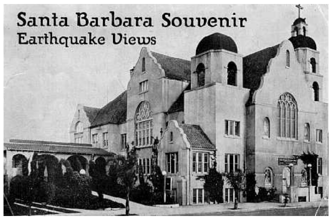

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RECURRENCE OF HORIZONTAL AMPLIFICATION AT ROCK SITES: A TEST USING H/V-BASED GROUND MOTION PREDICTION EQUATIONS

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ABSTRACT

Ambient noise and earthquake records of 226 three-component seismological stations installed on stiff rock are investigated using H/V spectral ratios and horizontal polarization analysis. H/V spectral ratios of ambient noise calculated on rotated horizontal components from 0° to 180° indicate that 56% of stations is affected by a significant (>2) amplification in site-dependent frequency bands. This effect is often strongly directional. A strict criterion, based on the covariance matrix diagonalization, is then applied to select sites with a strong local tendency to polarize ground motion in the horizontal plane. Results indicate that 36% of the entire data set honors this condition. This sample (81 stations) is investigated using a DEM to characterize local topography conditions as well as the proximity to seismogenic faults (DISS Working Group, 2010). Strongly polarized stations resulted to be installed on irregular topography and/or close to faults. For these stations we repeated the same analysis using earthquake records: earthquakes and ambient noise show a quite consistent pattern for 66 stations (29%). One of the possible causes of the strong directional site effect at rock stations is stiffness anisotropy which characterizes elongated ridges and intensely fractured rocks such as fault-related cracks and tectonically deformed structures. In several cases, a combination of these effects could be responsible for large observed amplifications that are generally underpredicted by theoretical models assuming massive, isotropic rock outcrops.

This study suggests that amplification at rock sites can be much larger than expected on the basis of conventional soft/stiff site classifications, at least along site-dependent directions. Effects of directionality on response spectra and the need of rotating the horizontal components to compare observations with GMPEs is discussed. The performance of the H/V-based site classification criterion recently proposed by Di Alessandro *et al*. (2008 and 2011) is also preliminarily investigated for the amplified rock stations.

INTRODUCTION

Seismic codes of many countries assume that rock sites, i.e. sites where shear-wave velocity of the uppermost layers is high (Vs > 800 m/s), are not affected by amplification during earthquakes. However, the scientific community is aware that this is only partially true. A well known cause for damage and ground motion increase at rock sites is the irregular topography (e.g. Griffiths and Bollinger, 1979; Géli *et al*., 1988; Kawase and Aki, 1990; Pedersen, 1994; Le Brun *et al*., 1999; Paolucci, 2002; Massa *et al*., 2010; Pischiutta *et al*., 2010). However theoretical models seldom reproduce the size of experienced amplifications, although the spectral shape of the topography response is easier to fit. To improve the fit quality, the topography model sometimes is complicated by introducing shallow lower velocity layers (e.g. see Paolucci *et al*., 1999). Topography seems not to be the unique cause for rock site amplification: observations of large directional motions in intensely fractured rocks increase in number in the recent literature (Del Gaudio and Wasowski, 2007; Rigano *et al*., 2008; Di Giulio *et al*., 2009; Burjanek *et al*., 2010; Falsaperla *et al*., 2010; Pischiutta *et al*., 2011; Marzorati *et al*., 2011). In these papers, amplifications reach a large level for site-specific directions of motion whereas are much smaller in the transversal direction. Bonamassa and Vidale (1991) first used the expression “directional resonances” to define site effects characterized by narrow-band amplification varying in amplitude as a function of azimuth. Directional resonances cause a large site-dependent ground motion polarization in the horizontal plane.

This study investigates a set of 226 permanent broad-band seismological stations installed at rock sites in Italy and neighboring countries to check the occurrence of horizontal ground motion amplification, with particular attention to site directional effects. It emerges that 56% of the sample shows an amplification > 2 of the horizontal component compared to the vertical component, and 29% (which is a not negligible percentage) is consistently characterized by a strongly directional effect both in ambient noise and earthquake records.

As a consequence, response spectra of these sites show largely different amplitudes for different directions of motion. We have found that ground motions along the minimum amplification azimuth are satisfactorily fitted by GMPEs of rock sites whereas response spectra along the maximum amplification azimuth go well beyond rock site expectations, even by more than 1 standard deviation. Preliminary attempts using the site classification based on the predominant period of the H/V response spectra ratio (Di Alessandro et al., 2008 and 2011) indicate that this approach would improve predictions but variability of ground motion intensity is large as a function of the rotation angle.

THE STATIONS

The station sample has been selected among 225 permanent broadband stations of the Italian Seismic Telemetered Network run by Istituto Nazionale di Geofisica e Vulcanologia (INGV). Other 9 stations from neighboring countries, that are also transmitted to the National Earthquake Center of Rome, were included in the analysis. The installation sites were investigated through a high-resolution Digital Elevation Model (DEM) and geological maps. Stations installed on alluvial deposits were excluded from the data set. The final station sample is composed of 226 stations installed on rock outcrops, they are represented by triangles in Fig. 1.

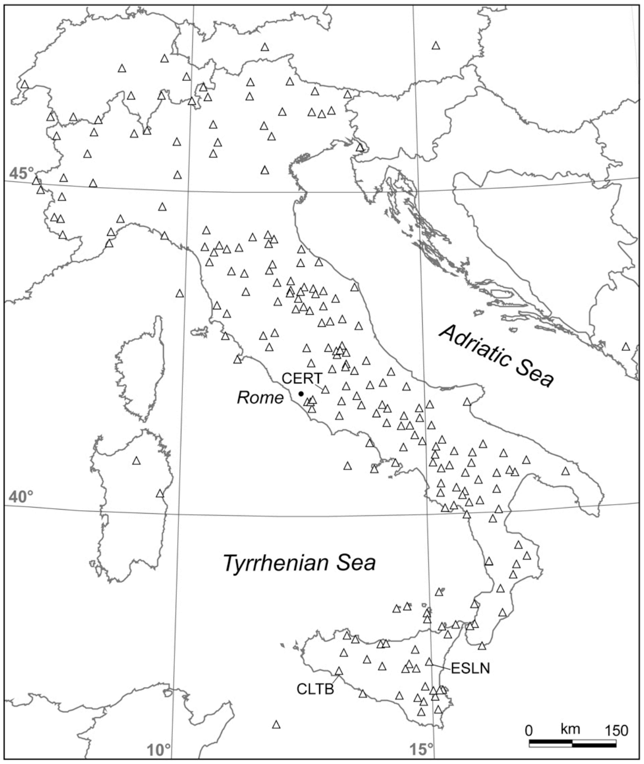

Fig. 1. Stations used in this study. Three of them (CERT, CLTB, and ESLN) are the object of a detailed analysis in the next figures.

THE ANALYSIS METHOD

In order to recognize the occurrence of horizontal amplification in the selected station sample, we apply an analysis method combining H/V spectral ratios in the frequency domain (Nakamura, 1989) and assessment of the horizontal polarization angle in the time domain, according to a methodology recently proposed by Pischiutta (2010).

As a first analysis step we have used one hour of calm ambient noise recorded at each station during the night. The preference for nightly hours is motivated by frequently observed distortion of the natural site polarization (e.g. see Cara et al., 2010) caused during the day by cultural activities. Moreover, wind and rain can also affect ambient noise characteristics, as documented by reports of the

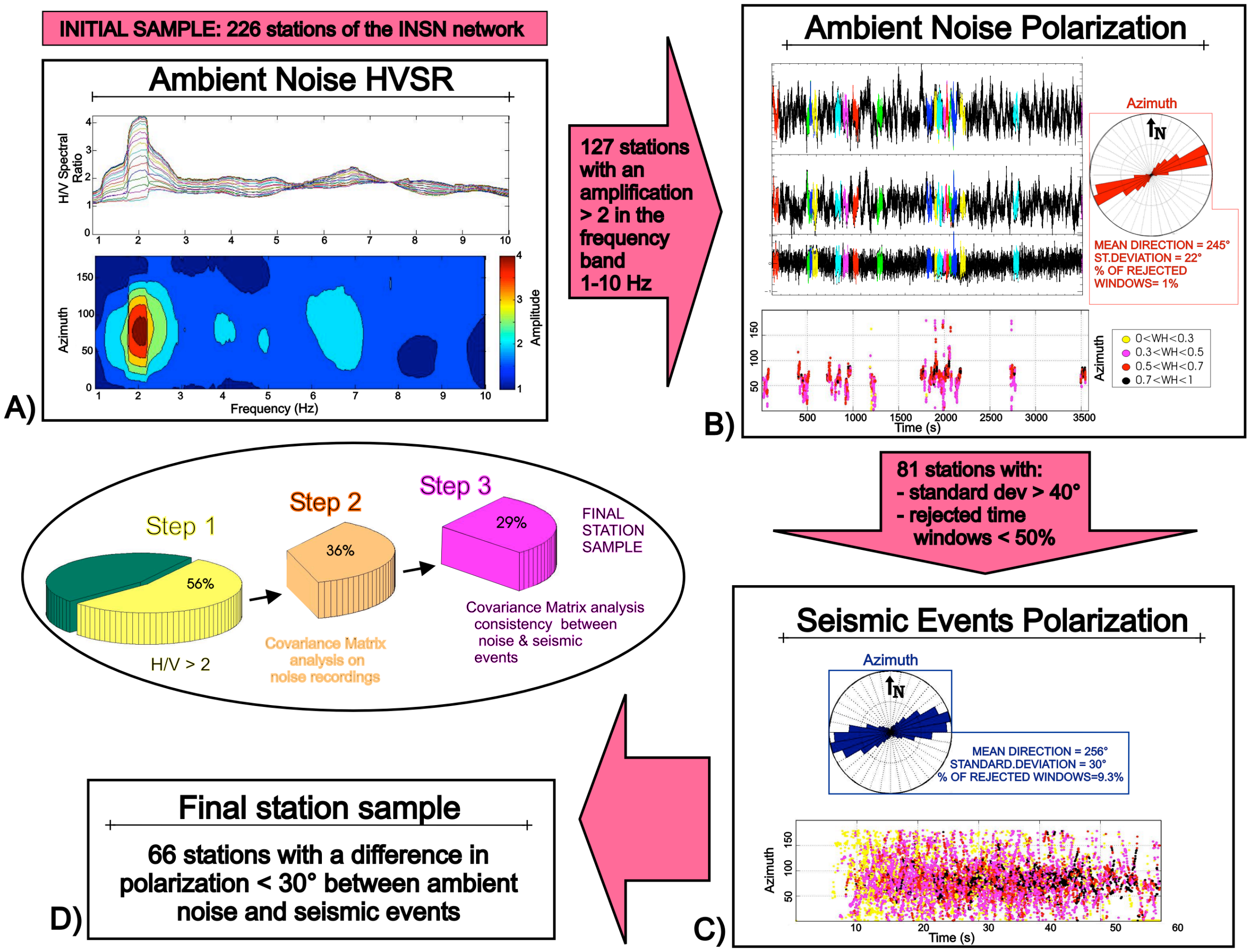

Fig. 2. Steps of the analysis performed on the selected data set. Station CERT (Cerreto Laziale) is shown as an example. (A) HVRSs are calculated on ambient noise records rotating the horizontal components from 0° to 180° by bins of 10°. (B) Polarization analysis is carried out in the time domain, through eigenvectors and eigenvalues of the covariance matrix computed in 2-s-long sliding windows. The noise record is plotted on the top, the colored portions representing the time window selection made using the antitrigger algorithm. Instantaneous polarization azimuths are represented through a color scale indicating their estimate quality, according to Pischiutta (2010). They are visualized using a rose diagram, histograms were fitted through Gaussian curves giving mean and standard deviation values. The percentage of time windows excluded because of their weak or uncertain horizontal polarization is also shown. (C) The polarization consistency during earthquakes is checked . The ellipse in the middle represents the percentage of stations found in the three analysis steps, the final result is shown in panel D.

SESAME project (Site EffectS assessment using AMbient Excitations - http://sesame-fp5.obs.ujf-grenoble.fr/index.htm), thus we selected not rainy and not windy nights, ensuring that wind velocity was lower than 5 m/s on the basis of information provided by the meteorological website of Italian Air Force (www. meteoam.it). Non-stationary disturbances were eliminated using the anti-trigger algorithm proposed in the SESAME guidelines.

On the selected time window signals of each station we calculated the horizontal-to-vertical spectral ratios (HVSRs) for rotation angles from 0° to 180°. This technique was firstly applied by Spudich et al. (1996) to detect topographic directional amplification effects, and was subsequently exploited by Cultrera et al.(1997), Rigano et al. (2008), Di Giulio et al. (2009), Pischiutta et al. (2011) to study horizontal polarization of ground motion in different areas. The Fast Fourier Transform (FFT) of horizontal and vertical components are calculated using a time window length of 60 s and applying a Hanning taper. The operation is repeated for 1-hour records. In each 60-s window, the horizontal components are rotated by angle increments of 10° and the amplitude spectrum for each rotation angle is computed. Spectra of both vertical and horizontal-rotated components are smoothed with a running mean filter (box width of 0.5 Hz), then the H/V ratio is computed for each rotation angle. The station average is computed over the 1-hour record. The mean spectral ratios for different rotation angles (from 10° to 180°) are drawn separately first, and then using contour plots versus frequency and angle of rotation. An example of HVSR calculated for one of the stations is shown in Fig. 2, panel A.

The analysis is applied to all of the sample stations. At the end, 127 of them (56% of the initial data set) resulted to be affected by an amplification higher than 2 in site-dependent frequency bands ($1 < f < 10$ Hz). Moreover, looking at the frequency where the H/V spectral ratios attain the maximum, we have often observed a significant variation of the peak amplitude between different rotation angles. This feature indicates that amplification is strongly directional (see Fig. 2).

In order to quantify the occurrence of directional amplifications and to select sites with a strong local tendency to polarize ground motion in the horizontal plane, a criterion based on the covariance matrix diagonalization (Jurkevics, 1988) is applied to stations that exceed a spectral H/V peak of 2. This second test is necessary because spectral ratios may be biased by anomalies in the denominator spectrum, providing an estimate depending on both numerator and denominator of the ratio, and deamplifications of the vertical component cannot be distinguished from real horizontal amplifications.

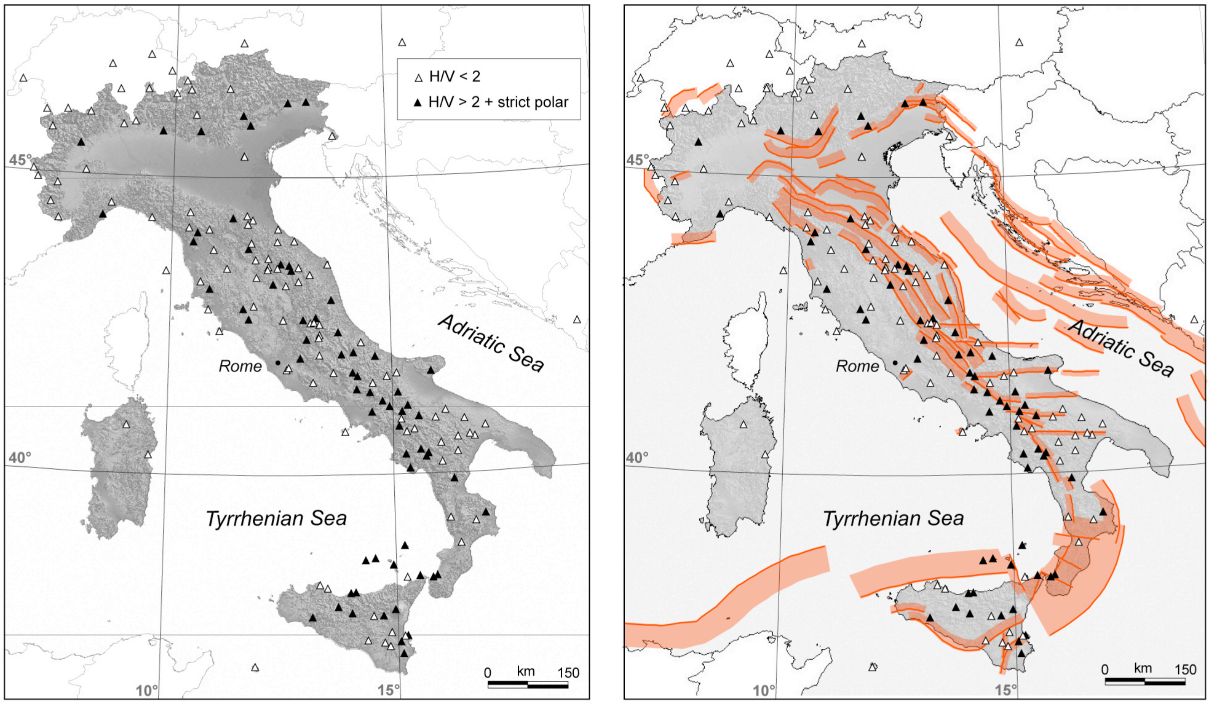

Fig. 3. Rock stations with a H/V spectral ratio < 2 in the frequency band 1 -10 Hz (99 over the sample of 226) are represented by open triangles, full triangles are stations (66 over 226) that are characterized by a consistent directional amplification in ambient noise and earthquake records. Station symbols are drawn on a DEM (left-hand side panel) and on the map of the seismogenic fault systems (right-hand side) of the DISS Working Group (2010).

The polarization ellipsoid is computed by solving the eigenproblem for the covariance matrix (Jurkevics, 1988) within time windows of 2-s width and 0.1-s overlap moving along the signal. Time series are preliminarily band-pass filtered in the frequency band 1-10 Hz, according to the selected frequency band of analysis. We have applied the code POLARSAC (courtesy of Mario La Rocca) to compute incidence, polarization azimuth, and rectilinearity using the eigenvector associated with the highest eigenvalue and the three eigenvalues λ_1, λ_2, λ_3 of the covariance matrix (La Rocca *et al.*, 2004). The polarization incidence (the angle *i*) is the angle between the polarization vector and the vertical axis, and the polarization azimuth is the angle between the projection on the horizontal plane of this vector and geographic north, measured clockwise. The rectilinearity is calculated as:

$$r = 1 - \frac{\lambda_2 + \lambda_3}{2\lambda_1}\,. \qquad (1)$$

It takes values between 0 (spherical motion) and 1 (rectilinear motion).

In panel B of Fig. 2, the resulting instantaneous polarization azimuths are plotted along with noise recordings (EW, NS and Z components respectively from the top to the bottom), only for those windows accepted by the anti-trigger algorithm (that are drawn with colored lines). In order to enhance the results of time windows with strictly rectilinear and horizontal particle motion, we attribute a quality coefficient to each instantaneous azimuth, based on the constraint of high rectilinearity ($r > 0.5$) and predominantly horizontal motion ($i > 45°$), according to the criteria first introduced by Pischiutta (2010). Azimuth values from time windows not satisfying both these conditions were not included in the analysis. When rejected windows were more than 50%, the station was excluded from the statistics.

In each window obeying to the imposed horizontal polarization constraint, a quality coefficient is calculated as

$$\mathrm{WH} = r * i \qquad (2)$$

where the values of r and i, not excluded in the previous step are lying in the ranges $0.5 < r < 1$ and $45° < i < 90°$ and are linearly transformed into a scale ranging between 0 and 1.

In Fig. 2, the polarization azimuths resulting from the analysis performed on ambient noise (panel B) and on seismic events (panel C) are plotted versus time. The quality coefficient WH associated to the polarization azimuth of each window is expressed through a color scale, different colors corresponding to different quality classes.

Quality coefficients WH are then used to construct weighted rose diagrams of polarization azimuths. Finally, these histograms are fitted by a Gaussian function and the mean direction and the standard deviation are assessed. Stations showing a broad distribution around the mean (1 standard deviation larger than 40°) were excluded from the final station selection, horizontal polarization being not accepted as clearly directional. The application of these strict criteria results in 81 stations affected by a horizontal ground motion amplification along a preferential direction. In order to check their stability, the polarization analysis was also performed on earthquake records.

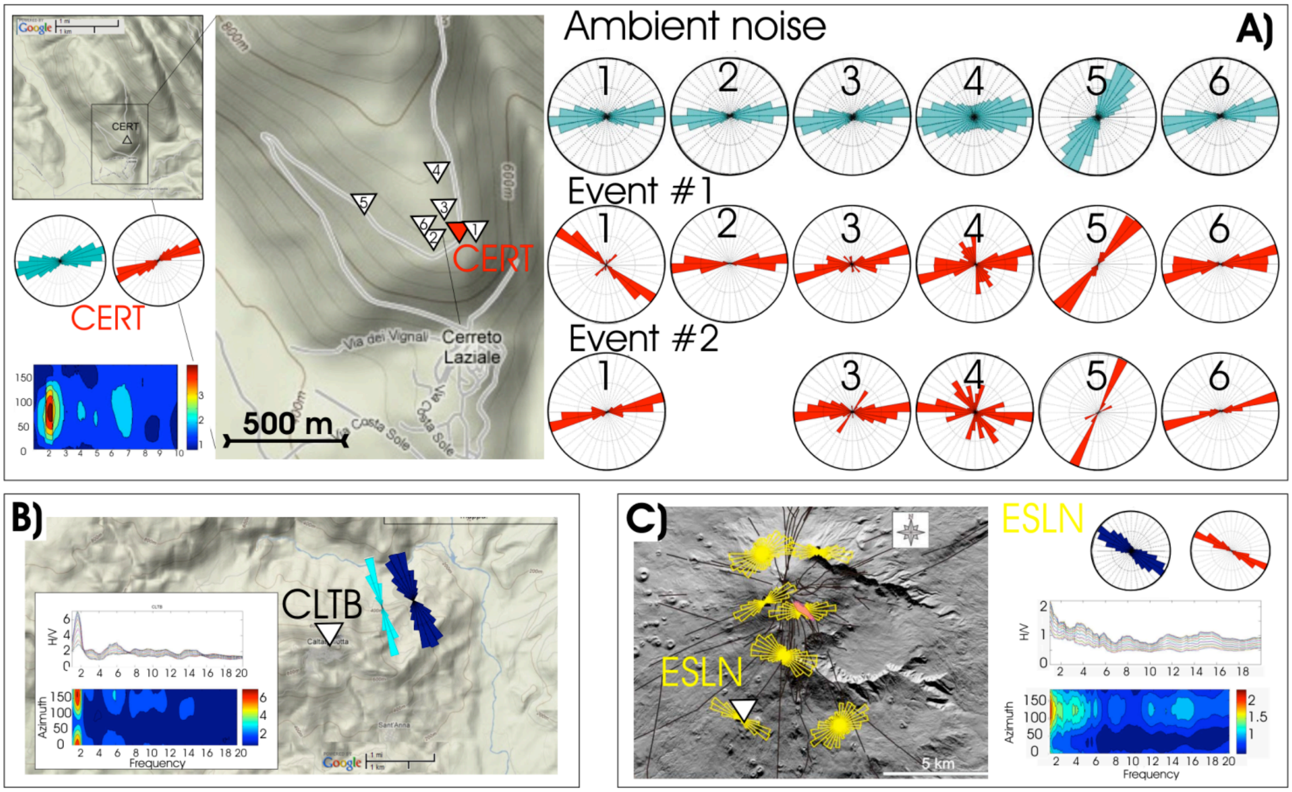

Fig. 4. Results of polarization analysis for three representative stations and interpretation of results at the local-site scale. Panel A shows the polarization result at station CERT (Cerreto Laziale), on a 1 km wide and 300 m high ridge for ambient noise (cyan rose diagram) and seismic events (red rose diagram). In the middle, the array deployment is drawn on a DEM. In panel B, results of polarization at station CLTB (Caltabellotta) are illustrated. The H/V spectral ratios are shown on the left bottom, and the two rose diagrams represent polarization obtained from ambient noise (cyan rose diagram) and seismic events (blue rose diagram). Panel C describes observations at station ESLN, located on the top of Mt. Etna. The polarization pattern around the crater area was estimated by Falsaperla et al. (2010) that found a polarization orientation perpendicular to the radial fracture field. At ESLN, the result of our polarization analysis on ambient noise (blue rose diagram) and earthquake records (red rose diagram) confirms the site orientation previously found by Falsaperla et al. (2010).

Seismic events were selected among those occurred in Italy in the period January 2008 – March 2011, with magnitude higher than 3. As a general rule, for each station at least 10 events were used, only in few cases the number of available events was smaller. The polarization angle calculated by cumulating seismic events was compared to the mean polarization of ambient noise, for all the 81 selected stations. When the difference between these angles was higher than 30°, the station was not included in the selection. As a result, 66 stations (29% of the initial data set) were finally selected and are the object of our analysis in the following sections.

ANALYSIS OF RESULTS

Several studies have been recently performed on polarization and its relation with morphological, geological and tectonic features (Spudich *et al.*, 1996; Del Gaudio and Wasowski, 2007; Rigano *et al.*, 2008; Di Giulio *et al.*, 2009; Pischiutta *et al.*, 2010; Burjànek *et al.*, 2010; Massa *et al.*, 2010; Pischiutta *et al*, 2011, Panzera *et al.*, 2011; Marzorati *et al.*, 2011). The occurrence of amplification on the top of topographic irregularities has been studied since the 1970s (Boore, 1972; Bouchon, 1973; Sills, 1978; Griffiths and Bollinger, 1979; Sanchez-Sesma *et al.*, 1982). Many of the above quoted papers find that ground motion is polarized in the direction transverse to the relief major axis.

Also the presence of densely fractured rocks can affect ground motion polarization due to the reduction of the effective rock stiffness in a direction perpendicular to the fracture orientation. The polarization due to cracks in fault damage zones was observed on many faults of Mt. Etna (Rigano *et al.*, 2008; Di Giulio *et al.*, 2009) as well as associated to fractures produced on rockslide zones and fractured rock blocks (Burjànek *et al.*, 2010; Marzorati *et al.*, 2011). Burjànek *et al.* (2010) hypothesized that the strong directional

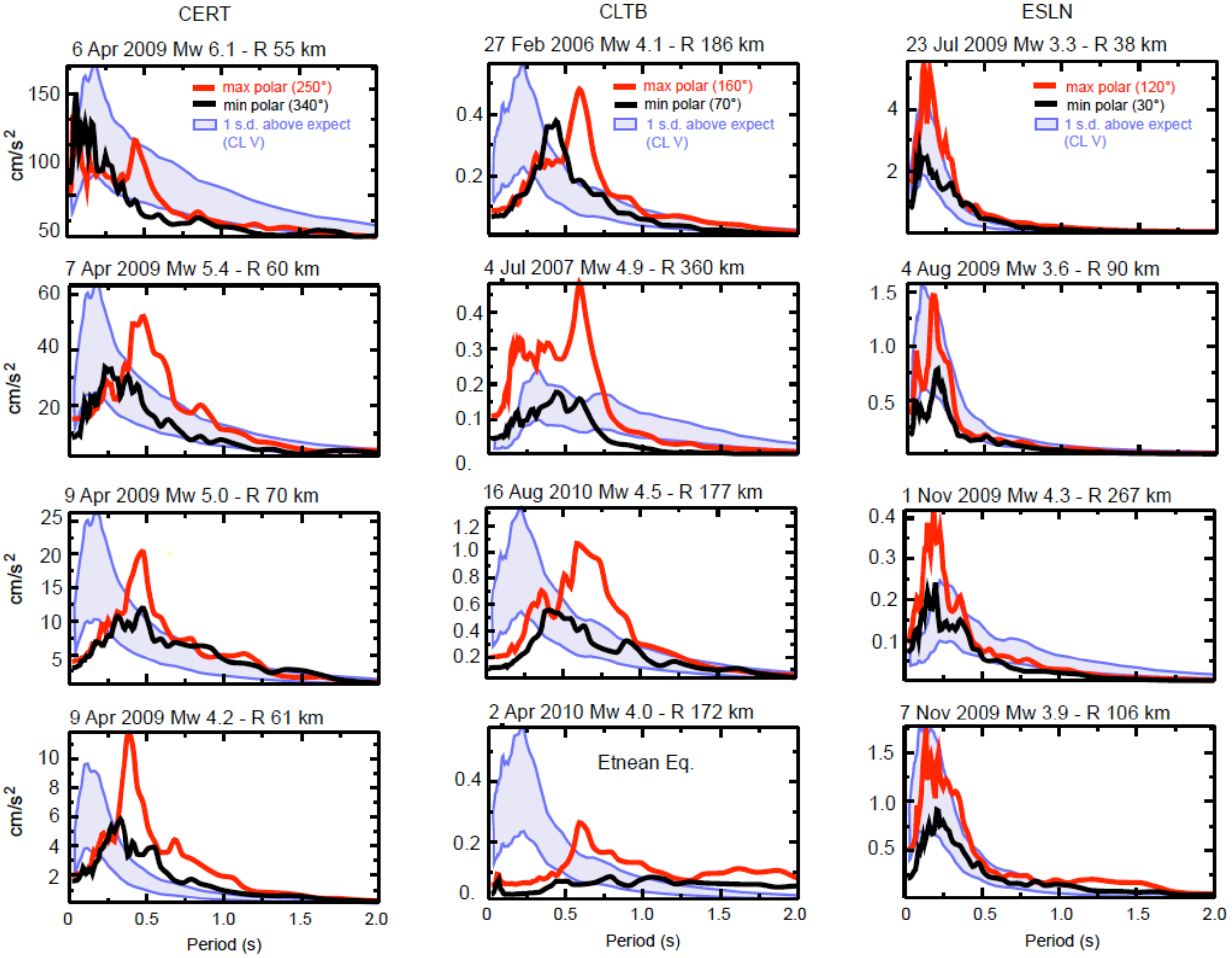

Fig. 5. Response spectra at rotation angles corresponding to the maximum- (red curve) and minimum-amplitude azimuths (black curves) of each station. The bleu colored band represents +1 s.d. above the expected curve of GMPEs by Di Alessandro et al. (2011) for class CL-V sites. Note the anomaly of the long-period volcanic earthquake recorded at CLTB (bottom panel): it is poor in high-frequency content and rich in low frequencies, according to findings by Milana et al. (2009) for Etnean earthquakes.

motions of unstable rock slopes are due to normal modes of rock mass compartments cut by macro-fractures and vibrating orthogonally to the fracture orientation. Pischiutta *et al.* (2011) found a systematic orthogonal relationship between predominant crack orientation and observed polarization in many fault zones.

Thus horizontal polarization seems to be controlled by factors at a local scale, and related to characteristics dependent on the site specificities. Our statistical analysis is performed at a regional scale and we cannot formulate a global interpretation unless studying every station singularly. This is the object of a paper in progress. However, as an example, in Fig. 3 we have plotted selected stations on a digital elevation model (DEM) of Italy (panel in the left-hand side) and on the major seismogenic faults (right-hand side) as identified by the DISS Working Group (2010). Stations are plotted with different symbols to distinguish stations with H/V ratio lower than 2 (open triangles) from stations with H/V higher than 2 and satisfying the prescribed conditions of strict horizontal polarization and consistency between ambient noise and earthquakes (black triangles). Fig. 3 shows that topography and tectonics can play a role on observations although an interpretation for each station is only possible at the local scale. In Fig. 4 we provide a local-scale description for three stations chosen as representative of the most common cases. Panel A is relative to station CERT (Cerreto Laziale, see Fig. 1) located on the top of an elongated ridge with an elevation of 300 m from the valley and about 1 km wide. The topography isolines are drawn in the top-left inset. Below this inset, ambient noise polarization (cyan rose diagram) and earthquake polarization (red rose diagram) at station CERT are compared, the contour map of H/V spectral ratios is shown as well. Moreover, on 04/17/2009 an array composed by six stations was deployed near CERT. Each array station was equipped with Kinemetrics Q330 digitizers coupled to Lennartz 5s seismometers. They simultaneously measured ambient noise windows of 30 minutes, two aftershocks of L'Aquila, central Italy Mw 6.3 earthquake were recorded as well. Polarization of ambient noise at each station of the array is shown on the top-right with cyan rose diagrams, polarization of the two seismic events (considering the whole seismograms) is below with red rose diagrams. On the Cerreto Laziale hill, predominant polarization is oriented N80° in a large area around CERT, there is a strict consistency between ambient noise and earthquake polarization, and the predominant azimuth is transversal to the hill major axis.

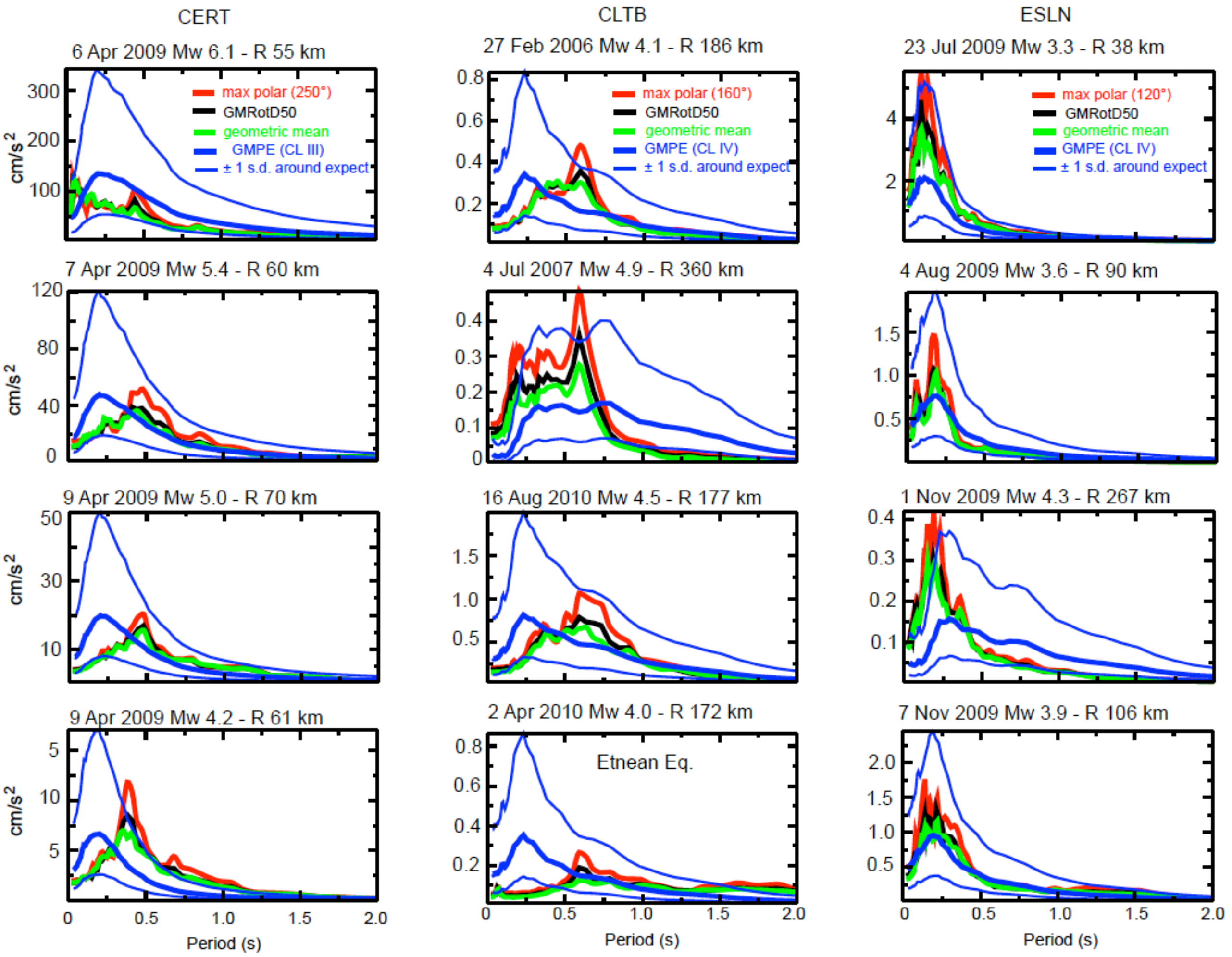

Fig. 6. Response spectra of Fig. 5 are compared to expectations (thick bleu curves) of GMPEs by Di Alessandro et al. (2011) for class CL-III (CERT) and CL-IV (CLTB and ESLN). Thin bleu curves represent the ± 1 s. d. uncertainty around expectations.

A second example (panel B of Fig. 4) is relative to station CLTB (Caltabellotta) located on the top of an elongated ridge, which is 600 m high from the valley and 1 km wide. The analysis performed on ambient noise (cyan rose diagram) and earthquakes (blue rose diagram) consistently reveals a polarization oriented N160°. Also in this case the polarization angle is perpendicular to the hill elongation.

Finally, in panel C, an example of polarization on densely fractured rocks is shown. Results of polarization analysis (yellow rose diagrams) are from Falsaperla *et al*. (2010) who found that a fracture system produced by the 1989 volcanic activity on Mt. Etna strongly controls horizontal polarization at the crater stations. Among stations analyzed by Falsaperla *et al*. (2010), we consider ESLN which is part of the Italian Seismic Network (Fig. 1). Polarization derived from ambient noise (cyan rose diagram) and earthquake records (red rose diagram) are drawn with H/V spectral ratios. The horizontal polarization is oriented N120°, in agreement with Falsaperla *et al*. (2010): this direction is perpendicular to the local fracture system, that spreads radially from to the volcano crater. Station ESLN is an example of effects found in a volcanic context. Nevertheless in non-volcanic settings too the predominant fracture orientation has been recognized to affect polarization, with an orthogonal relation between fracture directions and observed polarization (Pischiutta *et al*., 2011).

EFFECTS ON RESPONSE SPECTRA

During earthquakes, horizontal motion polarization can have a strong influence on the response of engineered structures, their rigidity too depending on azimuth. Measures of the intensity shaking using rotated horizontal components were proposed in the past to take into account the ground motion variability versus azimuth. Boore *et al*. (2006) defined GMRotDnn as response spectra obtained for period-dependent rotation angle, where nn is the fractile of the geometric means for rotation angles $0° < \theta < 180°$ sorted by amplitudes (e.g. GMRotD50 is the median value and GMRotD100 is the largest geometric mean over all rotation angles). A systematic study is in progress using the sample of the 66 stations selected in the previous analysis and different azimuth-dependent intensity parameters. Here we show the results obtained in a preliminary analysis on the example stations illustrated in Fig. 4.

We start from the evidence of significantly largest horizontal motions along a site-specific azimuth in the frequency band 1 – 10 Hz (see the H/V contour plots of Fig. 4). We compute response spectra of stations CERT, CLTB and ESLN along the maximum amplitude azimuth of each site and in the transversal (minimum amplitude) direction. Response spectra are also computed for rotation angles from 10° to 180° with increments by 10°. Fig. 5 shows response spectra for the two orthogonal directions using available earthquake records (magnitude and distance of each earthquake are written in the figure). For the sake of comparison, the bleu curves represent the expected response spectrum and its + 1 s.d. uncertainty as derived by Di Alessandro et al. (2008 and 2011) using a site category (Class V) characterized by a flat (<2) H/V response spectra ratio. Fig. 5 indicates that response spectra in the minimum amplitude direction tend to lie within 1 s.d. above the expectation of GMPEs of not amplified rock sites. In contrast, ground motions of sites affected by directional effects tend to exceed the + 1 s.d. curve along the maximum amplitude direction. Often the excess is not limited to the fundamental site resonance but affects different period intervals: this is particularly evident at ESLN where both the 1-2 s site resonance and short ($T \approx 0.25$ s) periods are significantly amplified.

The GMPEs assessed by Di Alessandro *et al*. (2008 and 2011) for sites classes depending on the site resonant period are also checked. This check is significant because the earthquake records of the test were not included in the data set used by Di alessandro *et al*. (2011). Based on the H/V contour plots of Fig. 4, the class CL-III is assigned to CERT and CL-IV to CLTB and ESLN. Fig. 6 suggests that the ± 1 s. d. uncertainty (thin bleu lines) encompasses satisfactorily observations in terms of period-independent geometric mean and GMRotD50 as defined by Boore *et al*. (2006). Only response spectra along the maximum amplitude direction, in rare cases, exceed the + 1 s. d. curve. A more systematic study is necessary to reach stable conclusions, however the results of preliminary attempts to quantify azimuth-dependent variability are encouraging.

CONCLUDING REMARKS

We have investigated the persistency of ground motion site-dependent directional effects at rock stations. We have found that 29% of rock stations in Italy suffer directional amplification in the horizontal plane, with a consistent effect between ambient noise and earthquake records. Although the systematic study at local scale is still in progress, irregular topography and intense rock fracturing are recurrent features that characterize the sites where large amplifications are found. Our conclusion is that, similarly to many successful applications to horizontally layered soft deposits, ambient noise measurements can provide valid indications on detailed features of the rock site response during earthquakes, not only in terms of generic amplification (e.g. Chávez-García *et al*., 1996).

The size of the azimuth-dependent amplification on response spectra is preliminary investigated as well. We have found a significant difference between spectral ordinates along maximum- and minimum-amplitude directions, that could have implications in terms of damage increase at rock sites although limitedly to specific directions of motion. Since the identification of directional amplification effects is made using a H/V spectral ratio approach, the efficiency of GMPEs derived for Italy using a site classification based on the predominant period of H/V 5%-damped response spectra ratio has been preliminary tested. It is a unique tool to predict ground motion amplification at rock sites, the conventional soft/stiff classification being not applicable.

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