, the records of seismic events might be biased by the frequencies of vibrations of the structure. Moreover for VOBA station, since the eigenfrequencies of the structure (figures 10) are very close to the fundamental frequency of the alluvial deposits (figure 11), resonance phenomena are possible. At present more exhaustive analyses are needed to discriminate how strong is the contribution of local site condition with respect the observed amplification factor.

On the contrary, in the case of BAG8 and AUL stations, where the sensors are installed on rock, the measurements at the bottom show a flat response in the whole frequency range, even if the station are located inside structures. In these case, where both the foundations and the sensors are placed on rock but not connected togheter, the structure seems not able to produce a significant variation on seismic response of the site.

It is worth noting that even if BAG8 and AUL represent a good case study, in different conditions the variability of the stiffness of the soil/rock where sensors are directly placed and/or different building/soil stiffness-ratio might produce variations in the results.

On the basis of our evidences it is possible to state that where a free-field site is not available for an installation, in some cases (such as at the school of Bagolino) it is possible to locate a sensor at the bottom of a structure without significantly modify the seismic recordings. Even if this remark has not to be considered of general application, it represents an important consideration for installation of seismic network in particular condition such as for the Strong Motion Network of Northern Italy (RAIS, http://rais.mi.ingv.it) where many stations are necessarily installed inside building due to the lack of free-field sites, caused by the high density of both civil and industrial structures.

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Caption

Figure 1 - Map showing the location of the 4 stations considered in this study (grey triangles). AUL station is managed by DPC while the other stations by INGV (departement of Milano-Pavia). In figure also the epicenters of the earthquakes used for HVSRs are plotted (white circles).

Figure 2 - Geological maps related to the sites where the strong-motion stations are installed. In each panel both the instrumentation and the lithology are indicated. The blue triangles indicate the measurements performed close to the stations, the red triangles indicate the measurements performed inside structures and the green triangles indicate the measurements performed outside structures.

Figure 3 - HVNRs from the noise measurement performed close to BAG8 station (bottom of the structure); in the inset in the top-right corner the HVNRs from the noise measure performed at the top of the structure are reported. The right panel shows the polar plot obtained from the measure performed close to the station.

Figure 4 - HVSRs from earthquakes recorded at BAG8. Blue, green and red indicate the results obtained considering 5s and 15 s of S-phase and 20 s of coda. For each analysed window the polar plot are also reported.

Figure 5 - HVNRs from the noise measurements performed inside the fortress of Aulla. Blue lines indicate the results of the measure performed at the bottom of the structure while the red lines indicate the results of the measure performed at the top of the tower; in the inset in the top-right corner the HVNRs from the noise measure performed at the base of the hill are reported.
The polar plots are also shown.

Figure 6 - SSR obtained considering the measures performed inside the fortress of Aulla (the bottom is considred as a reference).

Figure 7 - HVSRs calculated for AUL station and related to the earthquakes available for this station (23th december 2008, Ml 5.1 and Ml 4.7 events). The H/V amplitude are plotted for different azimuth considering step of 5°.

Figure 8 - HVNRs from the noise measurements performed inside the fortress of Asolo. Blue lines indicate the results of the measure performed at the bottom of the structure while the red lines indicate the results of the measure performed at the top of the tower; in the inset in the top-left

corner the HVNRs from the measure performed on the slope (middle) of the hill are reported. The polar plots are also shown.

Figure 9 - HVSRs from earthquakes recorded at ASO7. Blue, green and red indicate the results obtained considering 5s and 15 s of S-phase and 20 s of coda. For each analysed window the polar plots are also reported.

Figure 10 - HVNRs from the noise measurements performed inside the school of Vobarno. Blue lines indicate the results of the measure performed at the bottom of the structure while the red lines indicate the results of the measure performed at the top of the tower. The polar plots are also reported.

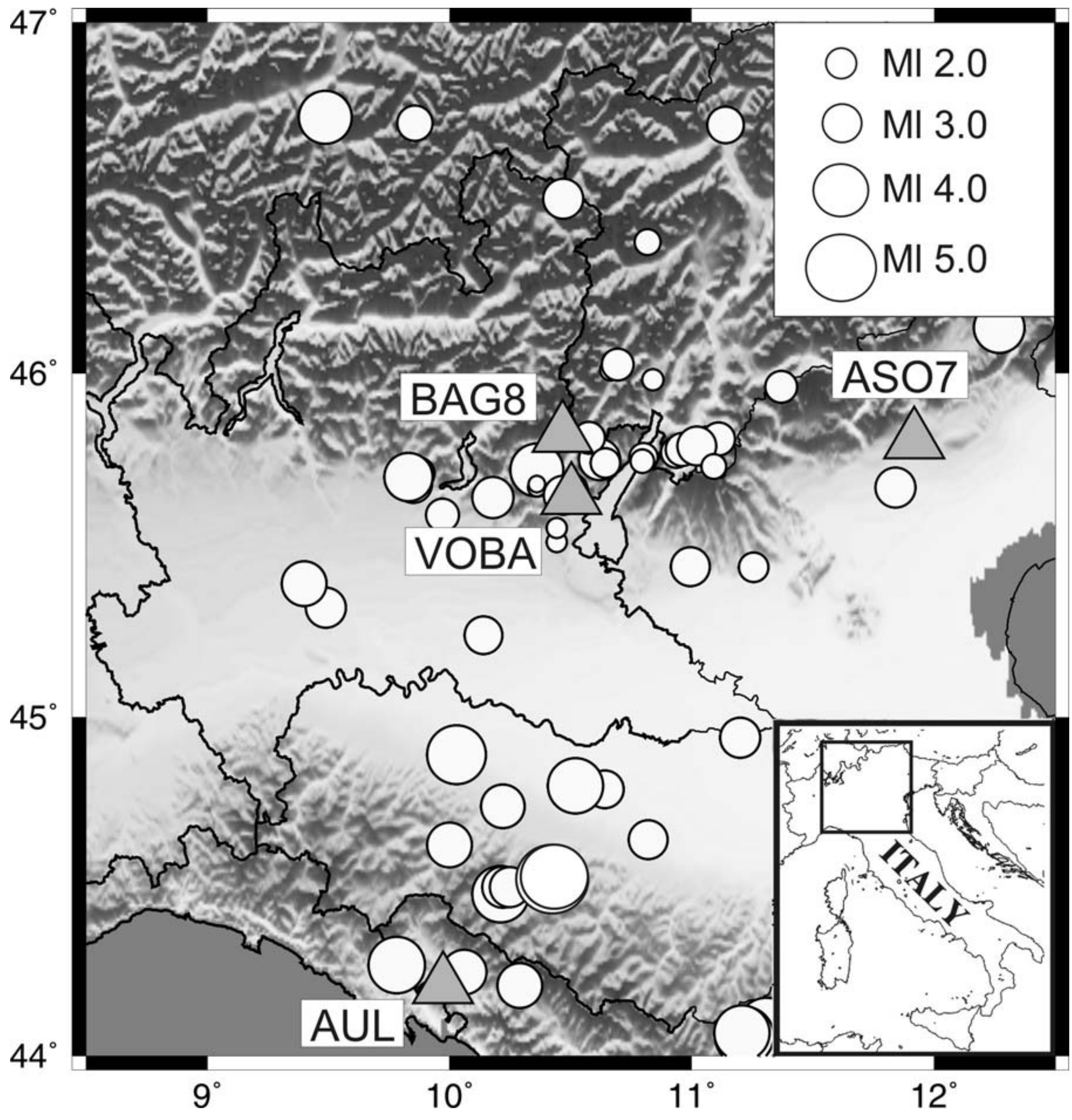
Figure 11 - HVNR from the noise measures performed outside the school of Vobarno (on the alluvial deposits). Black lines indicate the measure performed 1 km far from the school, while the green lines indicate the measure performed 20 m outside the school. The blue line indicates the 170°N direction.

Figure 12 - SSR obtained considering the measures performed inside the school of Vobarno (the bottom is considred as a reference).

Figure 13 - HVSRs from earthquakes recorded at VOBA. Blue, green and red indicate the results obtained considering 5s and 15 s of S-phase and 20 s of coda. For each analysed window the polar plot are also reported.

Figure 14 - Top panels: 140°N Waveform (left), polar plot and spectrogram (right) calculated for the 28th december 2006, Ml 3.6, earthquake, recorded 46 km NE of ASO7 station. Bottom panels: 135°N Waveform (left), polar plot and spectrogram (right) calculated for the 14th july 2008, Ml 3.5, earthquake recorded 6 km North of VOBA station.

Table 1 - Strong-motion stations considered in this study. In the last three rows the maximum amplitude is reported in parenthesis. The grouping in EC8 soil classes (CEN, 2004) has been based on V_s30 Italian Map presented in Bordoni et al. (2003).



47°
46°
45°
44°
9°
10°
11°
12°
Ml 2.0
Ml 3.0
Ml 4.0
Ml 5.0
BAG8
ASO7
VOBA
AUL
ITALY

Figure 1

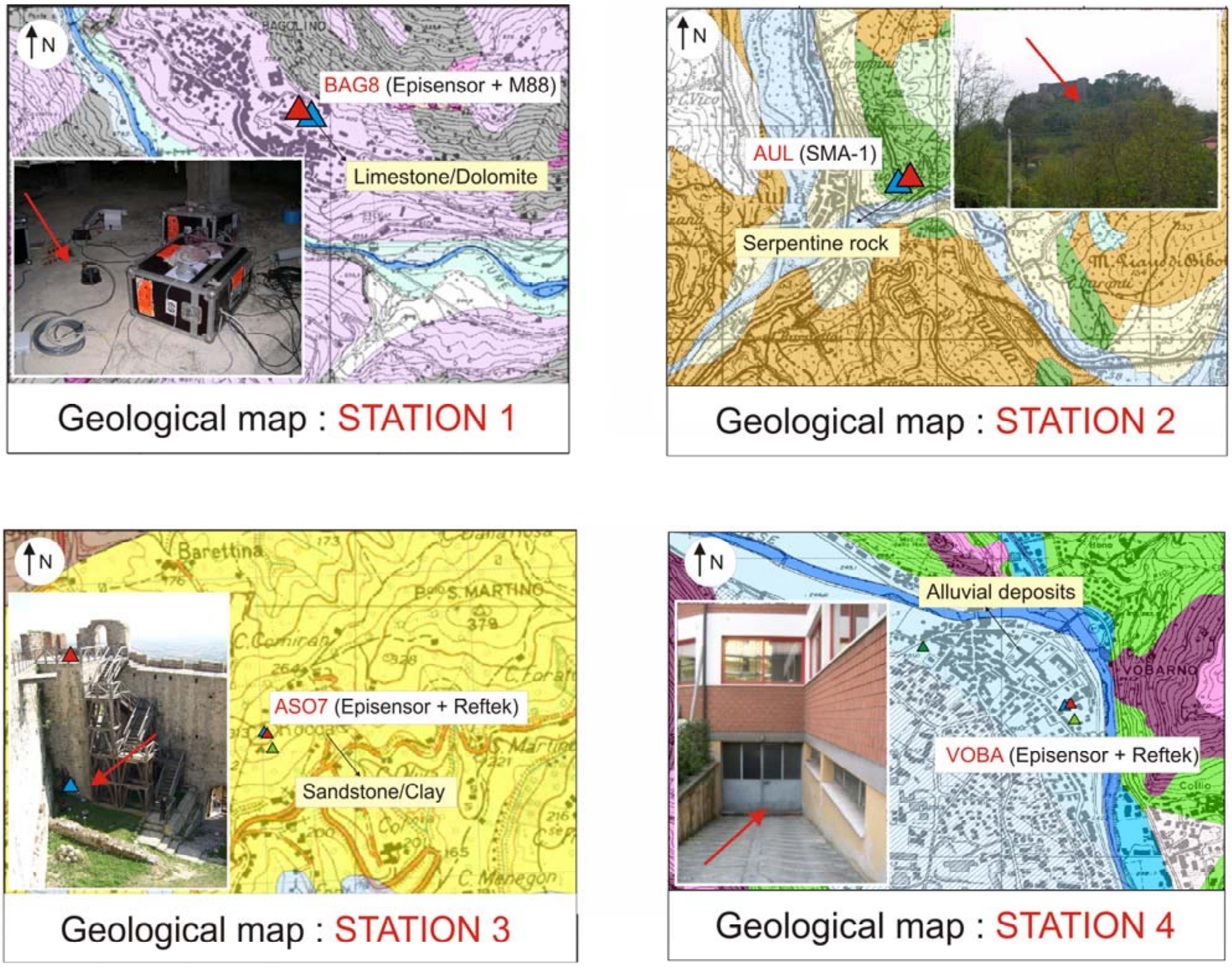
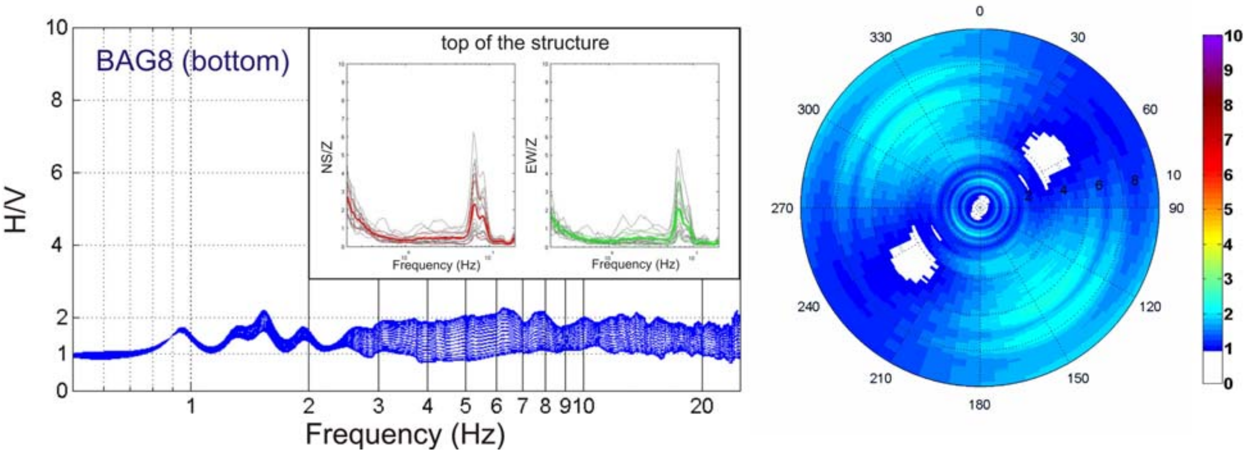
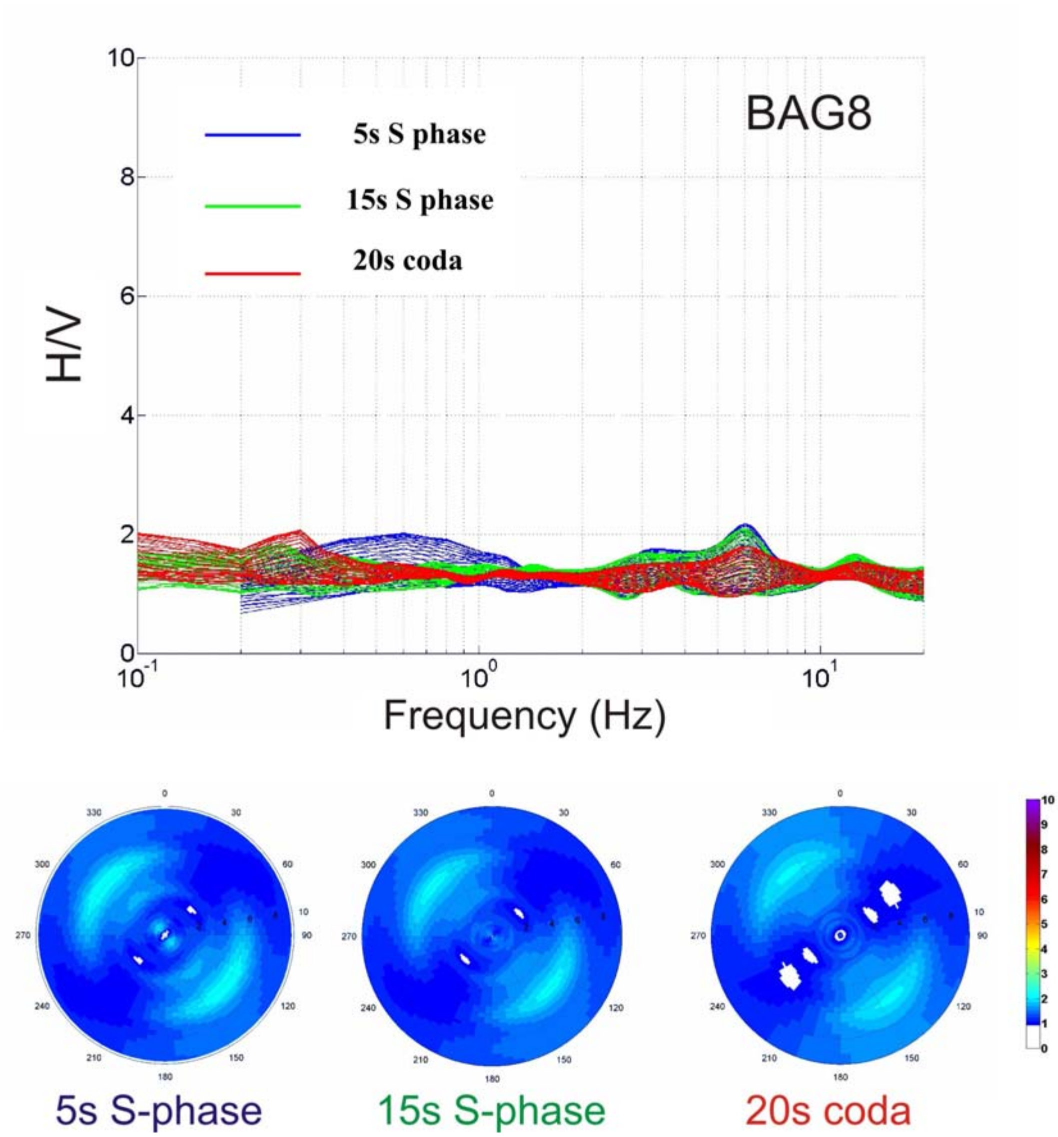

N
BAG8 (Episensor + M88)
Limestone/Dolomite
Geological map : STATION 1
N
AUL (SMA-1)
Serpentine rock
Geological map : STATION 2
N
Barettina
ASO7 (Episensor + Reftek)
Sandstone/Clay
Geological map : STATION 3
N
Alluvial deposits
VOBARNO
VOBA (Episensor + Reftek)
Geological map : STATION 4

Figure 2



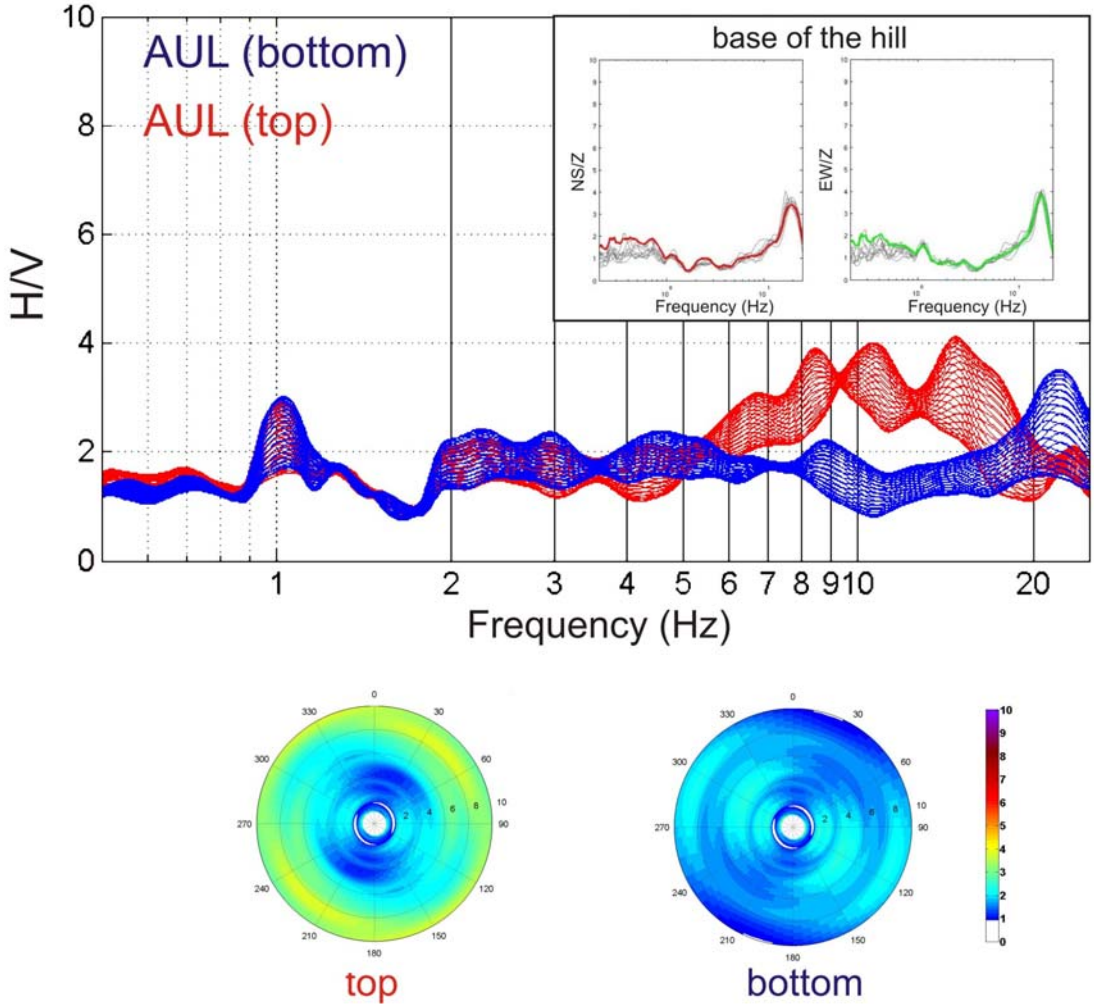
BAG8 (bottom)
top of the structure
NS/Z
EW/Z
Frequency (Hz)
H/V
Frequency (Hz)

Figure 3



BAG8
5s S phase
15s S phase
20s coda
H/V
Frequency (Hz)
5s S-phase
15s S-phase
20s coda

Figure 4



AUL (bottom)
AUL (top)
H/V
Frequency (Hz)
base of the hill
NS/Z
EW/Z
Frequency (Hz)
top
bottom

Figure 5

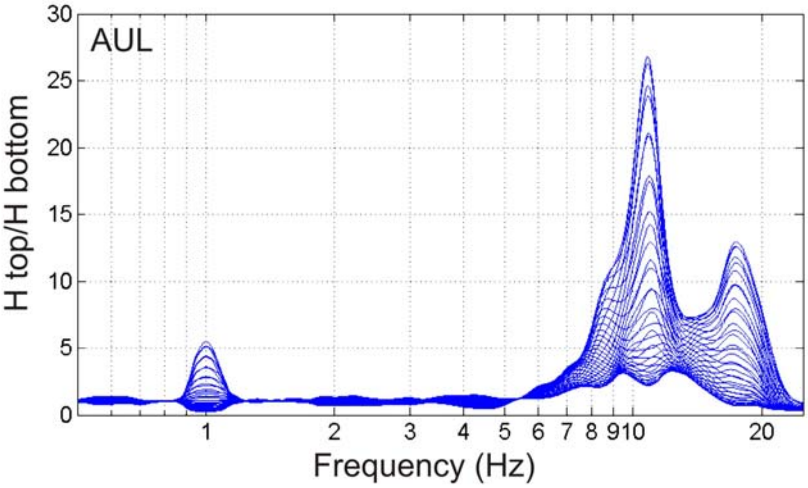
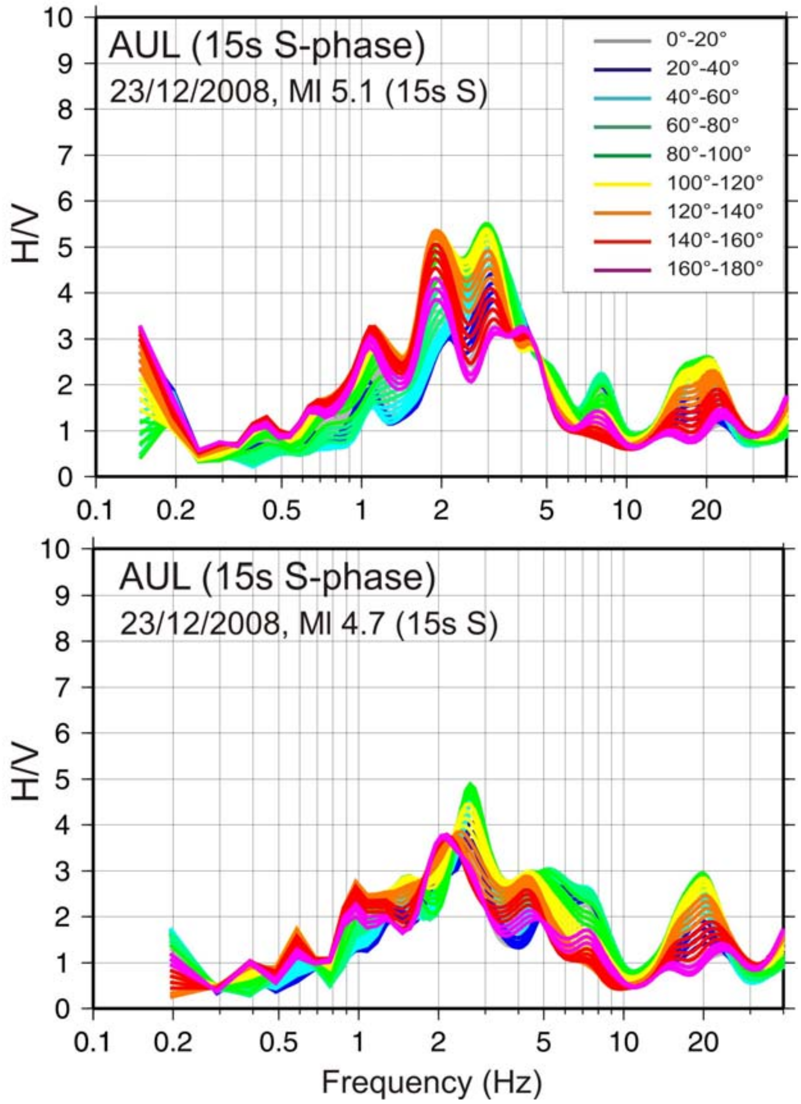
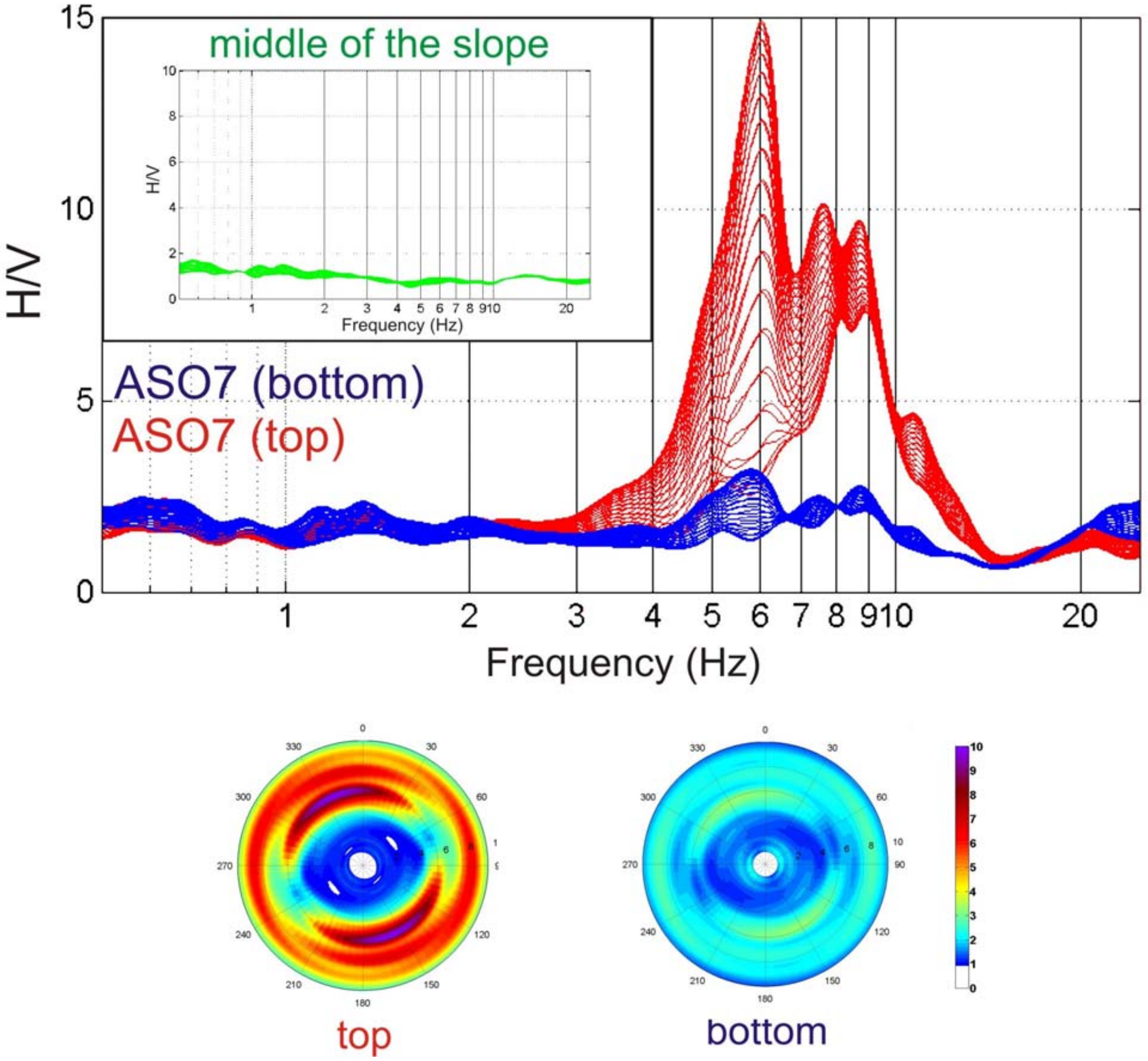

AUL
H top/H bottom
Frequency (Hz)
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
20

Figure 6



AUL (15s S-phase)
23/12/2008, Ml 5.1 (15s S)
0°-20°
20°-40°
40°-60°
60°-80°
80°-100°
100°-120°
120°-140°
140°-160°
160°-180°
H/V
AUL (15s S-phase)
23/12/2008, Ml 4.7 (15s S)
H/V
Frequency (Hz)

Figure 7



middle of the slope
H/V
Frequency (Hz)
ASO7 (bottom)
ASO7 (top)
top
bottom

Figure 8

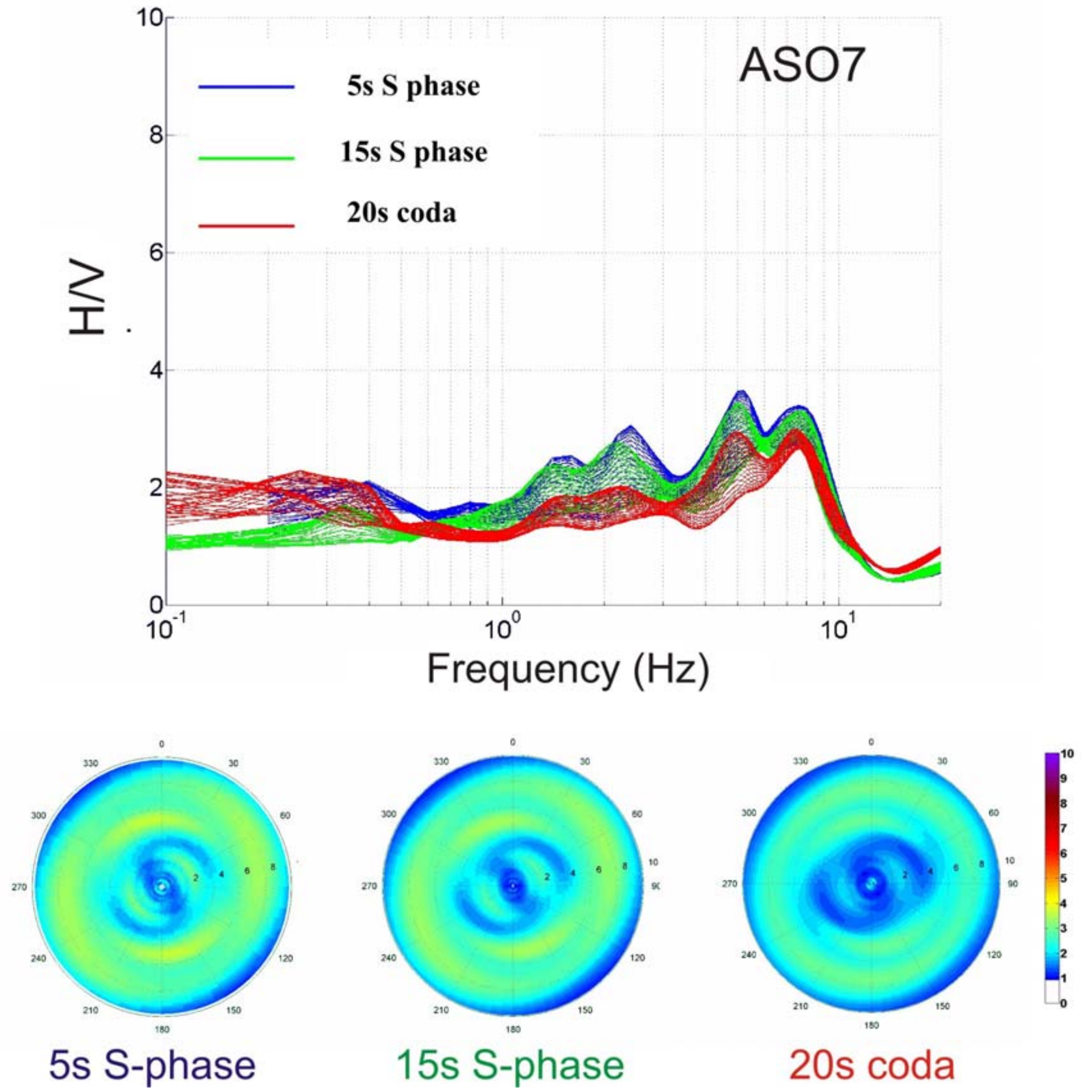

ASO7
5s S phase
15s S phase
20s coda
H/V
Frequency (Hz)
5s S-phase
15s S-phase
20s coda

Figure 9

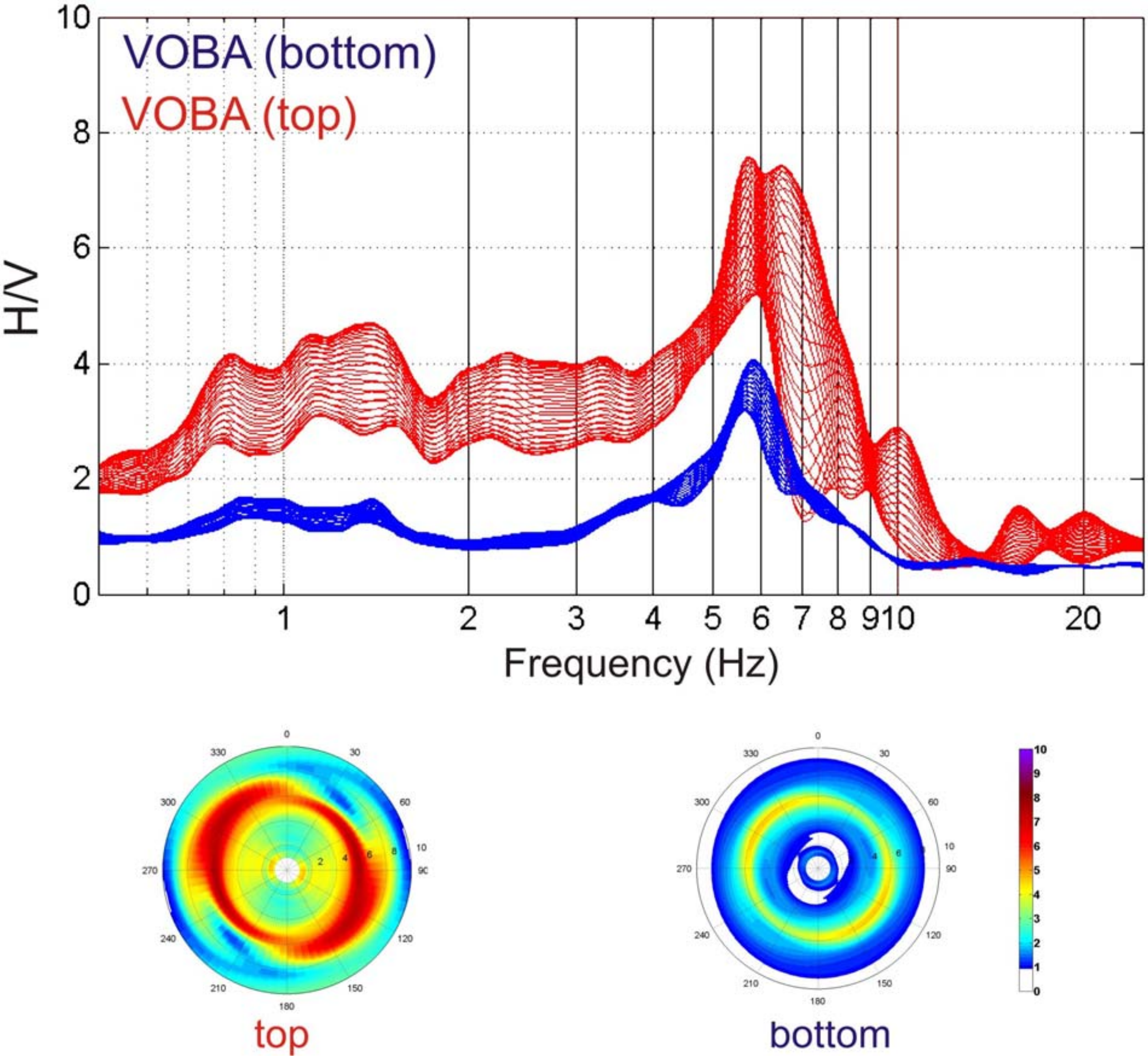


Figure 10

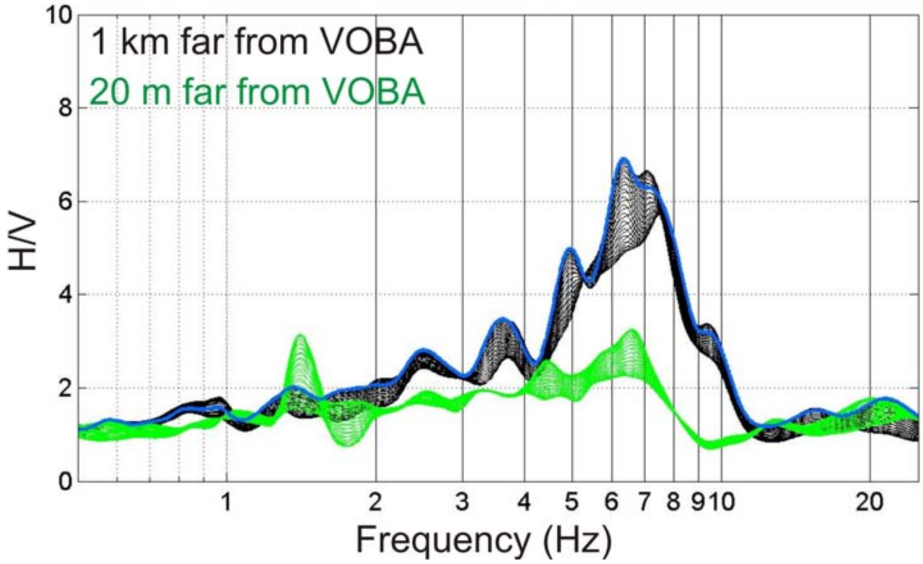
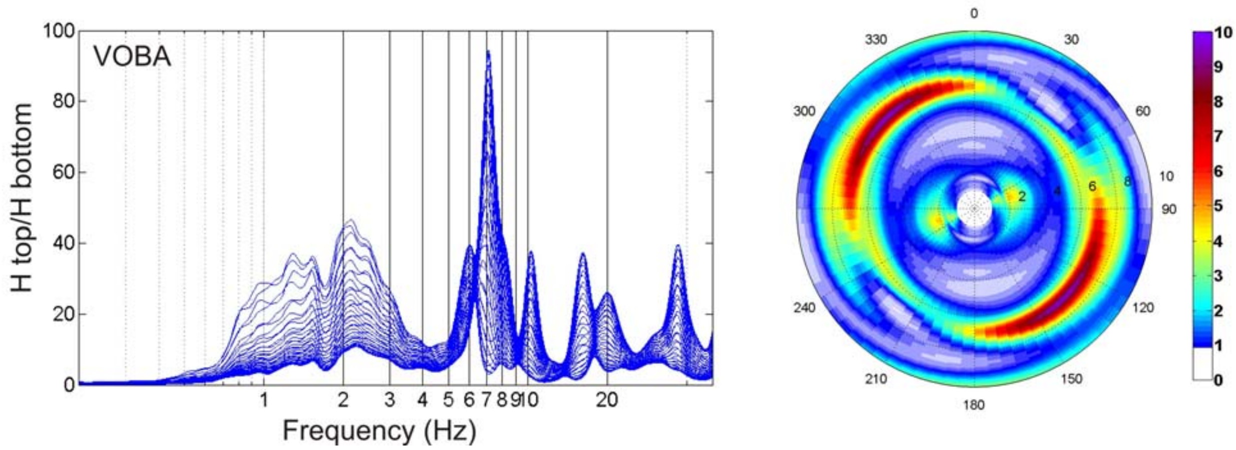
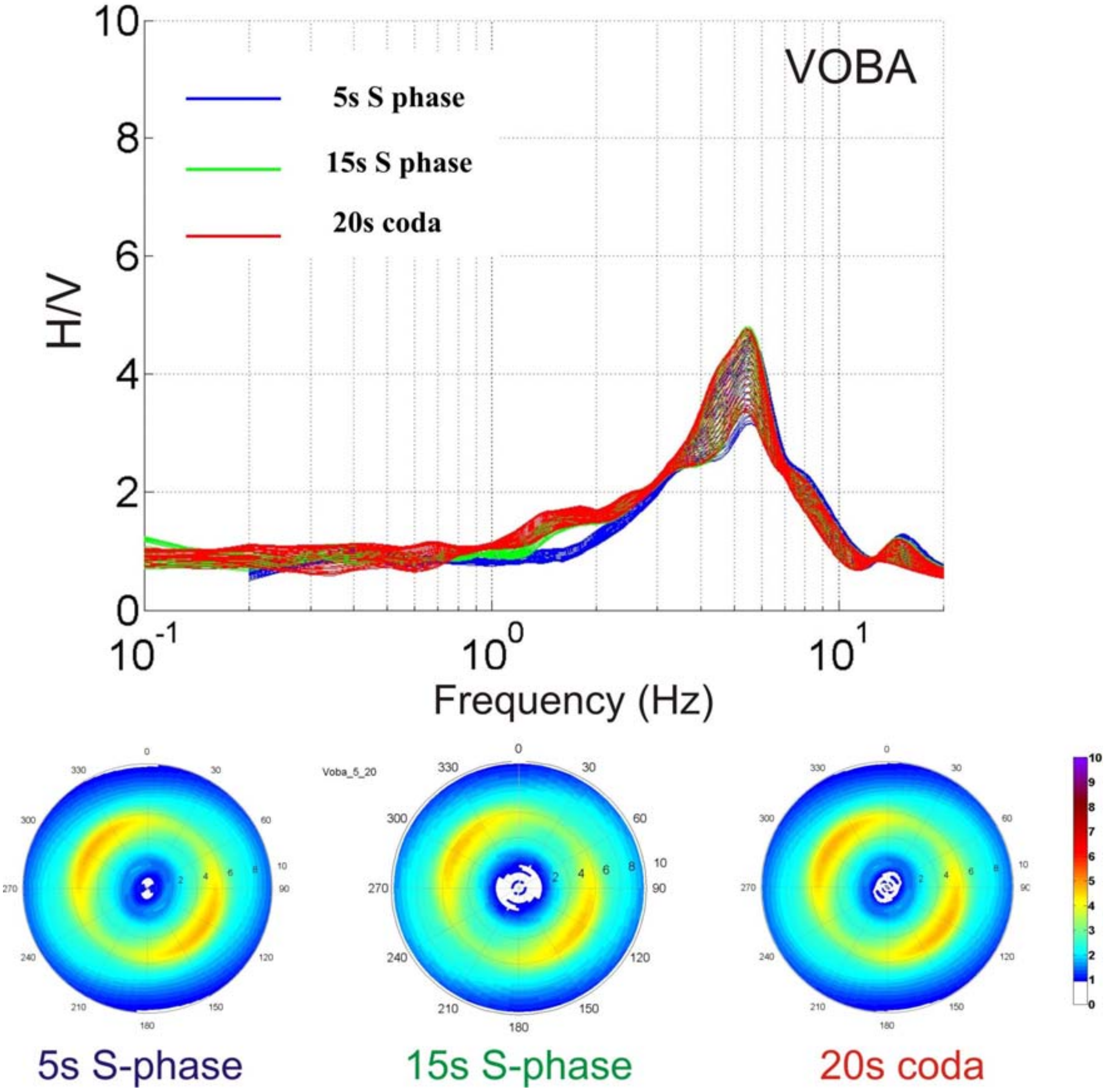

1 km far from VOBA
20 m far from VOBA
H/V
Frequency (Hz)
10
8
6
4
2
0
1
2
3
4
5
6
7
8
9
10
20

Figure 11



VOBA
H top/H bottom
Frequency (Hz)
0
20
40
60
80
100
1
2
3
4
5
6
7
8
9
10
20
0
30
60
90
120
150
180
210
240
300
330
2
4
6
8
10
0
1
2
3
4
5
6
7
8
9
10

Figure 12



VOBA
5s S phase
15s S phase
20s coda
H/V
Frequency (Hz)
Voba_5_20
5s S-phase
15s S-phase
20s coda

Figure 13

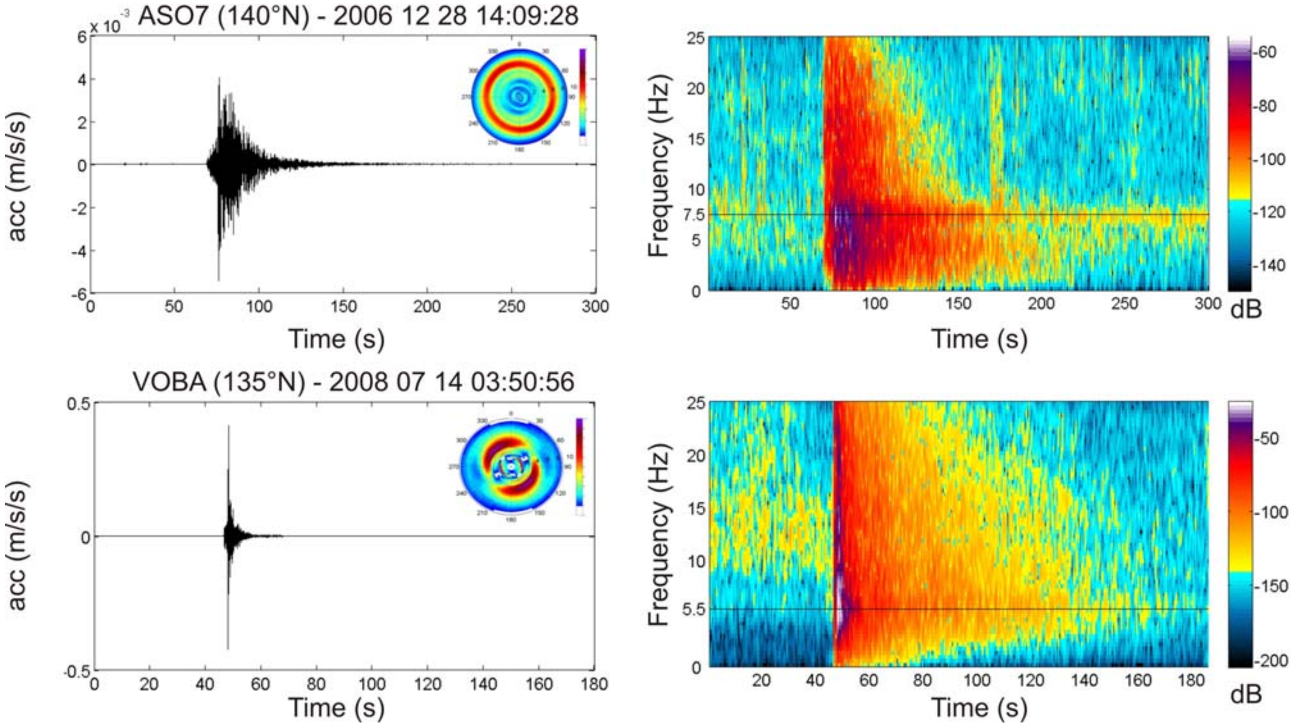

ASO7 (140°N) - 2006 12 28 14:09:28
acc (m/s/s)
Time (s)
Frequency (Hz)
dB
VOBA (135°N) - 2008 07 14 03:50:56
acc (m/s/s)
Time (s)
Frequency (Hz)
dB

Figure 14

station code	BAG8	AUL	ASO7	VOBA
Location	Bagolino	Aulla	Asolo	Vobarno
Longitude	10.46E	9.97E	11.91E	10.50E
Latitude	45.82N	44.20N	45.80N	45.64N
Quota	807	176	221	292
EC8 soil class	A	A	A	B
Geological units	rock (Limestone)	rock (Serpentine)	rock (Sandstone)	Alluvial deposits
Morphological setting	on the slope	top of a hill	top of a hill	plain
Type of installation	directly on rock	directly on rock	on the foundation	on the foundation
Structure	RC (2 stories)	bearing-wall	bearing-wall	RC (2 stories)
Main HVNR peak (bottom)	6.2 Hz (2.2)	21 Hz (3.5)	5.8 Hz (3)	5.8 Hz (4.1)
Main HVNR peak (top)	6.5 Hz (6.3)	11 Hz (4)	6 Hz (14.9)	5.7 Hz (7.4)
Main HVSR peak	6.1 Hz (2.2)	3 Hz (5.5)	6 Hz (3.7)	5.5 Hz (4.7)

Table 1