GROUND MOTION AMPLIFICATION AT SITES WITH PRONOUNCED TOPOGRAPHY: THE CONTROVERSIAL ROLE OF LOCAL GEOLOGY

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Introduction. The topographic amplification of seismic waves has received an increasing interest in the last four decades following observations of large amplification on mountain tops (e.g. Davis and West, 1973; Griffiths and Bollinger, 1979; Çelebi, 1987; Umeda *et al*., 1987; Kawase and Aki, 1990; Ponti and Wells, 1991; Hartzell *et al.,* 1994; Pedersen *et al*., 1994a; Chavez-Garcia *et al*., 1996). The recurrence and consistency of these observations has motivated much work both in terms of theoretical investigations and numerical simulations of the diffraction of seismic waves caused by the topography (e.g. Bouchon, 1973; Bard and Tucker, 1985; Géli *et al*., 1988; Anooshehpoor and Brune, 1989; Gaffet and Bouchon, 1989; Sanchez-Sesma and Campillo, 1991; Pedersen *et al*., 1994b; Le Brun *et al*., 1999; Paolucci, 2002).

The simulations and the observations are often in qualitative agreement with the amplification at the topography top and for wavelengths comparable to the mountain width. The disagreement concerns the calculated amplification level that tends to underestimates observations. This discrepancy has suggested that other effects could be responsible of the amplification effect, as the geological setting, complicated incident wave field, more complex topography, etc. (Bard and Chaljub, 2009).

Beside strong amplification, topographic irregularities have been recognized to produce directional effect of resonance; the scattered wave field is polarized in a site-characteristic direction. Spudich *et al*. (1996) found that directional amplification occurs transversally to the hill major axis, as subsequently assessed by several other authors (e.g., Del Gaudio and Wasowski, 2007; Massa *et al*., 2010; Pischiutta *et al*., 2010). In the framework of a statistical study performed using stations of the Italian seismic network to check the recurrence of directional amplification effects, Pischiutta *et al*. (2010, 2011) and Rovelli *et al*. (2011) investigated the relation between the direction of maximum amplification and the hill elongation at around 40 selected stations of the Italian seismic network. They found that only the 25% of stations showed an angular relation between directional amplification and the hill elongation ranging from 80 and 90 degrees. The same conclusions were reached by Burjanek *et al*. (2014a, 2014b) who investigated the relation between the S-wave velocity profiles and the amplification occurrence at 25-instrumented sites with complex topography in Switzerland and Japan. They stressed that the amplification was controlled primarily by the sub-surface velocity structure and they did not identify any link between the surface topography and the observed response at the studied 25 sites.

Thus recent findings have suggested that large systematic amplifications at topographic sites cannot be explained by surface geometry only, and that although the effect of geometry is present, it cannot be simply decoupled from the site response.

We think that directional amplification observed at sites with pronounced topography are often correlated with rock fractures. This feature has not considered adequately so far. Here we propose a model that could explain directional amplification. Similar effects have been recently observed (Marzorati *et al.,* 2011) and associated to gravitational instabilities (Burjanek *et al*., 2010) as well as to fault damage zones (Falsaperla *et al*., 2010; Pischiutta *et al*., 2012, 2013; Di Giulio *et al.,* 2013). Pischiutta *et al*. (2014) interpreted the strong polarization in terms of fracture fields that make the rock more compliant in the strike-transverse direction (Pischiutta *et al*., 2012, 2014).

Directional amplification effects on topographic irregularities and elongated ridges: results from previous studies. A statistical study on stations of the Italian seismic network was performed by Pischiutta *et al*. (2011) and Rovelli *et al*. (2011) to investigate the recurrence of

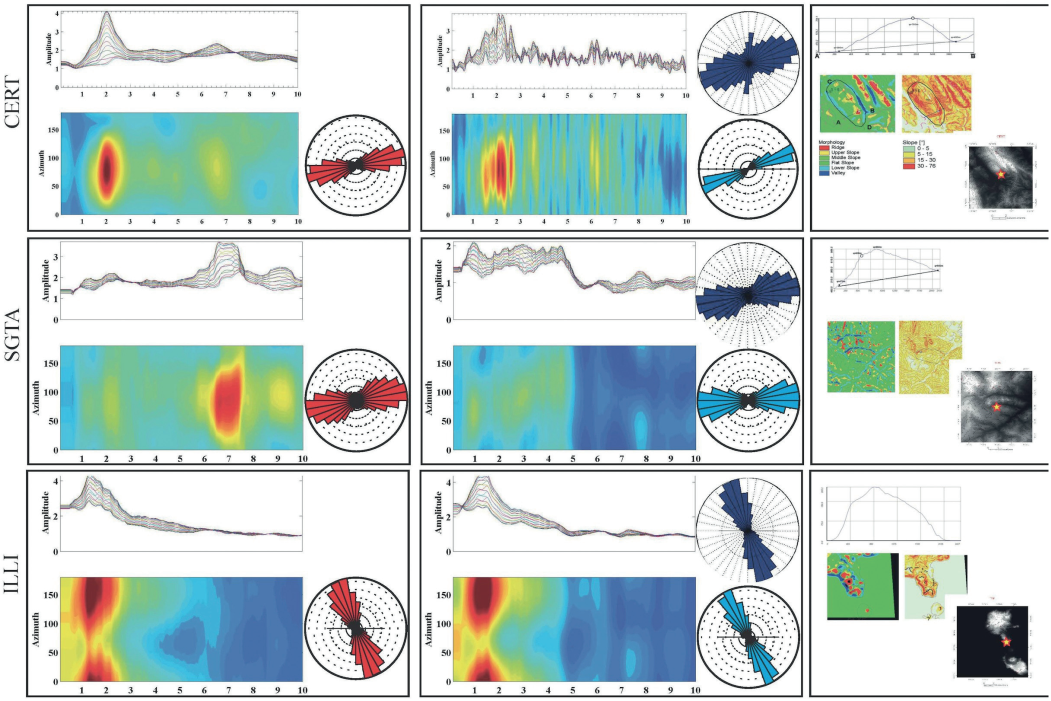

Fig. 1 – Results of polarization analysis for three representative stations. The top panel shows the polarization result at station CERT (Cerreto Laziale), on a 1 km wide and 300 m high ridge with a nearly ellyptical shape. This station is an example of a systematic directional amplification occurring transversally to the topographic elongation. The middle and bottom panels represent results from stations SGTA (Sant'Agata Puglia) and ILLI (Lipari), respectively.

horizontal directional amplification at rock sites and the relation with topography. Ambient noise and earthquake records of 226 three-component seismological stations installed on apparently stiff rock were investigated using H/V spectral ratios and horizontal polarization analysis. At first, H/V spectral ratios of ambient noise were calculated on rotated horizontal components from 0° to 180°, indicating that 127 (56% of the initial data set) of stations was affected by a significant amplification in site-dependent frequency bands (HVSR amplitude >2). This effect was also found to be strongly directional. A strict criterion, based on the covariance matrix diagonalization (Jurkevics, 1988) was then applied to select sites with a strong local tendency to polarize ground motion in the horizontal plane. Results indicated that 81 (36% of the initial data set) honored this condition. In order to check the stability of the effect, excluding the possibility that they could be artifacts of the noise signals or that they could be related to human activities, the analysis was repeated using earthquake records selected among those occurred in Italy in the period January 2008 – March 2011, with magnitude higher than 3. Pischiutta *et al.* (2011) concluded that an horizontal amplification larger than 2 was found at 66 stations (29% of the initial data set, which is a not negligible percentage) and that this amplification was strongly directional.

Because of the Italian territory is affected by significant topographic variations, inevitably many stations of the Italian Seismic Network are installed on topographic irregularities. In order to characterize the local topographic conditions they have analyzed the DEM finding that, as expected, the most part of the selected stations showing directional amplification are installed on topographic irregularities (Rovelli *et al.*, 2011).

In Fig. 1 we provide a local-scale description for three stations chosen as representative of the most common cases. The top panel is relative to station CERT (Cerreto Laziale) 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-right inset. Also ambient noise polarization (red rose diagram) and earthquake polarization (blue rose diagram) at station CERT are compared, the contour map of H/V spectral ratios being shown as well. On the Cerreto Laziale hill, predominant polarization is oriented N80°, there is a strict consistency between ambient noise and earthquake polarization, and the predominant azimuth is transversal to the hill major axis. During earthquakes, horizontal motion polarization can have a strong influence on the response of engineered structures, their rigidity too depending on azimuth. Measures of intensity shaking 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). Response spectra were computed for rotation angles from 10° to 180° with increments by 10°. In Fig. 1 we also compare the maximum amplitude azimuth of response spectra (cyan rose diagram) with the horizontal polarization calculated by using seismic events (blue rose diagram). We found a good consistency between response spectra and polarization analysis in terms of polarization direction.

Analogously, in the middle and bottom panels results of stations ILLI (Lipari) and SGTA (Sant'Agata di Puglia) are drawn, respectively. At these stations the directional amplification effect is evident even though the directional amplification effect occurs in a direction that is not orthogonal to the topography elongation. Pischiutta *et al*. (2011) also calculated the observed response spectra by rotating the horizontal components, finding largely different amplitudes for different directions of motion. They deduced the potential amplification from the comparison of the observed response spectra for a number of earthquakes and ground motion prediction model, finding a general (but not systematic) tendency of GMPEs to underestimate the observed amplification levels. More details can be found in Pischiutta *et al*. (2011) and Burjanek *et al*. (2014b).

The main finding of Pischiutta *et al*. (2011) statistical study was that surprisingly at least 30% of stations of the Italian seismic network are unexpectedly affected by directional amplification and horizontal polarization. This observation was consistently found using ambient noise and earthquake recordings. We stress that these stations were installed in a rocky environment (supposedly stiff rock) to exclude as much as possible the contribution of the site, and so no site amplification would be expected.

The conclusion by Rovelli *et al*. (2011) was that the orthogonal relation between directional amplification and hill elongation was found for only 25% of total stations. This means that the remaining 75% have a variable geometrical relation with topography.

Also Burjanek *et al*. (2014a) performed a systematic study using 25 stations with pronounced topography of Swiss CHNet and Japanese KiK-net sites. The advantage of using these sites was that a detailed site characterization was available, including measured S-wave velocity profiles down to 30-100 m. They found that many stations on rock sites (EC8 class A) did not exhibit any systematic amplification even if installed in pronounced topography conditions. On the other hand, the rest of the sites (non EC8 class A) presented systematic frequency dependent amplification, ground motion vibrating along site-specific directions. This feature was observed on the both ambient vibration and earthquake recordings, the effect being source independent. Burjanek *et al*. (2014a) finally stressed that some of sites identified as outcropping rock sites looking at the borehole lithology log, were characterized by Vs30 values which are usually measured in sediment sites (see Fig. 2).

All the described studies concluded that the strong systematic amplification observed at sites with pronounced topography is controlled by subsurface velocity structure, rather than the shape of the topography. Thus, although the effect of geometry is present, it cannot be simply decoupled from the site response, as assessed by Burjanek *et al*. (2014b).

CODE	Borehole depth (m)	Vs100 (m/s)	Vs30 (m/s)	EC8 Class	f_0^{ampl} (Hz) / f_0^{pol} (Hz)	Lithology
AICH07	201	1001	428	B	-	Gravel and Sand (14m), Gneiss
NARH01	99	792	338	C	-	Slate
WKYH08	112	590	344	C	1.7 / 1.8	Hard weathered sandstone (27m), Sandstone
KMMH10	300	712	463	B	-	Talus deposit (11m), Sandstone, Shale
NGSH06	200	1803	1421	A	-	Strongly weathered green schist (7m),Schist
OITH10	100	1366	837	A	-	Clay (4m), Sandstone / Shale
MYGH09	100	560	358	C	13.5 / 16.0	Sand+Gravel(6m), Ash breccia and Curd / Silt
EHMH08	100	729	364	B	-	Gravel clay mixed (18m), Green and red shale rock
KGSH12	150	977	452	B	-	Aplite (25m), Granodiorite
YMGH15	110	1120	549	B	7.1 / 6.3	Weathered crystalline schist (16m), Sandy / Pelticschists
KNGH20	106	503	273	C	-	Soil (2m), Tuff, Conglomerate
SZOH34	118	699	430	B	6.4 / 6.0	Loam (13m), Lapilli tuff, Sandstone / Conglomerate / Basaltic rock
SZOH35	300	324	158	D	2.1 / 1.5	Sand and Gravel (13m), Rocks / Basaltic rock, Ash breccia and Curd
CHBH16	2003	542	361	B	-	Mudstone / Sandstone interbedded (140m)
ACB	-	-	658	B	-	Station in weathered rock (Jurassic sediments), about 10m below the surface. Surface material: gravels
AIGLE	-	-	1243	A	-	Station about 20m below the surface in rock: Jurassic (Malm) sediments ,limestones
BALST	-	-	1348	A	-	Rock: Jurassic (Malm) sediments,
FLACH	-	-	610	B	5.6 /4.8	Lower Freswater Molasse (USM, Aquitanien): layered sandstones, marl and conglomerates; Surface material: unconsolidated, loose scree.
HASLI	-	-	1603	A	-	Rock: Jurassic (Malm) sedimentshard, massive limestone
MUO	-	-	1086	A	-	Lower Cretaceous limestone
PLONS	-	-	1810	A	-	Permian sedimentary rock(Verrucano)
SLE	-	-	686	B	-	Mesozoic sediment ridge (limestone and marl)
STEIN	-	-	387	B	-	Rock composed of sediments of the Upper Freshwater Molasse (OSM, Miocene). Surface material: loose sediments.
SULZ	-	-	1028	A	-	Mesozoic sediment ridge (massive limestones)
WILA	-	-	683	B	4.2 /4.1	Unsorted conglomerates (Nagelfluh) (Upper Freshwater Molasse)

Fig. 2 – Redrawn from Burjanek *et al.* (2014a, 2014b). Site characterization of the sites located on ridges. EC8 classification is based on Vs30 values. The colour of the field in the 6th column distinguishes the level of directionality: strong directionality (red), weak directionality (green), no directionality + no amplification (blue), not classified (white).

Directional amplification as the effect of fractured rocks. The Campo Imperatore case-study. It is well known that a typical condition that favors amplification of horizontal motions is the presence of compliant horizontal layers over stiffer bedrocks. Such cases produce increasing amplitudes of the incident seismic input and increasing ground motion duration due to seismic energy that is trapped and resonates between the free surface and the bedrock interface. Vertical discontinuities have been shown to produce variations of ground motion (e.g. Irikura and Kawanaka, 1980) that can generate trapped-waves and large motion amplification parallel to the fault zone (e.g. Ben-Zion and Aki, 1990; Li *et al.,* 1994; Mizuno and Nishigami, 2006). On the other hand, various recent observations of ground motion in fault zone environments documented a strong directional amplification with high angle to the fault strike (e.g. Rigano *et al.,* 2008; Di Giulio *et al.,* 2009; Pischiutta *et al.,* 2012). Using both volcanic tremor and local earthquakes, Falsaperla *et al.* (2010) found clear motion polarizations at stations in the crater area of Mt Etna, with polarization directions varying among sites but everywhere transverse to the orientation of the local fracture field. 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.*, 2013). Pischiutta *et al.* (2012) concluded that the polarization of amplified motion tends to be near perpendicular to the orientation of the predominant fracture field expected from analogical and numerical modeling. Moreover, Pischiutta *et al.* (2014) recently found an orthogonal relation between ground motion polarization and S-wave fast direction in the Val d'Agri region. Therefore, they postulated that the existence of an anisotropic medium represented by fractured rocks causes shear wave velocity to be larger in the crack-parallel component (making S wave velocity to be higher in fracture-parallel direction) and compliance to be larger perpendicular to the crack strike (causing ground motion polarization in the fracture-perpendicular direction).

In a different framework, Burjànek *et al.* (2010, 2012) found strongly polarized motions on unstable mountain slopes on Swiss Alps and ascribed the effect to the resonance of rock blocks separated by large open cracks (see also Moore *et al.,* 2011). Marzorati *et al.* (2011) related directional ground motions on a ridge to large open fractures, polarization direction being transversal to the fractures. These are cases where directional horizontal motions occur but the amplification level is not controlled by topography. In other words, geometry of topography is not the main factor controlling amplification.

We have assessed ground motion polarization across the damage zone of the Campo Imperatore fault, Abruzzo, Central Italy. This site was chosen because of the coexistence of the two factors so far recognized to have an influence on directional amplification effects: topography and fractured rocks. This study is still in progress but some preliminary results are shown in Fig. 3. The fault is oriented ENE-WSW and the footwall block of the Campo Imperatore fault zone is exposed on a pronounced crest. The relief is elongated in a nearly fault-parallel direction, up to 500 m high. The other important reason why we chose this site is that a very detailed structural geological survey has been carried out. Exactly in the same sector where structural geological features were measured, we acquired ambient noise for around 1 hour, using 25 stations along a 200 m transect crossing the fault. Stations were installed exactly in the sector where structural geological features were measured. Signals were processed to compute the horizontal-to-vertical noise spectral ratio as a function of frequency and direction of motion. Wavefield polarization was investigated in the time–frequency domain as well. In Fig. 3 we show results at four stations (CAM2, CAM 11, CAM15 and CAM20) drawing the rose diagram (cyan) obtained by the covariance matrix analysis as well as HVSR contour plots (the amplitude scale is different for each plot). We report measures of extensional fractures and faults at one location (violet star), through violet circular histograms. We find that, in spite of the high complexity of results, the observed polarization pattern is generally oriented orthogonal to the outcropping predominant fracture fields, confirming the existence of a high angle relation between ground motion polarization and fracture fields.

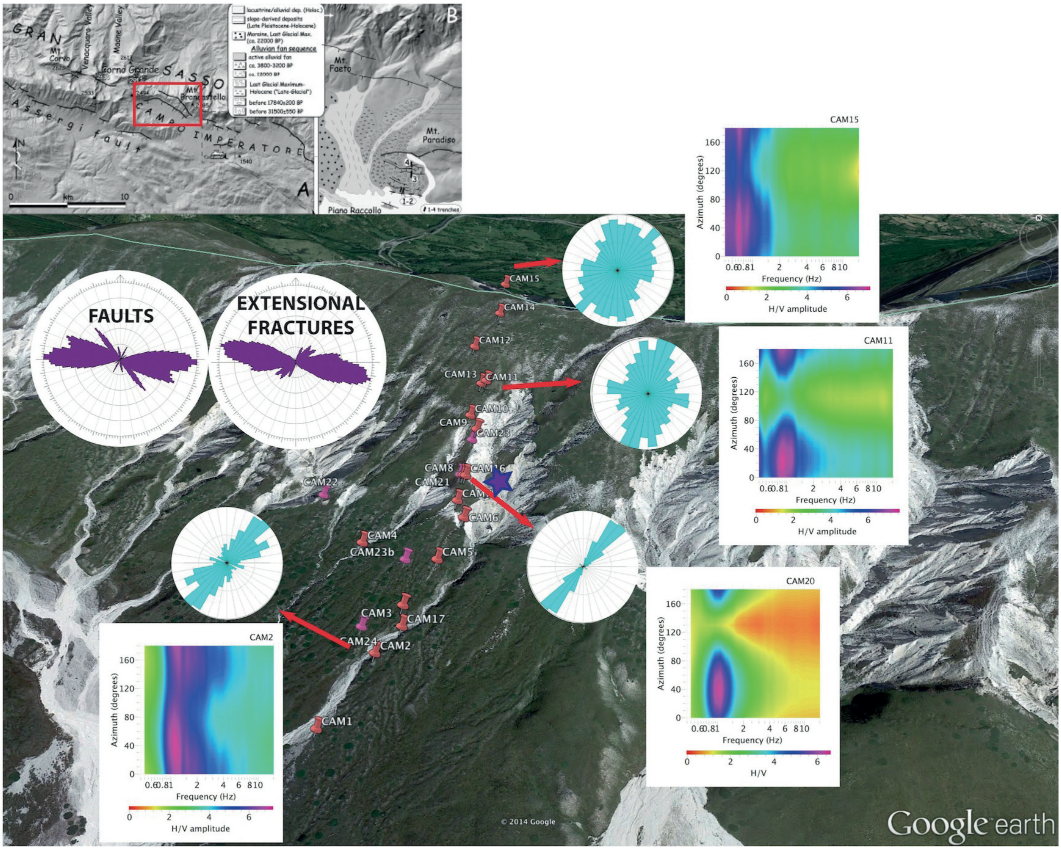

Fig. 3 – Ambient noise polarization at four stations installed across the Campo Imperatore normal fault (CAM2, CAM 11, CAM15 and CAM20). At each station the rose diagram (cyan) obtained by the covariance matrix analysis are drawn as well as HVSR contour plots (the amplitude scale is different for each plot). The strike of faults and extensional fractures measured by a detailed geological survey at one location (violet star) are reported as well through violet circular histograms.

Since the hill morphology is parallel to the fault, polarization is found to be nearly orthogonal to the hill elongation. We stress that the earth surface morphology has a strict relation with fracture zones (areas of more intense, closely spaced fracturing) or other discontinuities (faults, geologic contacts) that undergo differential weathering. In fact, fractured zones are more susceptible to mechanical and chemical weathering than unfractured rocks (Mabee *et al*., 1994). This is the common link between tectonics and the earth surface morphology.

Conclusions. According to Burjanek *et al*. (2014b) the main conclusion is that the amplification is controlled in first place by the sub-surface rock properties and cannot be simply ascribed to the topography geometry. Previous papers stress that:

1 The subsurface velocity and structure play a major role. Burjanek *et al*. (2014a, 2014b) have found that the rock sites (EC8 class A) with pronounced topography did not exhibit any systematic amplification on average whereas the rest of the sites (non EC8 class A) presented systematic frequency dependent amplifications.

2 The observed amplifications are strongly directional. Burjanek *et al*. (2014b) and Pischiutta *et al*. (2011) assessed that a general link between polarization and topography elongation has not been identified yet since the expected transversal relation was not recurrently found.

3 Effects are very persistent. Pischiutta *et al*. (2011) 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 geometry of the surface has an effect on the ground motion, this effect is small (in general a factor of 2, see Lee *et al.*, 2009). The observed large amplifications at topographic sites are probably related to site-geological as variations of subsurface velocity surface and fractured rocks. The latter would explain also the observed directionality of amplification. A common link between topography and fractures can be found in terms of lineaments which reflect stress state and tectonics at the regional scale, where topography and tectonic features are coaxial.

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