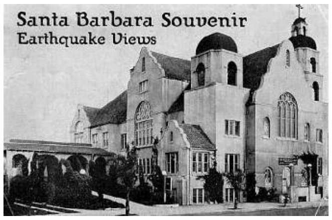

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THE ROLE OF SUBSOIL HETEROGENEITY IN THE SEISMIC RESPONSE OF BEDROCK CONSTITUTED RELIEF: TWO CASE STUDIES IN CENTRAL ITALY

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ABSTRACT

Local seismic amplification at Colle di Roio and Belmonte Castello limestone ridges, Central Italy, was studied by means of spectral analyses of both ambient vibration and earthquake records. Geological surveys highlighted the presence of intensely jointed rock masses at the Colle Roio hilltop, related to an anticline fold structure, while in the Belmonte Castello ridge a saddle zone characterized by filling deposits overlying the bedrock was individuated. HVSR analysis of ambient vibrations highlighted the presence of a main HVSR peak in the frequency range 4-6 Hz by the top of the ridge and in the frequency range 6.5-7.5 Hz in the saddle area of Belmonte Castello. The analyses showed the occurrence of directional seismic responses and local amplifications with amplitude level below 5 at Colle Roio and up to a 10 fold at Belmonte Castello in the same frequency ranges of the HVSR peaks. More in particular, in the case of Colle Roio the observed amplifications can be mainly related to jointing conditions of the outcropping rock masses, rather than to topographic effects.

INTRODUCTION

Site effects are well known to influence the observed damage pattern following major seismic sequences starting from the famous 1985 Michoacan, Mexico, earthquake to the recent 2009 L'Aquila, Italy, earthquake. In the scientific literature site effects are recognized to severely affect those areas where loose or soft deposits overlie stiff geologic units, such as geologic basins or sediment filled valleys, and consistent empirical and theoretical site effects estimation methods and procedures were developed, including soils non linear behaviour under cyclic loading and influence of seismic input incidence and subsoil 3D geometries on seismic ground-motion at the surface. Recentlym, some researches focused the attention on the seismic amplification phenomena affecting those specific areas where geologic media outcrop that cannot be considered as solid rock.

At a regional level it was recognized that also rock sites, under specific conditions which however result widespread in Italy, are potentially subjected to seismic amplification as a result of local geologic conditions not directly related to soft sediment filling (Rovelli et al., 2002; Martino et al., 2006; Pischiutta et al., 2010).

The bibliographic review pointed out that two types of site effects characterizing the seismic response of rock sites are observable in nature: topographic site amplification and fault zone related site effects.

The first type of phenomenon produces moderate site amplification, up to a factor of 5, and evident polarization of ground motion in direction perpendicular to the elongation axis of the usually 2D topographic

feature as a result of the wavefield scattering by topography (Spudich et al., 1996). As a general consideration these phenomena result well reproducible by numerical simulation as concerning the fundamental resonant frequencies of the morphological feature, while, on the contrary, the amplification levels are underestimated. This last observation is explained by many authors (Geli et al., 1988; Pedersen et al., 1994; LeBrun et al., 1999) as a consequence of the adoption of very simple homogeneous models as well as the influence of the input motion incidence and wave type. The second type of phenomena produce moderate to high level, up to a factor of 10, site amplification in a narrow area around the fault traces where the fault zones act as waveguides to critical reflected phases between the low velocity fault zone and high velocity surrounding rocks clearly observable on seismograms as wavetrains closely following the S waves with slight dispersion, called trapped modes (Li and Leary, 1990). These phenomena were recognized to be originated as a consequence of energy trapping either within superficial low velocity fault zone volumes or within fault zone volumes extending down to seismogenic depth; in the former case the earthquakes able to produce trapped waves can have hypocenters located in a wide region around the fault zone while in the second case the hypocenters have to be within the fault zone (Ben-Zion et al., 2003). Numerous researches conducted in California on strike-slip fault types demonstrated also that trapped modes produce polarization of ground motion in direction parallel to the fault strike as a result of crack iso-orientation (Karabulut and Bouchon, 2007).
In the light of these very recent studies, the present reasearch is devoted to the analysis of the seismic response of selected rock sites presenting characteristics such that the solid rock conditions are not satisfied, in order to provide a contribution concerning the evaluation of those geologic conditions in presence of geologic bedrock outcroppings that are prone to produce site amplification and the estimation of the amplification level observed. The achievement of these goals was pursued by the examination of the available scientific literature (Rovelli et al., 2002; Martino et al., 2006), selection and analyses of two Italian case studies: Colle di Roio (AQ), Belmonte Castello (FR).

GEOLOGICAL SETTING OF THE CASE STUDIES

a) COLLE DI ROIO

The study-area is located in the central part of the Italian Apennines which have a thrust-belt structure (Ciarapica and Passeri, 1998). The area represents a tectonic basin bordered by NW-SE trending carbonate ridges and the geomorphological evolution of the basin is strongly conditioned by the tectonic setting, by the alternation of sedimentary and erosive processes related to the climatic cycles and the significant uplift of this sector of the Appeninnes active since the lower Pliocene.

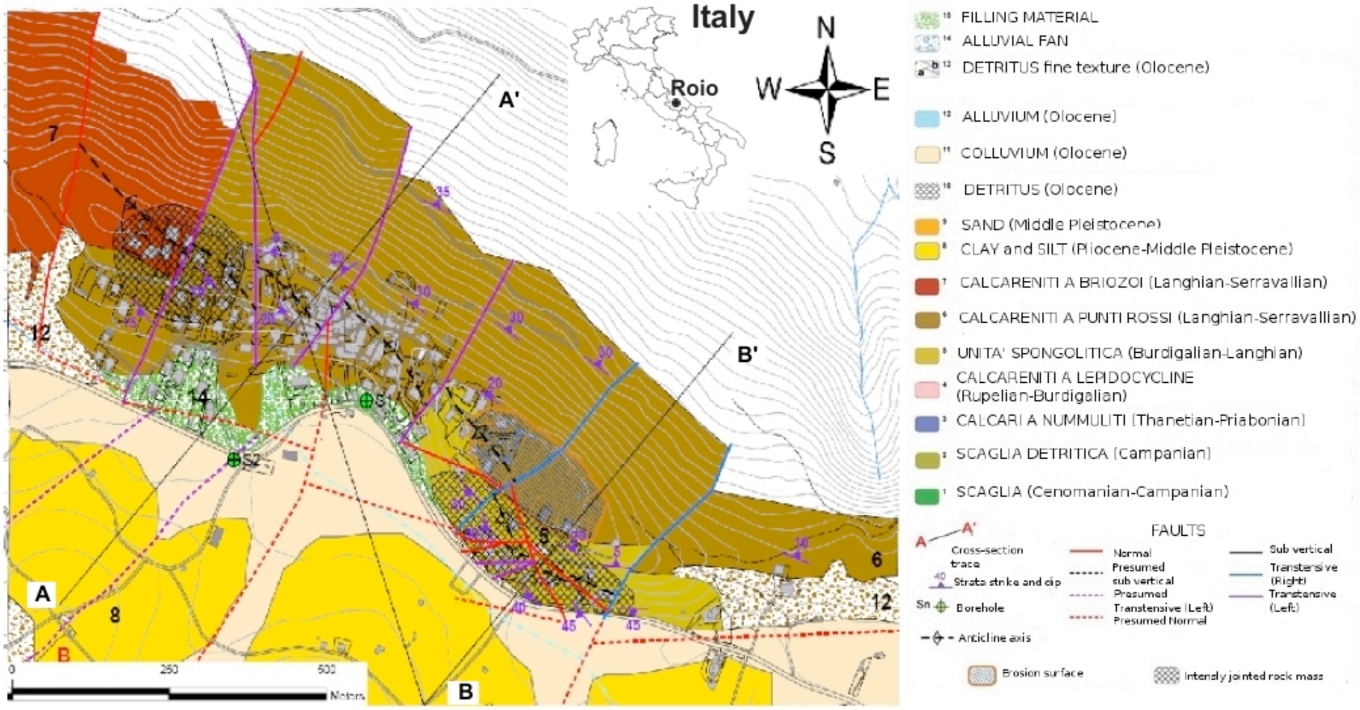

Fig. 1 . Detailed Geologic map of the Colle di Roio area

It is located at higher altitude with respect to the wider Aterno River Valley and surrounded by carbonatic relief which rise to an height of about 1400 m a.s.l. on the SW limit, while the basin is bordered by a NW-SE trending carbonate ridge on the north eastern side, where the Poggio di Roio village is located. It is worth noting that since the Colle di Roio village lies on the culmination, partially at the SW slope of the homonymous ridge and partially, on the northern basin edge, the geological, geotechnical and geophysical surveys and site response analyses were conducted with the aim of identifying potentially topographic and/or jointed induced or fault zone related site effects.

From a paleogeographic point of view the Roio Basin belongs to the NE border of the Latium-Abruzzi carbonate platform at the transition to the Umbria-Marche pelagic basin. The outcropping geologic successions are mesozoic-cretaceous lithofacies of ramp-basin domains overlain by paleogenic and miocenic terms (Fig.1, 2).

The Roio basin represents a tectonic basin with half graben structure bordered by normal faults with NW-SE (appenninic direction) and SW-NE (anti-appenninic direction) strike. The fault system of plio-pleistocenic age is superimposed on the compressive and transcurrent neogenic structures. The main faults with N140°-160° strike and SW dip represent the eastern and northern borders of the basin and on the field show evidences of pure dip-slip movements. These main structures are limited northward and on the eastern relief by EW strike transtensive faults. The SW-NE (N20°-N50°) strike faults present high inclination angles with both SE and NW dipping and show evidences of transcurrent and transtensive movement both right and left on the field. The main structure of the Colle di Roio area which witnesses the previous compressive regime of the region is the Colle di Roio anticline.

It presents appenninic axial direction (N130°-N140°), NE vergence and it develops along the Colle di Roio ridge as a fault propagation fold related to a major thrust (not present in map) which put the carbonatic mesozoic formations over the marly and clayey miocenic formations (Fig.2).

The superimposing of different deformation events caused an intense jointing of the rock mass along the hinge zone, coinciding with the culmination of the topographic feature as well as the historic centre of the Colle di Roio hamlet. Moreover, the anticline results dissected by the antiappenninic strike faults complicating the jointing pattern of the hinge zone. The geologic survey allowed the identification of at least two joint families: one related to pressure-solution cleavage originated during compressive regime and another related to sub-vertical extensional joints with strike parallel to the fault plane originated in extensive regime.

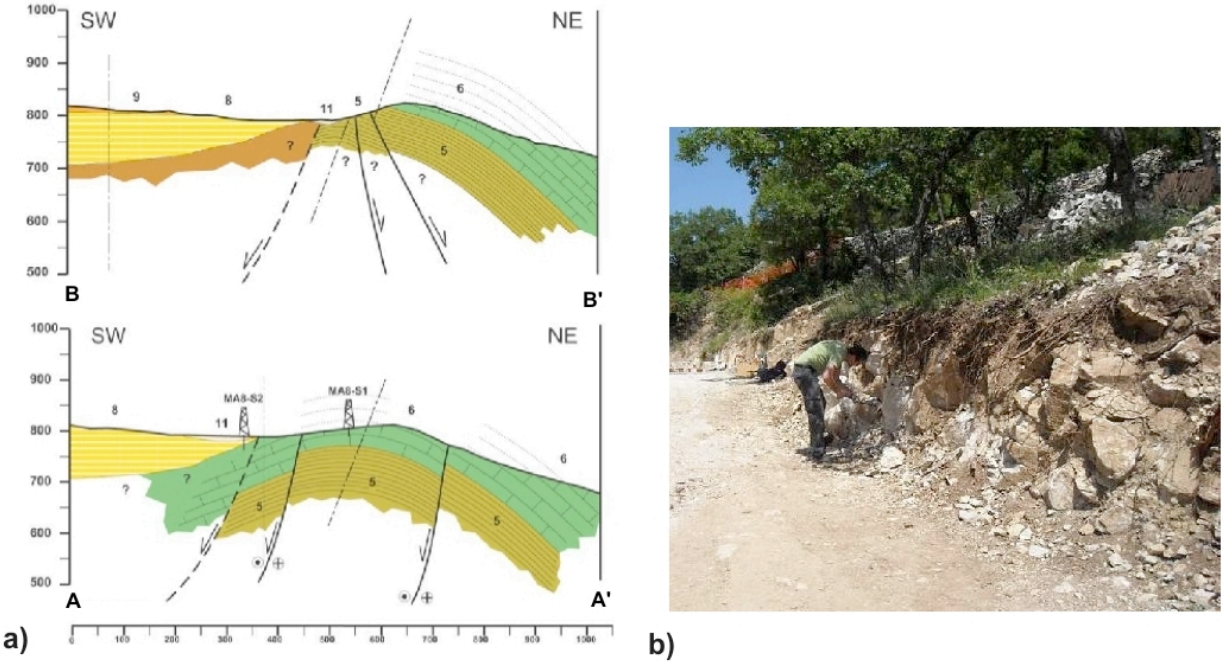

Fig.2 .a) Geological crosssections of the Colle di Roio hill (see Fig.1 for traces) and b) intensely jointed limestones outcropping at the top of the hill along the hinge of the fold.

b) BELMONTE CASTELLO

The Belmonte Castello village is located in southern Latium region within the inner sector of the central Appennine chain, on the eastern margin of a carbonate ridge structure which results as an isolated block. The study focused on the most ancient part of the village which is located along the NW-SE trending Belmonte Castello carbonate ridge, whose origin and geomorphological setting results strongly conditioned by the tectonic evolution of this sector of the Appennines.

The area is characterized by the wide outcropping of mesozoic carbonate formations mainly belonging to the Latium-Abruzzi carbonate platform palegeographic domain of nerithic and back reef facies (Calcari Detritici unit) and miocene age carbonate ramp facies calcarenites and terrigenous Flysch units. Moreover, continental quaternary units, locally overlying the mesozoic and miocenic bedrock, widely outcrop in the less elevated areas.

The Belmonte Castello ridge presents an irregular topographic profile characterised by variable elevation between 300 m and 550m. The irregularity is related to the interaction of the tectonic setting and the karst phenomena which affected the carbonate formations and formed several funnel shaped depression partially covered by residual soils in the central and NW sector of the area. This interaction produced also a saddle zone developed in NE-SW direction that resulted covered by a colluvium deposit made of carbonate clasts in sandy-silty matrix with a non horizontal contact over the bedrock with shallowing depth moving from the centre of the saddle towards NW and SE. The foothill is covered by talus deposits and rock mass movements were recognized on the slopes in the SW part of the ridge and in general on the carbonate steep slopes distributed in the study area.

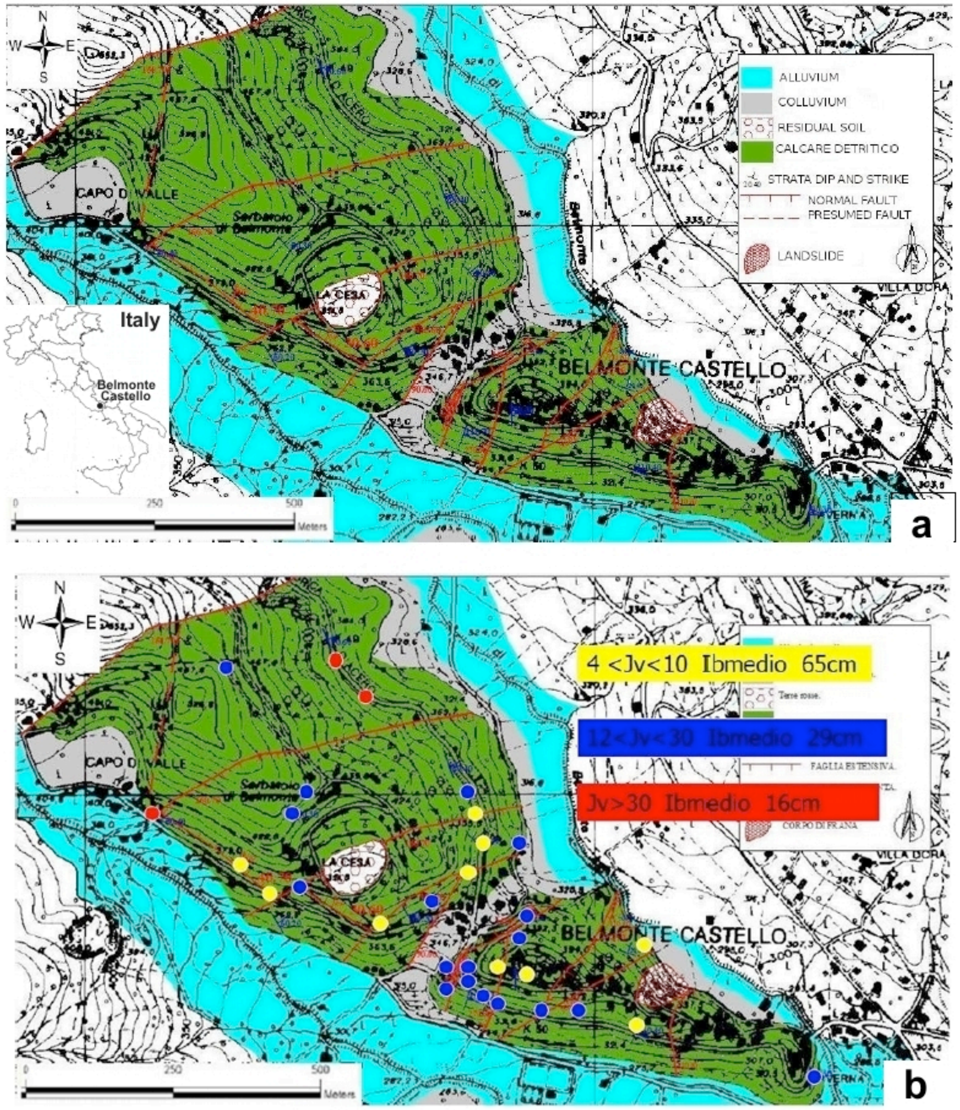

Fig. 3 . a) Detailed Geologic map of the Belmonte Castello area; b) location of the geomechnaical scan-lines with related geomechanical indexes Jv (number of joints for cubic meter) and Ib (tipical block dimension)

The general setting of the area is characterized by a complex tectonic pattern; in particular, this tectonic pattern affected the structural setting of the Belmonte Castello carbonate ridge which is interested by numerous NE-SW trending faults with strike and dip components that controlled the topographic profile of the ridge along appenninc direction. Moreover, a secondary thrust which put the Calcari Detritici unit over the miocenic formations was recognized in the NW sector of the study area. The geologic reconstruction leads to hypothesize the presence of buried tectonic structures with strike slip and dip slip components bounding the Belmonte Castello ridge towards NE and SW below the adjacent river valleys.

DATA ACQUISITION AND DATA PROCESSING

a) COLLE DI ROIO

In addition to the acquisition of results coming from previous surveys several investigations were conducted in the Colle di Roio area; in particular:

- detailed geologic and geomorphological survey aimed at defining the engineering geologic model of the area;

- realization of 2 borehole logs, aimed at defining the engineering geologic model of the area;
- 1 down-hole test aimed at evaluating the elastic moduli of the engineering-geologic units recognized in the borehole logs and geologic survey;
- geomechanic surveys at outcropping scale, aimed at defining the jointing conditions and elastic moduli estimation of the rock masses;
- 42 location of single station ambient vibration recordings and analyses by HVSR during the period 1 June-31 July 2009. The recording stations were located along the ridge and in its SW slope.

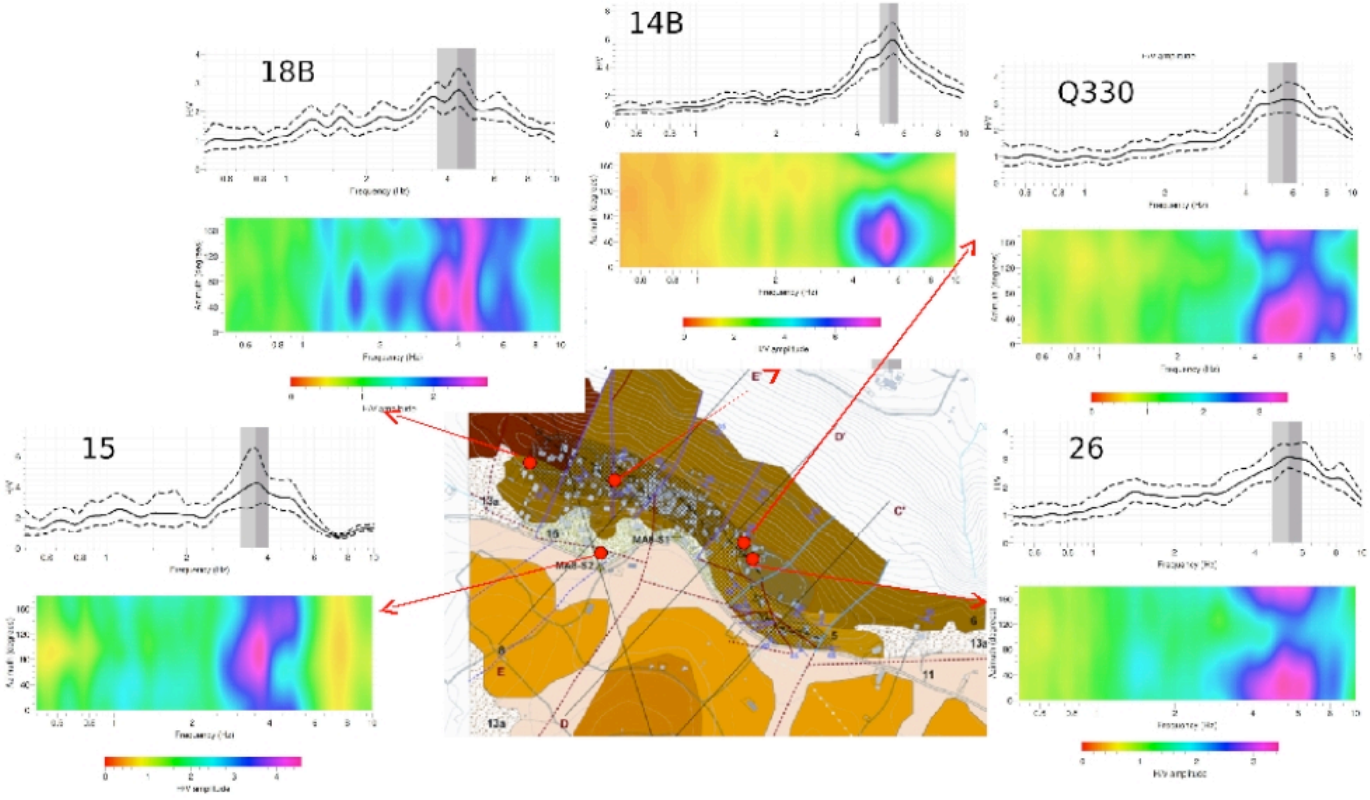

Fig.4 . HVSRs and related azimuthal distribution referred to the noise measurements performed along the top of the Colle di Roio hill and its SW slope

With the purpose of identifying potential fundamental resonance frequencies of the subsoil structure by HVSR, several equipments were used to record ambient vibrations by single stations:

- Ranger SS1 uniaxial 1 Hz sensors coupled with digitizer/ acquisition system K2 Kinemetrics; this system used 3 uniaxial sensors in order to record the three components of ground motion for total duration of at least 15 minutes and digitizer was set to sampling frequency of 200 sps;
- Three component Tromino system; the total duration length was set up to 20 minutes and sampling frequency to 128 sps.

In addition, it must be noted that the same analyses were performed at the installation positions of the temporary network stations; in particular, apart from the above mentioned Kinemetrics system operated by ENEA institution, one accelerograph instrumentation was located at the top of Colle di Roio ridge operated by Sapienza University institution and one nearby seismograph instrumentation operated by INGV-Rome1 institution were used at this aim. In detail, the selected equipment was composed of:

- Episensor Kinemetrics accelerometer coupled with digitizer/ acquisition system Quanterra Q330 Kinemetrics, digitizer was set up to sample frequency of 100 sps;
- Lennartz Le3D 5 sec. sensor coupled with digitizer/acquisition system Quanterra Q330 Kinemetrics, digitizer was set up to sample frequency of 100 sps.

The records were processed dividing the signals in time windows (20 or 40s), which were de-trended, 5% cosine tapered and converted to the frequency domain. The spectra were smoothed using the Konno-Omachi smoothing algorithm with parameter value b set to 20. The smoothed spectra of the north-south (NS), west-east (WE) and vertical (V) components, were used to calculate the NS/V and WE/V spectral ratios and the geometric average HVSR curve for each time window. The final HVSR function is calculated as the mean HVSR on the results of all the time windows. Also a directional analysis was performed by rotating the horizontal component by 10° bins in order to evaluate the amplitude of the resulting HVSR curve as a function of azimuth.
The results in terms of HVSR functions were analysed in the frequency range of engineering interest 0.5-10 Hz. According to SESAME project criteria (Bard and SESAME-team, 2005) only amplitude ratio values larger than two were taken into account.

Table 1. List of analysed earthquakes recorded at Colle di Roio hill, depth is expressed in Km.

ID	DATE	TIME UTC	LAT.	LONG.	DEPTH	Ml	DISTRICT
1	2009/06/15	15:21:31	42.439	13.445	10.1	3.1	Gran Sasso
2	2009/06/16	18:52:57	42.297	13.391	12.3	3.1	Aquilano
3	2009/06/19	19:47:09	42.302	13.383	9.9	3.3	Aquilano
4	2009/06/20	05:41:15	42.332	13.377	10.7	3.1	Aquilano
5	2009/06/21	00:55:17	42.282	13.489	10.0	3.2	Valle Aterno
6	2009/06/21	16:31:11	42.567	13.195	9.9	3.4	Monti Reatini
7	2009/06/22	20:58:40	42.446	13.356	14.2	4.5	Gran Sasso
8	2009/06/23	00:41:56	42.441	13.369	15.6	3.8	Gran Sasso
9	2009/06/23	08:35:08	42.462	13.347	10.7	3.5	Gran Sasso
10	2009/06/23	20:58:50	42.445	13.360	13.0	3.2	Gran Sasso
11	2009/06/25	16:14:57	42.569	13.193	9.9	3.3	Monti Reatini
12	2009/06/25	21:00:08	42.570	13.206	10.9	3.9	Monti Reatini
13	2009/06/25	23:31:54	42.256	13.085	7.6	3.2	Appennino Maceratese
14	2009/06/26	07:14:30	42.567	13.189	9.9	3.4	Monti Reatini
15	2009/06/29	05:54:33	42.463	13.366	13.5	3.1	Gran Sasso
16	2009/06/30	00:38:10	42.569	13.198	10.5	3.4	Monti Reatini
17	2009/07/03	01:14:07	42.320	13.378	11.6	3.4	Aquilano
18	2009/07/03	09:43:53	42.328	13.361	10.1	3.6	Aquilano
19	2009/07/03	11:03:07	42.409	13.387	8.8	4.1	Aquilano

The HVSR results are reported in Figure 4; since many measurements did not evidence clear peaks in the analysed frequency range, only examples of HVSR curve showing clearpeaks are depicted. The results highlight the presence of two areas located very close to the culmination of the fold hinge zone at the top of the ridge in the northwestern and southeastern portions of the relief, which are characterized by HVSR peaks in the frequency range 4-6 Hz. The amplitude resulted in general very small, below value 3, whereas HVSR curve 14B exhibited a peak amplitude of 6. Furthermore the azimuthal distribution of amplitude clearly showed a non uniform distribution of ground motion amplitude which seemed to be polarized at about N40E direction.
Differently, in the SW slope of the ridge and in the overlooking plain HVSR curves exhibit a non unique seismic response highlighted by peaks at frequencies ranging from 1.8 to 10 Hz.
In order to confirm the observations of directional site response effects, an analysis aimed at estimating the polarization angle by the covariance matrix method (Jurkevics, 1988) using the code POLARSAC developed by M. La Rocca. The analysis was applied to band passed noise recordings in the frequency range 2-8 Hz and total duration of 20 minutes. The algorithm operated on 2 s length time windows with 50% overlap. The results are shown by plotting the azimuth of polarization vector on the horizontal plane as rose diagrams (Fig. 5). The figures clearly show that the polarization of ground motion is always oriented in direction about NE-SW for the measurements showing a clear peak in the frequency band 4-6 Hz, as observed by azimuthal

analysis of HVSR, while the polarization resulted in NNW-SSE direction for the measure showing a clear peak in a lower frequency band and located at the SW ridge slope. It is worth noting that the polarization azimuth of stations showing a clear peak at nearby ridge top, presented direction rotated about 20° clockwise with respect to North direction, or about normal to the ridge trending axis, the latter being also the direction of the superficial projection of the anticline axis.

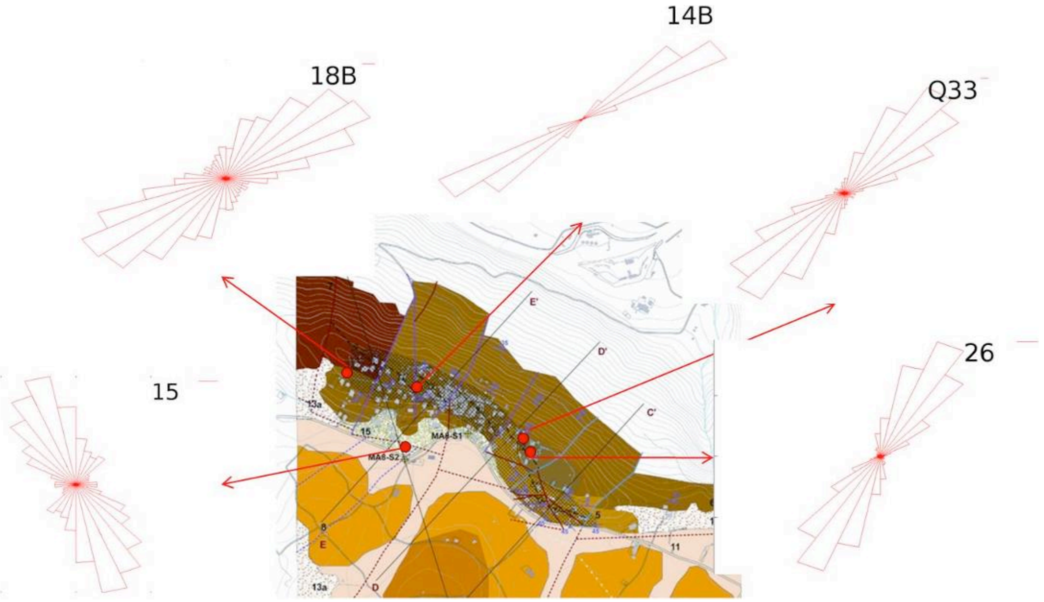

Fig.5. Results of polarization analysis obtained using ambient vibration records performed along the top of the Colle di Roio hill and its SW slope

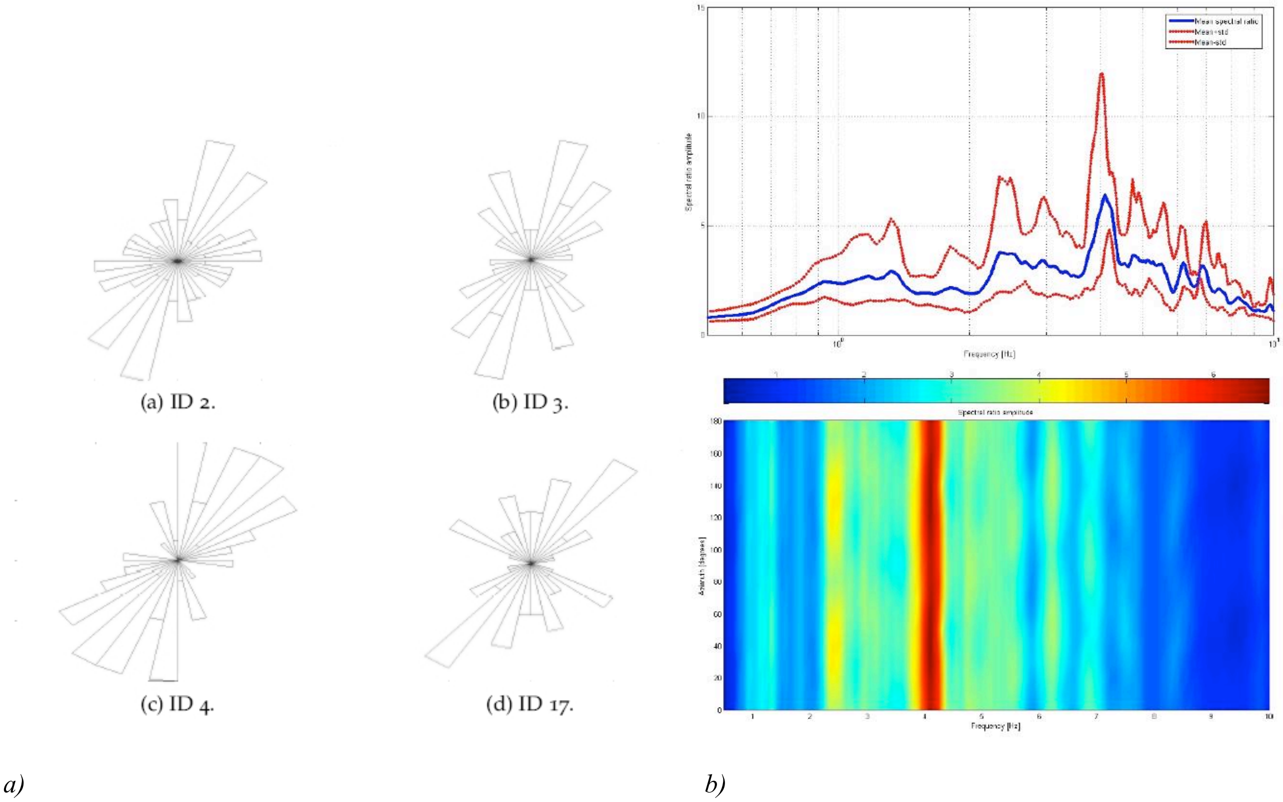

Fig. 6. Accelerometric records at Colle di Roio hill: a) example of polarization analysis (see Table 1 for the ID number of the

earthquakes); b) example of receiver function and related azimuthal distribution analysis.

These findings are in very good agreement with the analyses obtained from the earthquakes and recorded by the Q330 device which was installed in correspondence to the top of the Colle di Roio hill (Table 1), i.e. where the noise measurements showed the above described amplification effects. The accelerometric records were corrected for the instrument, successively for each event and component a 10s length time window was cut around the S-wave phase, 5% cosine tapered and converted to the frequency domain after trend removal. The spectra were smoothed using a 0.35-Hz running frequency window. The smoothed spectra of the northsouth (NS), west-east (WE) and vertical (V) components, were used to calculate the NS/V and WE/V spectral ratios and the geometric average of the two ratios was calculated in order to obtain the Receiver Function (RF) curve for each event. Similarly to the ambient vibrations analyses, also a directional analysis was performed by rotating the horizontal component by 10° bins in order to evaluate the amplitude of the resulting RF curve as a function of azimuth. Furthermore the covariance matrix method (Jurkevics, 1988) was again applied to band passed earthquake recordings in the frequency range 2-8 Hz on 1s length time windows with 50% overlap and total duration of 20 seconds.

The earthquakes analyses evidenced the significant amplification at the Colle di Roio hilltop around 4 Hz with amplitude level well above 5 for the N and S-SE back-azimuths (Fig.6). The polarization analyses showed results similar to that highlighted by the same study performed on ambient vibrations, even if the diagrams resulted rotated towards NNE-SSW direction and show dispersed pattern with respect to noise polarization study.

b) BELMONTE CASTELLO

In addition to the acquisition of results coming from previous studies and surveys several investigations were conducted in the Belmonte Castello area; in particular:

- detailed geologic and geomorphological survey aimed at defining the engineering geologic model of the area;
- realization of 1 borehole log, aimed at defining the engineering geologic model of the area;
- 1 down-hole test aimed at evaluating the elastic moduli of the engineering-geologic units recognized in the borehole log and geologic survey;
- geomechanic surveys at outcropping scale, aimed at defining the jointing conditions and elastic moduli estimation of the rock masses;
- 18 location of single station ambient vibration recordings and analyses by HVSR during January 2009.

Fig.7. Location of the temporary velocimetric network installed at Belmonte Castello hill.

With the purpose of identifying potential fundamental resonance frequencies of the subsoil structure by HVSR a tri-axial Tromino Micromed System was used to record ambient vibrations. The total duration length was set up to 20 minutes and sampling frequency to 128 sps. The records were processed as in the previous case study, using 30 s lenght time windows.

The results in terms of HVSR functions were analysed in the frequency range of engineering interest (0.5-10 Hz) and interpreted according to SESAME project criteria (Bard and SESAME-team, 2005). Further to the analyses it was observed that the HVSR curves obtained for the stations located in the saddle area showed a broad peak in the high frequency range between 4 and 10 Hz. This peak resulted not very sharp, temporally stable, with maximum amplitude value of 7 reached at about 8 Hz for both NS/V and EW/V ratios. This peak was observed in all saddle area, even if it broadens and decreases in amplitude moving from the most elevated point of measure down to the foot of the ridge flanks. This results may be interpreted as the effect of a non properly 1D resonance of the residual soil,colluvium and breccia deposits overlying the well cemented breccia and limestone bedrock in the saddle zone of the ridge. In fact the frequency at which the maximum value of HVSR function was observable resulted consistent with the mean Vs value of the quaternary covers and the depth of the seismic bedrock obtained in hole analysis; moreover the modification of the HVSR function observed in locations away from the saddle centre led to reconstruct the geometry of these deposits overlying the bedrock as of lens-shaped in cross section with maximum thickness in the centre thinning towards the saddle margins.

A temporary seismic network was installed in the Belmonte Castello village in order to evaluate the seismic response of the urbanized area of the saddle. In particular the network was constituted by three stations (Fig. 7):

1. one located in the basement of the Belmonte Castello Church on the top of the hill and used as reference station (RIF);
2. one located in the front yard of the school in the saddle centre (S1);
3. one located in the internal school court at the saddle northwestern limit (S2).

Each station was equipped with 3 SS1 Ranger 1 Hz Kinemetrics short period sensors oriented along the N, E and vertical directions connected to K2 Kinemetrics acquisition unit and GPS for absolute timing. The network operated in the time span April-May 2009; all stations used a manufacturer pre-defined STA/LTA triggering algorithm in order to detect and record events and the sampling frequency was set up to 200 sps.

In the above mentioned time span more than 30 earthquakes were recorded by the seismic network. The estimate of the UTC origin time epicentral coordinates and local magnitude level were obtained by consulting the Seismic Bullettin Catalogue of INGV institution. A sample of 24 earthquakes with magnitude level in the range 2.5 to 4.9 Ml were selected for the present study (Table 2). The seismic events were mainly associated to the L'Aquila sesimic swarm active since the beginning of 2009, thus the majority of earthquakes had an epicentral distance of about 100 Km.

The site effect at the saddle stations were estimated using the Receiver Function and Standard Spectral Ratio (SSR) methods. At this aim, the velocimetric records were corrected for the instrument response after de-trending and bandpass filtering in the frequency range 1 – 20Hz; for each event, station and component a 10s length time window was cut around the S-wave phase, starting about 1 second before the S phase onset, 5% cosine tapered and converted to the frequency domain after the trend removal. The spectra were smoothed using a 0.35-Hz running frequency window. The spectra of the RIF station were used to compute the SSR functions of the two saddle station S1 and S2 dividing each component spectrum by the same component spectrum recorded at the reference station.

Table 2. List of analysed earthquakes recorded at Belmonte Castello hill, depth is expressed in Km.

ID	DATE	TIME UTC	LAT.	LONG.	DEPTH	Ml	DISTRICT
1	2009/04/09	19:38:16	42.501	13.356	17.2	4.9	Gran Sasso
2	2009/04/09	22:40:06	42.481	13.298	10.9	3.6	Gran Sasso
3	2009/04/10	03:22:22	42.470	13.417	9.4	3.7	Gran Sasso
4	2009/04/10	11:53:09	42.243	13.484	9.6	3.1	Velino-Sirente
5	2009/04/10	15:22:43	42.248	13.484	10.2	3.0	Velino-Sirente
6	2009/04/10	15:46:17	42.349	13.376	9.9	3.3	Aquilano
7	2009/04/13	07:08:30	42.268	13.484	9.3	3.1	Valle Aterno
8	2009/04/13	19:09:49	42.360	13.348	10.4	3.8	Aquilano
9	2009/04/13	21:14:24	42.504	13.363	7.5	4.9	Gran Sasso
10	2009/04/14	13:56:21	42.543	13.312	10.0	3.9	Monti della Laga
11	2009/04/14	20:17:27	42.530	13.288	10.4	4.1	Monti della Laga
12	2009/04/15	22:53:07	42.505	13.312	8.6	3.8	Monti della Laga
13	2009/04/16	05:44:54	42.289	13.404	9.9	3.2	Aquilano
14	2009/04/21	14:31:45	41.405	13.886	8.9	2.5	Valle Latina
15	2009/04/21	22:26:30	41.986	14.023	7.6	3.2	Sulmona
16	2009/04/23	21:49:00	42.233	13.479	9.3	4.0	Velino-Sirente
17	2009/04/24	04:36:17	42.263	13.466	10.3	3.0	Velino-Sirente
18	2009/04/24	22:51:29	42.267	13.508	11.0	3.0	Valle Aterno
19	2009/04/25	02:08:23	42.294	13.454	8.3	3.1	Aquilano
20	2009/05/01	05:12:51	42.280	13.470	9.0	3.8	Valle Aterno
21	2009/05/08	01:02:47	42.268	13.583	7.9	3.2	Valle Aterno
22	2009/05/10	16:00:07	42.301	13.479	10.0	3.5	Valle Aterno
23	2009/05/12	18:33:08	41.839	13.601	10.4	2.6	Marsica
24	2009/05/14	06:30:22	42.501	13.406	7.9	3.8	Gran Sasso

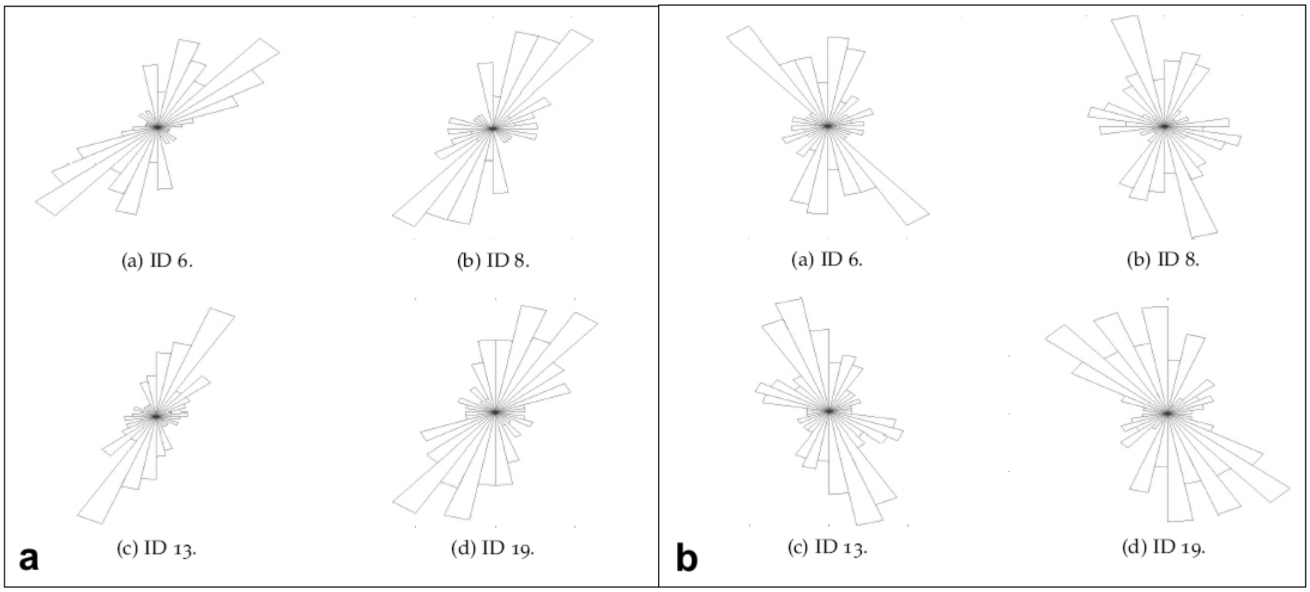

Fig. 8. Example of polarization analysis at Belmonte Castello hill (see Table 2 for the ID number of the earthquakes) referred to earthquake records at station RIF (a) and S2 (b) respectively (see Fig.7 for station location).

As in the case of RF calculation, the geometric average of the NS and EW ratios was calculated in order to obtain the SSR curve for each event and also the study of the vertical component behaviour was observed by this method. Furthermore a directional analysis was performed by rotating the horizontal component by 10° bins in order to evaluate the amplitude of the resulting RF and SSR curves as a function of azimuth. The spectral analyses of earthquakes evidenced the significant amplification at the saddle stations in the frequency range 6.5-7.5 Hz, while the RIF station showed a reference station behaviour. The amplitude levels at S2 station resulted underestimated by RF method (Fig. 9) since a moderate amplification of the vertical component was observed by the SSR method(Fig. 10).

Therefore, while a moderate amplification of a factor 5 was estimated for S1 station, an about doubled factor could be assumed for S2 station above 7 Hz. No strong directional response was observed in any of the station. In addition a secondary peak at 9 Hz was observable at S1 station for almost all analysed events.

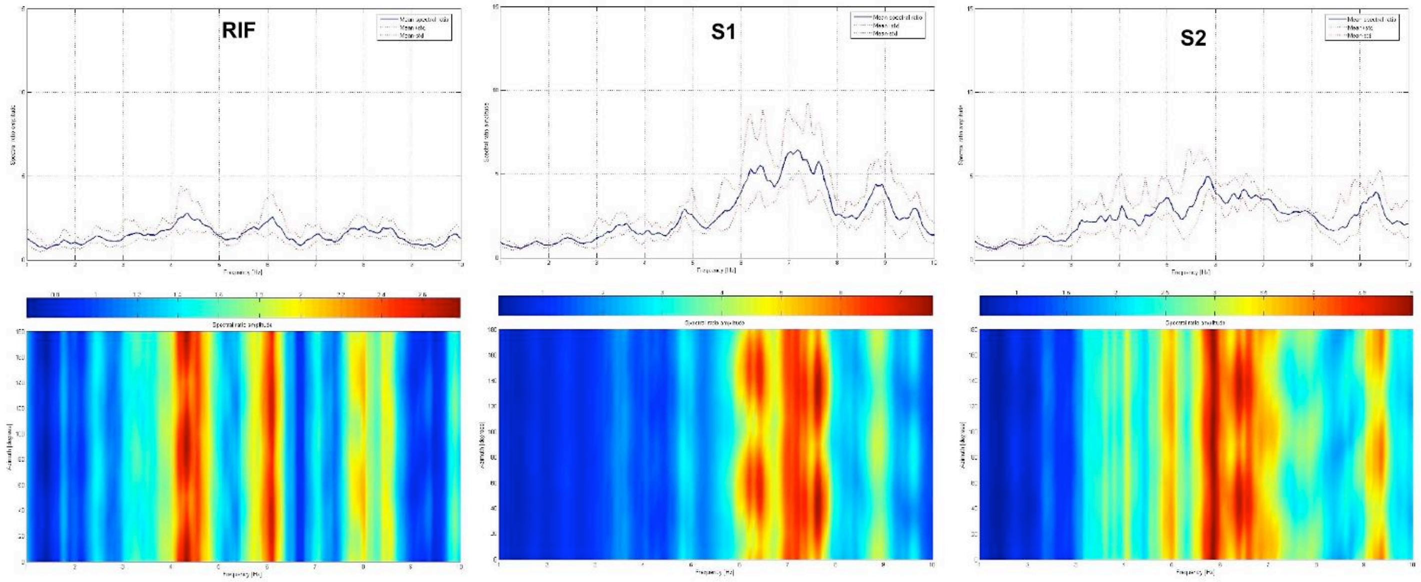

Fig.9. Average RFs and related directional analysis obatined for the Aquilano earthquakes (see Table 2 for the District) recorded by the Belmonte Castello velocimetric temporary network.

The covariance matrix method applied to 1s length time windows with 50% overlap, highlighted a very stable pattern of polarization independent on the event epicentral area for two of the three stations: at the reference station the ground motion resulted polarized in direction about NE-SW, while the ground motion at S2 station resulted polarized in direction about NW-SE (Fig. 8).

The S1 station did not show any preferential direction of the ground motion. The above described pattern at the reference station may be ascribed to the topographic polarization effect in direction normal to the Belmonte ridge axis, since the instrument location was on the Belmonte hilltop.

Difficulties in the interpretation of the polarization pattern at the saddle stations arose from the observations; since the two stations are located at about the same elevation and laid on colluvial deposits overlying the bedrock it can be hypothesized that the influence of the 3D subsoil structure at the saddle masked the topography contribution and characterized the ground motion presence or lack at these locations.

The investigations performed in the Belmonte Castello area highlighted the occurrence of seismic amplification in the saddle zone in the frequency range 6.5- 7.5 Hz with significant amplitude. This phenomenon is related to the presence in this area of an impedance contrast between breccia and colluvium deposits, which fill the saddle with a lens-like geometry of the subsoil, over well cemented breccia and calcareous rock. A second peak at 9 Hz was observed at S1 station as a result of the presence of a secondary impedance contrast between the residual soil and colluvium and the underlying breccia.

The polarization observed at the reference station confirmed the results of previous studies for which the preferential direction of ground motion at station located on top of topographic features is in general oriented in direction perpendicular to the ridge trending direction; while the results obtained at S1 and S2 station could be related to the subsoil structure in the saddle stations (Figs. 8, 9).

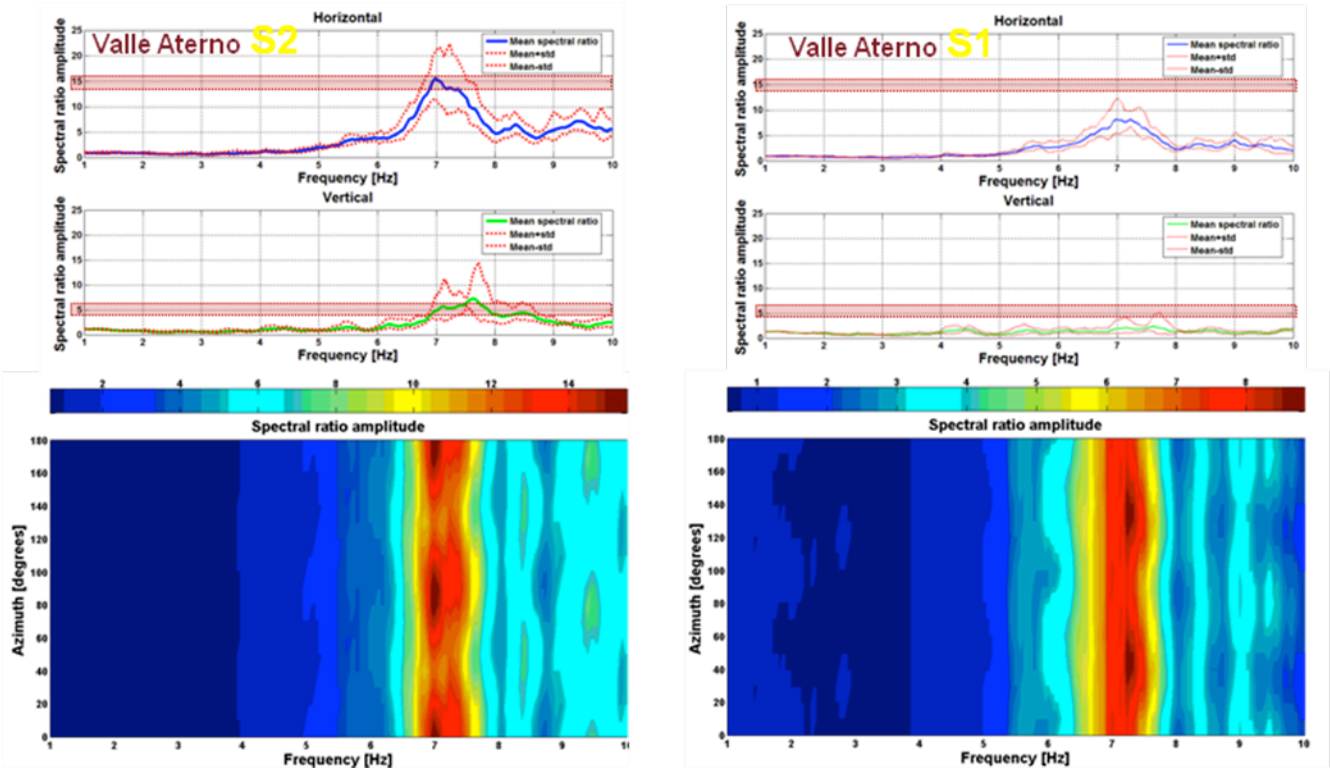

Fig.10. Average SSRs and directional analysis results obtained for the Valle Aterno earthquakes (see Table 2 for the District) recorded at station S2 (a) and S1 (b) by the Belmonte Castello velocimetric temporary network.

RESULTS

The present paper addressed the study of seismic amplification of rock sites which are usually considered not affected by seismic amplification phenomena.

The bibliographic review pointed out that two types of site effects characterizing the seismic response of rock sites are observable in nature: topographic site amplification and fault zone related site effects.

In the first case-study, Colle di Roio (AQ), geological, geomorphological, geomechanical and geophysical surveys, with particular reference to the HVSR method, led to the elaboration of an engineering-geologic model of the area consistent with the observation of the fundamental resonant frequency measured on top of the hill where the fold hinge zone of anticline structure was recognized in the field. It is worth mentioning that where only topographic amplification results clearly observable from spectral analysis of earthquake ground motion, no clear indications were obtained by ambient noise analysis excepting for the seismic amplification related to the combination of topography and trapped mode propagation (Martino et al., 2006).

It was observed a significant amplification at the Colle di Roio hilltop around 4 Hz with amplitude level well above 5 for the earthquakes with N and S-SE back-azimuths; with reference to more distant epicentres, the amplification shows a broad frequency range above 3 Hz with almost constant level. Furthermore the polarization analysis clearly highlighted the preferential direction of ground motion perpendicular to the ridge trending axis in agreement with previous results.

This empirical observation led to the interpretation of the site amplification as a result of the impedance contrast between the pervasively jointed rock in fold hinge zone, with wedge shape on ridge transversal cross-section and characterized by reduced elastic modulus and the surrounding bedrock. In this specific case the polarization resulted in agreement both with the general observation of topographic amplification in direction normal to the ridge trending axis and with the direction parallel to the σ3, or equivalently, with the direction normal to crack orientation; given that in anticline structures the radial crack pattern usually results oriented in direction parallel to fold axes. No clear identification of ground motion polarization could be obtained because of the undistinguishable contribution of the two potential origins.

In the second case study, Belmonte Castello , which is a NW-SE elongated carbonate ridge characterised by the presence of a peculiar morphological saddle area, the field surveys and geophysical investigations showed the presence of strong impedance contrast between quaternary residual and breccia loose deposits overlying carbonate bedrock compatible with the measured fundamental resonant frequency in the saddle area. In this case, the realization of a temporary network provided a useful dataset in order to estimate the site amplification at this specific location by three seismological stations. The site amplifications in the frequency range 6.5-7.5 Hz with amplitude level in the range 5-10 was confirmed by RF and SSR earthquake analyses and the polarization of ground motion showed a pattern leading to the interpretation of the local site effect as a result of a non properly 1D subsoil geometry of the filling material over the bedrock. In fact, in the saddle centre, where 1D geologic conditions were recognized, the amplification frequency of about 7 Hz with amplitude level well above 5 and dispersed polarization pattern were observed, while in the saddle NW margin, where basin edge-like conditions were reconstructed, the amplification in the high frequency range with amplitude level doubled with respect to the saddle centre and NW-SE ground motion polarization were observed. These latter observations led to assume that the effects of the 1D stratigraphic site conditions at the saddle centre and 2D stratigraphic site conditions at saddle margins strongly influence the site response of the area and results dominant in terms of site amplification and polarization with respect to the topographic effects.

CONCLUSIONS

The presented work confirmed the occurrence of site amplification in correspondence of rock outcroppings where the local geological conditions, and in particular the joint network spatial distribution, are able to produce significant impedance contrast between jointed rock masses. In the particular case of Colle di Roio, it was recognized for the first time in the author knowledge that the local conditions prone to seismic amplification resulted folding related, whereas only fault zone and topographic elevated conditions were considered able to produce seismic amplifications up to now.

It is worth mentioning that fold tectonics usually characterizes the geological setting of topographic relief in central Italy as a result of the tectonic regime that controlled the Appennines orogenesis. Furthermore, from a methodological point of view, the study suggested the possibility to identify site resonance frequencies related to lateral impedance contrast between rock masses by single station ambient vibrations analysis. Moreover the Belmonte Castello case study highlighted once more the importance of the recognition of small scale heterogeneities in seismic response studies as well as seismic microzonation studies of historical centres in Central Italy which represent an important part of the national cultural heritage. In fact the local geological conditions at a very detailed scale demonstrated in any case to influence the seismic response in the frequency range of engineering interest and confirmed the importance of the engineering-geological contribution to the individuation of seismic amplification prone areas, without neglecting the potential effects of jointing conditions referred to rock masses, at the aim of seismic risk reduction.

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