Cerreto di Spoleto (Umbria-Italy): Topographic amplification at the ENEA local array stations.

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SUMMARY
The study is part of a research project aiming at analysing natural disasters and their impact on the Italian cultural heritage. To this aim, ENEA installed in the 80's an accelerometric array in Umbria region (Central Italy), namely in the surrounding of Cerreto di Spoleto. The choice of this test site derives from the analysis of Italian seismic hazard maps, obtained in terms of peak ground velocity and taking into account regional geology. The maps highlight the considerable seismic hazard which characterises the Apennine belt and its possible increase due to the effect of alluvial deposits.. Due to the Umbria-Marche seismic sequence, several aftershocks were recorded at each array station. In addition to the accelerometric records, velocimetric records (obtained from a temporary array) of both ambient noise and small-magnitude earthquakes were analyzed in order to identify amplification conditions; records obtained at the BCT (Borgo Cerreto Torre) station seems to indicate that energy is azimuthally distributed mainly on three angles: 0°, 315°, 330°; moreover, the second angle distribution may be related to a topographic amplification. The analysis was carried out in the time domain, through directional energy evaluation, and in the frequency domain, through H/V spectral ratios and spectral ratios with respect to a reference station. Results of the above analysis show possible topographic amplification in the frequency range between 2 and 5 Hz.
Keywords: Topographic amplification, Energy azimuthal distribution, Time domain and frequency domain analysis

1. INTRODUCTION

Since many years ENEA recognized the importance of installing strong motion instrumentation in areas prone to seismic risk. The Umbria-Marche portion of the Apennine chain has a long history of seismic crisis characterized by small to moderate events, lasting several months (Boschi and Cocco, 1997).
During the '80-s ENEA installed several instruments in the Umbria portion of the Apennine around the Nerina valley. In Cerreto di Spoleto area, the array originally composed of 8 instruments, located in 5 sites, was modified in such a way that only 4 instruments were surviving when the 26 September 1997 events struck the Umbria-Marche region (Rinaldis, 2008). The instruments were CODISMA (Contraves Digital Strong Motion Accelerographs) with 12 bits acquisition system and PCB triaxial accelerometers. The 4 accelerographs were installed in 3 different sites: 1) Cerreto tower, BCT, rock site; 2) Cerreto football field, CCS, narrow alluvial valley, 200 m from CTO; 3) Cerreto City Hall basement, CMC, rock site, top hill, about 300 m from BCT; 4) Cerreto City Hall top floor, CMS (see figure 8a). Starting from January 2000, in all stations of the Cerreto di Spoleto permanent array ETNA 18-bits accelerographs were installed and CODISMA removed.

2. RECORDS FROM THE 26TH SEPTEMBER 1997 EVENTS

The record obtained in Borgo Cerreto Torre (BCT) during the fore shock of the 26 September 1997 at 00: 33 show a larger PGA (but shorter duration) if compared with the record obtained in the same station during the main shock of the 26 September 1997 at 09: 40 (see figure 1). This should be connected to the fault rupture propagation indicated in the NE-SW direction for the main shock and in the opposite direction for the fore shock. Records in Municipio Soffitta of Cerreto di Spoleto (CMS) station show a clear influence of the building. In fact both frequency and time domain analysis show resonant frequencies where the seismic waves are amplified. Comparing the Fourier Amplitude Spectrum (FAS) of the acceleration obtained at BCT station and the FAS of the acceleration obtained in CMS station (e.g. WE component), they are almost equal up to 2 Hz (see figure 2). Then, there is a departure on the FAS recorded at CMS, showatg much more energy than the FAS in BCT, up to 10 Hz.

Date	Time	PGA CMC (cm/s2)	PGA CMS(cm/s2)	PGA BCT(cm/s2)	BCT Code	Remarks
26.09.1997	00:33:13	-	487.0	184.0	BCT1	Ml=5.2
26.09.1997	09:40:27	-	393.0	93.5	BCT2	Ml=6.0
12.10.1997	11:08:37	-	-	162.0	BCT3	Ml=5.2
12.10.1997	20:15:29	-	-	22.9	BCT4	Ml=3.5
13.10.1997	13:09:21	-	-	42.6	BCT5	Ml=4.1
14.10.1997	15:23:11	-	607.0	349.0	BCT6	Ml=5.4
14.10.1997	16:24:42	-	-	30.0	BCT7	Ml=3.9

TABLE 1 : Records from Cerreto di Spoleto strong-motion array (CODISMA).

Unfortunately the station at CMC did not record the events, so that we were not able to de-aggregate the contribution to the FAS of the acceleration obtained at CMS due to the building amplification of the ground motion at the basement from some other contribution to seismic waves amplification. Seismic event recorded at Cerreto di Spoleto array stations are listed in Table 1.

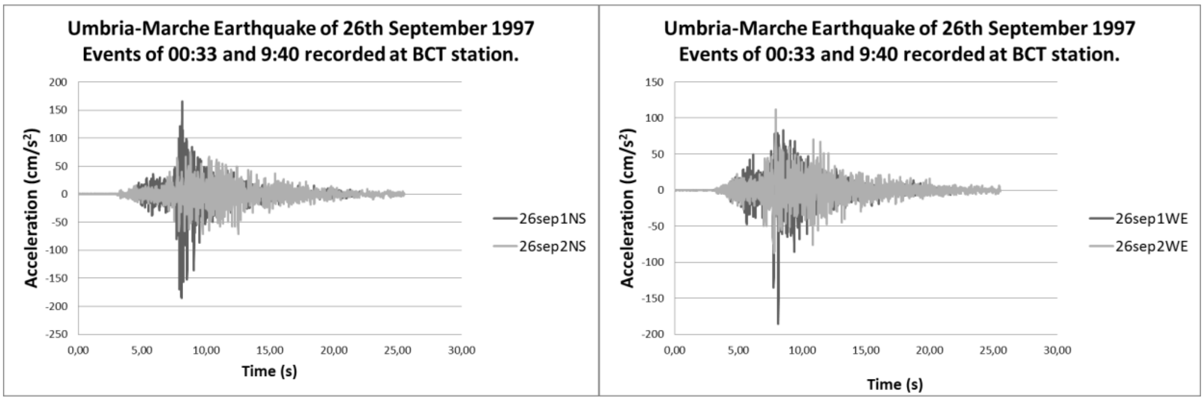


Figure 1. Comparison between Borgo Cerreto Torre (BCT) time-histories recorded during the main shock of September 26th, 1997 9:40 , Ml=5.9 (2) and the foreshock of September 26th,1997 00:33. Ml=5.4 (1).

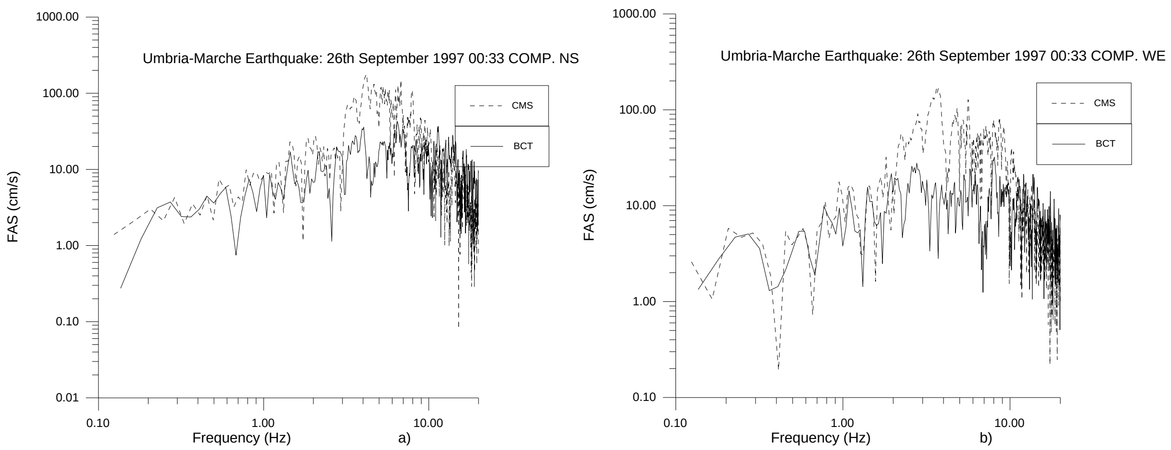


Figure. 2 FAS of NS (a) and WE (b) component of acceleration at BCT, and CMS

3. RECENT RECORDS.

Time and frequency domain analysis, by means of acceleration Fourier Amplitude Spectrum (FAS) of records obtained at the Cerreto di Spoleto array stations after the ETNA Kinemetrics 18-bit digital strong-motion accelerographs deployment, were performed. Events recorded at all stations (BCT, CMC and CMS) are listed in Table 2 with date, time origin, PGA and magnitude of events originating the analyzed records. As shown, event magnitudes were small, and ground-motion PGA was ranging between few gals to 0.1 g (at CMS station). In particular the event of the 15th December 2005 13:28:35 GMT, 4.2 Ml, was recorded at all the array stations. Figure 3 shows a comparison between the FAS of the recorded acceleration for the horizontal components obtained at BCT (rock site), at CMS (Municipio roof) and at CMC (Municipio basement). It is interesting to note that not significant departures are noticeable, both in WE and NS FAS of acceleration horizontal components, in the frequency interval between 0 and 2 Hz. At higher frequencies, the FAS of the recorded accelerations at CMS and CMC stations continued to be equivalent up to 7-8 Hz, but departed respect to the FAS of the acceleration recorded at BCT. It should be noted that BCT station is characterized by a different morphological condition respect to the CMS and CMC stations (Figure 8 a). Some contribution to the value of the spectral ordinates may due to an increase in jointing of the rock (increase in rock degree of fracturing), that produce a low velocity layer between two active faults (see the red lines starting from Municipio and Faglia, Figure 8 a): this phenomenon will amplify the seismic motion at frequencies between 6.5-7.0 Hz (see Bongiovanni et al., 2002). Comparing the FAS of BCT and CMC records, it is evident an amplification of the seismic waves in the 2-5 Hz frequency range. Figure 7a shows the FAS of acceleration for the Up components of the above mentioned event and the average of all recorded UP components (CMC, CMS and BCT). There is no evidence, from the spectral ordinates, of significant amplification. So H/V spectral ratio may give indication of the frequency band and amplitude of topographic amplification (see fig. 7b). Figure 9a shows spectral ratios for all recent events recorded at CMC station, when figure 9b shows the mean of H/V for either station CMC or BCT. It is evident, from that figure, some amplification peaks in 2-7 Hz frequency interval. Peaks are more evident (larger) for station CMC. As previously stated, peaks in the range 5-7 Hz may be associated a seismic waves amplification caused by trapped waves combined to beatings effect. Remain to explain peaks in the range 2 to 5 Hz that, because of waves polarization (see e.g. figure 4 for BCT station), may be associated to topographic amplification. Finally, if comparison is made between the plots of the FAS of acceleration recorded at CMS and CMC , the 6-12 Hz frequency range seems to contain the contribution of structural modes to the seismic amplification. It is very unlike the situation at frequencies close to 7 Hz where to the site amplification is adding some resonance frequency of the building (CMS).

Date	Time	PGA CMC (cm/s2)	PGA CMS(cm/s2)	PGA BCT(cm/s2)	BCT Code	Remarks
15.12.2005	06:00:30	8.40	31.40	11.75	AO012	Ml=3.3
15.12.2005	13:28:37	27.95	71.03	27.81	AO013	Ml=4.2
16.12.2005	20:12:36	7.64	29.77	10.76	AO014	Ml=3.4
18.12.2005	08:06:46	8.82	20.82	12.87	AO015	Ml=3.5
05.01.2006	17:30:39	11.86	35.70	20.18	AO016	Ml=3.6
08.02.2007	01:32:55	19.25	43.68	11.47	AZ006	Ml=3.8
06:08.2009	10:23:41	8.02	27.07	8.60	BG001	Ml=2.3
10.01.2010	08:33:38	6.77	20.63	6.86	BG019	Ml=4.0
12.01.2010	08:25:14	7.81	21.58	8.83	BG020	Ml=4.1
12.01.2010	13:35:48	5.92	14.23	6.74	BG021	Ml=4.2
28.08.2010	07:07:56	6.54	17.01	6.58	BH011	Ml=4.1
06.12.2010	10:32:04	19.24	96.10	27.29	BH012	Ml=3.4

Table 2 : Records from Cerreto di Spoleto strong-motion array (ETNA).

4. ENERGY AZIMUTHAL DISTRIBUTION.

Goal of this paragraph is the study records in time domain, by means of the graphic representation of the azimuthal distribution of the energy in the recording point normalized to the peak. The energy is intended in the sense given by Arias (Arias 1970).

$$I_A = \frac{\pi}{2g}\int \left(a_x^2 + a_y^2 + a_z^2\right)dt$$

Figure 4 shows the Arias Intensity azimuthal distribution of several accelerometric records obtained at Borgo Cerreto Torre (BCT) station. All records were obtained during the main shocks (September 26th and October 14th, 1997) that stroke the Umbria-Marche Apennine area. They were recorded by CODISMA strong-motion accelerograph. Starting from June 2000, several events (see Table 2) were recorded by an ETNA digital recorder. The instrument was installed as N50E, instead of NS.

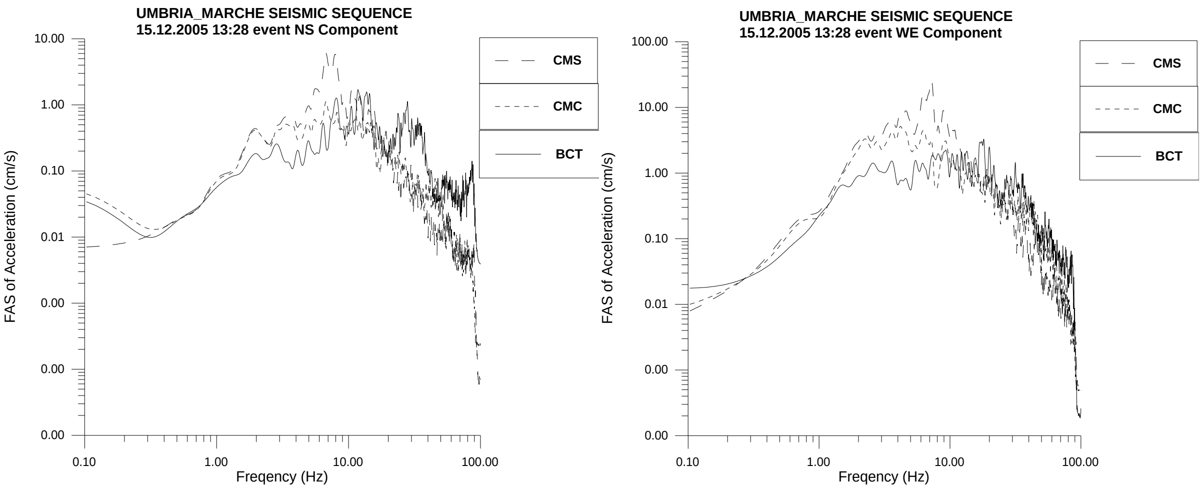
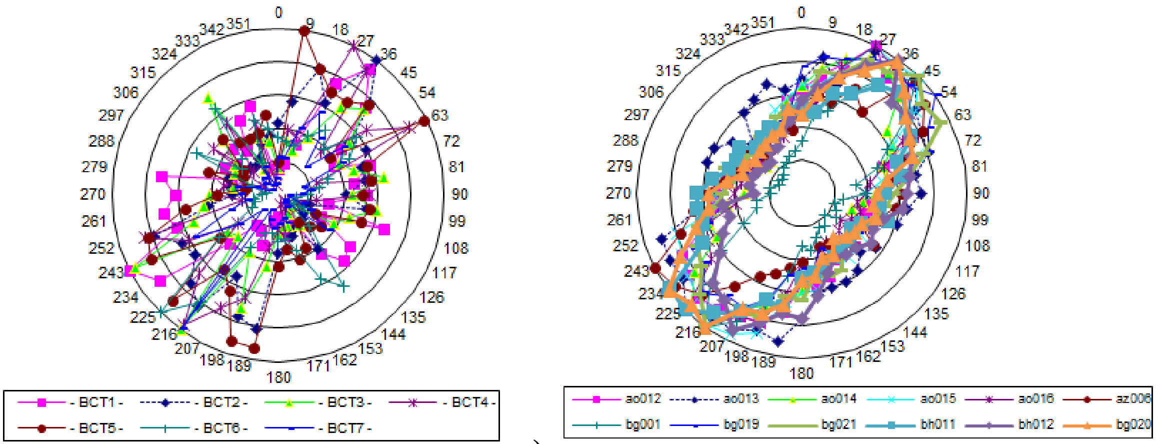


Figure 3. Comparison between the FAS of the recorded acceleration for the horizontal components obtained in BCT (rock site), at CMS (Municipio roof) and at CMC (Municipio basement) stations.



a) b)

Figure 4 : Azimuthal distribution of energy at BCT station: CODISMA records (a) and ETNA records (b); data were normalized to the maximum AED (ARIAS).

At today date instrument are SN oriented.The AED is mainly distributed between 27° and 63° of azimuth. The waves polarization lies in a direction almost normal to the hill where the instrument was installed indicating a possible topographic amplification. Values from CODISMA records seem to indicate the possibility of some others phenomena intervening in the AED (e.g. waves trapping in the supposed fault area).

5. THE 5-7 HZ FREQUENCY BAND.

To investigate these results, seismometric surveys aiming the analysis of the seismic response in the carbonate ridge were performed (see Martino & al. 2006). In particular, the velocimetric records obtained during the Umbria-Marche sequence in the temporary array stations "Antenne" and the one installed at the bottom of the slope were analysed (fig. 8a). Station "Antenne" shows an energy distribution at, more or less, 315°, roughly perpendicular to the direction of the ridge. This energy distribution cannot be observed in the others recording stations of the temporary velocimetric array (see figure 5a) and in particular at the station "Provinciale". As "Antenne" site is deployed not far from the top of the relief, the peak energy distribution at 315° may be produced by a topographic effect. Authors (Martino & al. 2006) observed that: "two main fault systems were identified: the first, transtensional, with an approximately NS ± 10° direction; the second, estensional, with an about N30°W direction". As already stated in the previous paragraph, one fault of the second system is supposed to be not far from the BCT station.

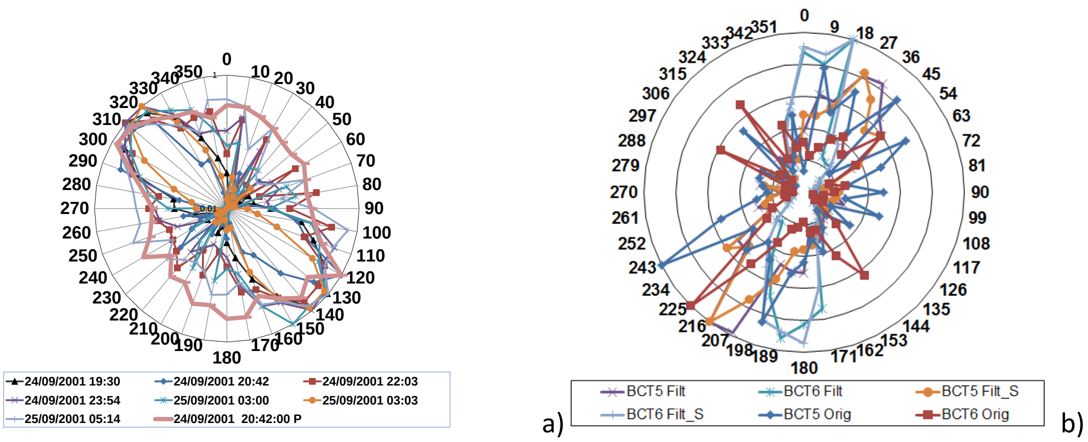


Figure 5 : AED of recorded velocities for 7 events at "Antenne" station compared with the recorded velocity at "Provinciale" station for the 24/09/2001 event (a). AED at BCT station: original and band-pass filtered at 5-7 Hz (b).

Corrected versions (5-7 Hz band-pass filtered) of accelerometric records obtained at the BCT station during the October 13th, 1997 at 13:05:46 UTM event (Md=3.9) and October 14th, 1997 at 15:23:00 (Ml=5.4), were analysed and results of the azimuthal energy distribution are shown in Figure 5 b). It is interesting to note that the October 13th filtered and unfiltered accelerations show similar azimuthal energy distribution. On the contrary, the October 14th ones show that the main contribution to the azimuthal distribution of energy of the filtered acceleration, is in the NS direction. Figure 6 a) and Figure 6 b) show a very interesting result. The filtered time-histories show a shape that suggest the presence of a peculiar physical phenomenon named beating effect (see Rinaldis & al., 2004); this phenomenon is well observed during both the strong phases for the WE component, starting at 7 seconds (BCT6) and at 6 seconds (BCT5) and ending respectively at 8 and 7 seconds. Looking at the FAS graph (Figure 7), the frequency of beating may be computed as f2-f1 where f2=6.25 Hz (BCT6) and f2=6.20 Hz (BCT5) and f1=5.75 Hz and 5.55 Hz respectively: in this way, fb1=0.5 and fb2=0.65 with Tb1=2 and Tb2= 1.5 seconds. Moreover, the NS component of the October 14th event shows a stationary wave lasting at least 1 second and starting at 7.8 seconds.

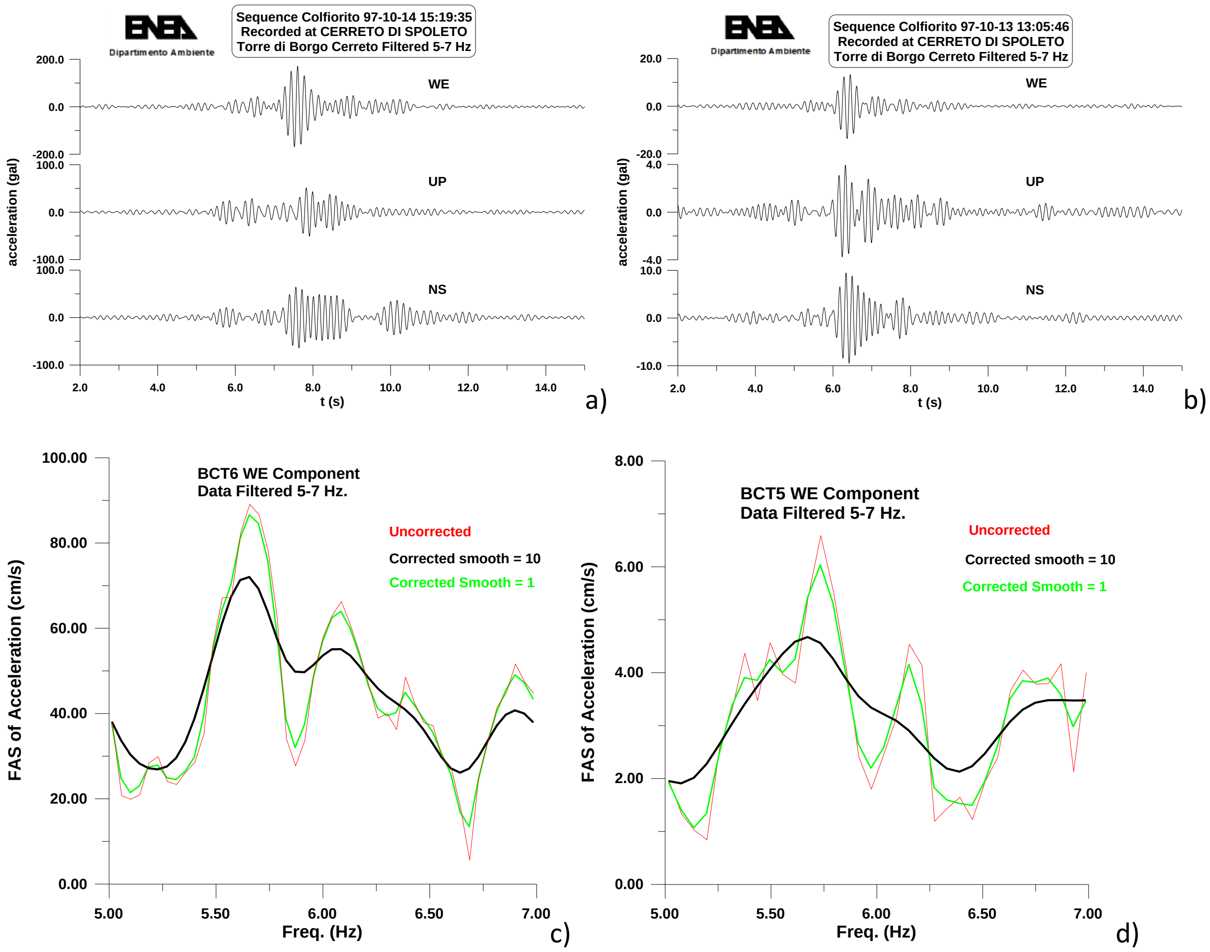


Figure 6 : Time-histories of the acceleration at BCT: October 14th, 1997 (a,c) and October 13th, 1997 (b,d) time-histories and FAS (WE component) of accelerometric records.

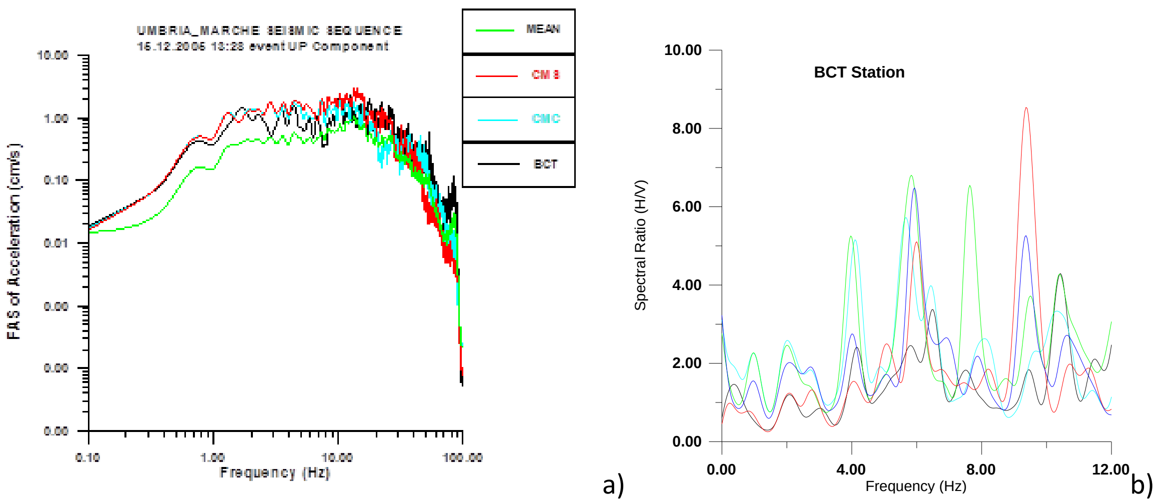


Figure 7: FAS of acceleration recorded at Cerreto di Spoleto Array stations: a) UP components for the15.12.2005 06:00:30 event and average on UP recorded acceleration components; b) Spectral ratios (H/V) for some events recorded at the BCT station;

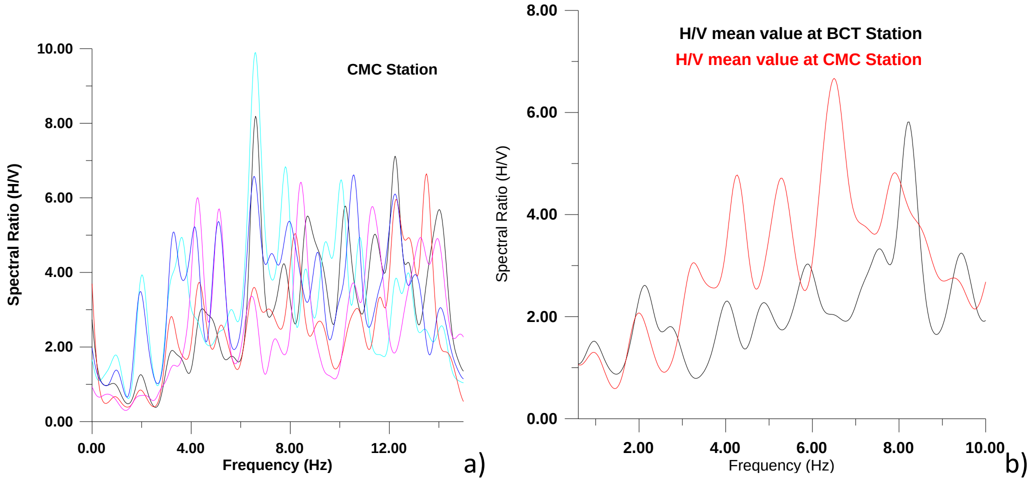


Figure 9: a) Spectral ratios (H/V) for some events recorded at the CMC station; b) Mean spectral ratios (H/V) for all events recorded at the CMC and BCT stations.

6. SIMPLIFIED MODELS FOR THE TOPOGRAPHIC AMPLIFICATION

The model to apply in trying to analytically calculate the topographic amplification on the Cerreto di Spoleto ridge may depends, besides some other parameters, on the selection of the causative effect. If we model the ridge as a steep slope, a 1-D model (parallel layers with normally incident SV and SH waves) may be proposed. In this case the results of a parametric study (Scott & al., 1997) for a linear viscoelastic half-space underlying a GTE (generalized transmitting boundaries) may be applied to the Cerreto di Spoleto hill. Summarizing the model, the analysis of a stepped half-space (considered isotropic) is obtained summing the effects of SH waves (frequency interval 0.5 10 Hz) and of SV waves on a vertical slope and of the slope angle. For the proposed model the influence of the damping is negligible and the amplification at the crest occurs when $H/\lambda=0.2$ where H is the slope height and λ the wavelength of the motion. As it is possible to see in Figure 8 b), the slope height above sea level is varying between 450 and 590 m. In particular, the height of the Municipio recording station is 506 m. The shear waves velocity is ranging between 400 to 500 m/s, and ft (topographic effect frequency) = Vs/5H, both for vertically incident SV and SH waves. By these input data, a range of ft between .12 Hz to .25 Hz can be calculated. If we instead analyse the hypothesis where the emerging height of the Cerreto ridge is involved in the topographic effect, an interval of 70 m to 210 m should be considered in the model with a resulting ft of 0.4 to 1.4 Hz. For the above mentioned model, the influence of the slope angle on ft is negligible. The magnitude of the motion amplification in the crest area should be relatively unaffected by damping, as observed by Boore (1972) as well. This amplification can be calculated of the order of 25% for SH waves and 50% for the SV waves. A further choice of analysis is the extension the study of topographic effect to 2-D models: on this subject Razmkhah & al. (2008) proposed a parametric analysis, modelling the ridge as a triangular hill. This 2-D parametric analysis has been carried out by means of two-dimensional hybrid finite element/boundary element method applied to obtain the site response analysis of homogeneous and non-homogeneous topographic structures subjected to incident in-plane motion (BEM/FEM code named HYBRID). An average amplification of vertical and horizontal components of ground motion as function of the shape ratio of the hill can be expressed as:

AH = 0.38 (S.R.) + 0.8

AV = 0.18 (S.R.) – 0.05

If we consider a range from 400 to 500 m/s for wave velocities, then the hill height ranging between 70 m to 210 m and 200 m to 300 m (corresponding to the half width of the dimensionless period) will be included in the analysis. The calculation has been performed considering as input data a shape ratio h/b, (were h is the height and b the half width of the hill) ranging from 0.2 to 1.0 and a dimensionless period T=tc2/2b varying between 0.25 and 8.33, where c2 is the wave propagation velocity. The amplification factor will be:

AH=0.876 – 1.18

AV= 0.03 – 0,13
The obtained values seems to be too small if compared with the obtained FAS at the BCT and CMC stations, for the horizontal components of the acceleration.

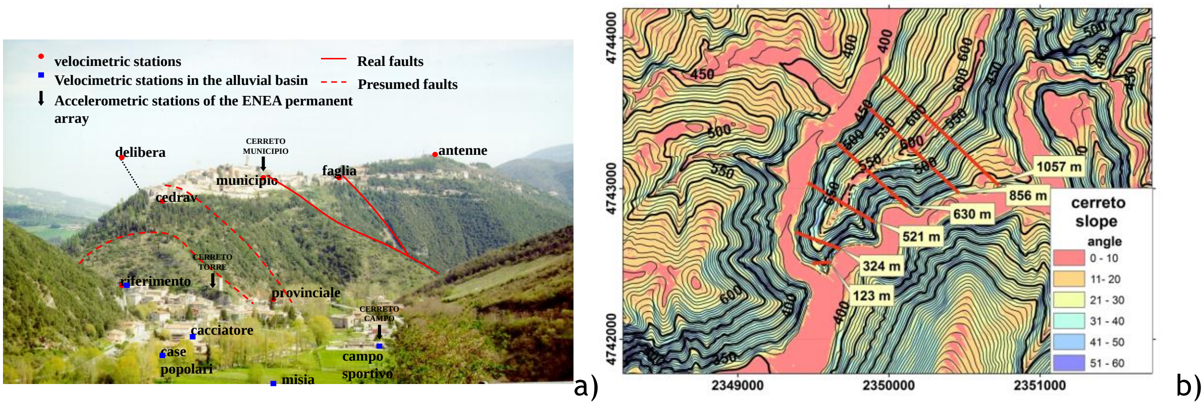


Figure 8 : Velocimetric and accelerometric Stations at the ENEA temporary and permanent seismic arrays of Cerreto di Spoleto(PG): in particular, Position of Antenne (A), Faglia (F) and M(Municipio), stations on the velocimetric Array) are shown a); map of contour lines and width dimensions of the Cerreto di Spoleto ridge b).

7. CONCLUSIONS

Records obtained at the BCT station seems to indicate that energy is azimuthally distributed mainly et two angles: 225 and 240; these values are 90° oriented respect to the hill direction . The first peak, in energy distribution, may be attributed to the topographic amplification. The second one is instead a new observation; the proposed interpretation of this peak, in the AED, is due to an estensional fault system, with an about N30°W direction. The investigation in the 5-7 Hz frequency band carried out two main results: first of all, filterd and unfiltered acceleration gave similar AED for weak motion records. The frequency domain analysis evidenced a main peak at 7 Hz that correspond to the time-histories strong phases: the shape of the time-histories seems to indicate that seismic waves, traveling in this fault system, were amplified. A further result is obtained from the 14th October event record: filtered data (5-7 Hz) show a different AED if compared with the unfiltered ones, where the main peak correspond to the 0° angle (i.e. trapped waves amplification). The comparison between FAS of acceleration at the BCT and CMC and CMS stations for the 15th Decenber 2005 weak motion event, shows how useful could be the AED analysis to evaluate the seismic risk for the Municipio building: record at the BCT do not shows a peak in the distribution at 0° , indicating that trapped waves phenomenon is not the main contribution to the amplification. Other events, of larger magnitude, show instead an evident peak at 0° in the AED giving the idea of seismic waves amplification in a frequency interval were the main resonance frequencies of the Municipio (and other important buildings) are included. Spectral ratios (H/V) evidenced seismic waves amplification in 2-7 Hz frequency interval: due to waves polarization, peaks in the 2-5 Hz frequency range may be associated to topographic amplification. Finally simplified models are able to identify, roughly, the frequency interval where topographic amplification may influence the seismic motion.

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