Seismic amplification in presence of topography and their consequences for ground motion predictions and seismic code for building: the case of Italy

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SUMMARY:
This work talks about the relevance of topographic effects in local site response evaluations. In this way some Italian test sites, characterized by the presence of a seismic station installed at the top of a steep topography, were investigated. The influence of the morphology was evaluated, at first, by performing rotational spectral ratio analyses, both in term of single station measurements (i.e. horizontal to vertical spectral ratio, HVSR) and, if possible, also considering reference sites (i.e.standard spectral ratio, SSR) and, at second, evaluating the residuals (logarithmic difference between observed and predicted data) estimated in term of acceleration response spectra for period up to 2.0 s. In this way, the ground motion prediction equations calibrated for Italy by Bindi et al., 2010 were considered. Finally, in correspondence of two selected topographies with seismic stations installed both at the top and at the base, the design elastic acceleration response spectra as proposed by the Italian seismic regulations (NTC, 2008) were evaluated in terms of shape and amplitude.

Keywords: topographic effects, ground motion prediction equations, seismic regulations

1. INTRODUCTION

Observation of localized damages near topographic irregularities suggests that the morphology of the relief plays a significant role in the propagation of seismic waves. Relevance influence of the topography on ground shaking were hypothesized during many past earthquakes (e.g. 3rd March 1985, Mw 7.8, Chile earthquake, Celebi, 1987; 17th October 1989, Mw 6.9, Loma Prieta earthquake, Hartzell et al., 1994; 17th January 1994, Mw 6.9, Northridge earthquake, Spudich, 1996; 25th January 1999, Mw 6.2, Eje Cafetero-Colombia earthquake, Rastrepo and Cowan, 2000). In Italy, damages at the top of ridges were noticed during the 6th May 1976, Mw 6.4, Friuli earthquake (Bramati et al., 1980), 23th November 1980, Mw 6.9, Irpinia earthquake (Faccioli, 1986), 26th September 1997, Mw 6.0, Umbria-Marche earthquake (e.g. Pischiutta et al., 2010), 31th October 2002, Mw 5.6, Molise earthquake (Massa et al., 2004) and recent 6th April 2009, Mw 6.3, Aquila earthquake (Marzorati et al., 2011).
From a theoretical point of view the topographic effects can be due both to the amplification involving the whole relief (i.e. resonance of the whole relief in case of incident seismic-field with wavelength comparable to the dimension of the topography, Boore 1972) and to ground motion variations caused by different physical phenomena, such as the focusing of seismic waves near the crest, because of the reflection on free surface and/or the interaction between incident and diffraction waves (Bard 1982).
At present, in the Italian seismic rules for buildings (Norme tecniche per le Costruzioni, NTC, 2008) the reference model to describe the seismic motion at a particular site is represented by the elastic acceleration response spectrum, expressed by a normalized spectrum with a damping of 5% multiplied for the value of horizontal maximum acceleration a_g at a reference rock site**,** defined at national scale in the framework of a recent INGV-DPC project (i.e. S1-project 2004-2006, http://esse1.mi.ingv.it/index.html). In order to move from a rock site (A category, Vs30 > 800 m/s) to different categories, the design spectrum is then multiplied by a factor that takes into account the stratigraphic (S_S) or topographic (S_T) conditions.

In particular, the definition of S_T is essentially based on 2D numerical analyses and therefore it is properly applicable only to crests of elongated ridges. Italian NTC 2008 provides a classification for 4 different topographical categories ranging from T1 to T4, depending on the geometry of the relief. To every topographical categories a topographic amplification factor S_T (ranging from 1 to 1.4, see table 1) is correlated. The S_T value has to be applied for 2D geometric configuration such as crest or elongated ridge with height higher than 30 m. For more complex morphologies the regulations require specific site effect evaluations. Following NTC 2008, topographical effects can be neglected for mean slope of a hillside < 15° for which S_T is equal to 1.

Table 1. NTC 2008 Topographical categories. *i* indicates the slope of the relief.

Category	Features of topography	Location of buildings	S_T
T1	plane surface, slope or isolated relief with $i \leq 15°$	/	1.0
T2	slope with $i > 15°$	top of the relief	1.2
T3	width of the crest < width of the base, $15° \leq i \leq 30°$	crest of the relief	1.2
T4	width of the crest < width of the base, $i > 30°$	crest of the relief	1.4

2. SELECTED SITES AND DATA PROCESSING

In this work qualitative, and if possible (if a reference site at the base of the topography is available), quantitative tests were performed in correspondence of some Italian steep topographies at the top of which seismic stations (permanent or temporary) are (or were) installed.
The results obtained for many experimental evidences reported in bibliography (Hartzell et al., 1994; Spudich et al., 1996; Pischiutta et al., 2010; Buech eta l., 2010; Massa et al., 2010; Marzorati et al., 2011) evidence that relevant effects on ground shaking due to the morphology are observed, in almost cases, only where the station is installed at the top of the site; on the contrary a strongly decrease of the amplification is observed moving along the slopes from the top to the bottom.
Following this suggestion, we select five permanent accelerometric stations belonging to the RAN network (Rete Accelerometrica Nazionale, www.protezionecivile.it) and installed in the villages of Narni (NRN), Aulla (AUL), Lauria (LRS), Arquata del Tronto (ARQ) and Sellano (SELE) and four temporary velocimetric stations installed in Narni (NRN7, top, and NRN2, base) and Castelvecchio Subequo (CA03, top, and CA02, base) during the 2009 field experiments described in Massa et al., 2010 and Marzorati et al., 2011, respectively. All sites, having dimension (both in length and width) of few hundreds of meters (see figure 1), are included in T2 or T3 NTC 2008 categories (see table 1).
The processing of signals included the removal of both the mean and linear trend, the application of a 5% cosine tapering and then of an acausal 4-poles Butterworth band-pass filter, usually ranging from 0.2 to 35 Hz (little differences in the cut-off threshold depend on the considered magnitudes). Subsequently, after selecting for each event 10 s of S-phase and coda, the Fourier spectra were computed and the NS component was then rotated between 0° and 175°, using a rotation step of 5°. Thus, it was possible to analyse 36 different directions. The spectra were finally smoothed, using the Konno and Ohmachi (1998) function with a smoothing coefficient equal to 20. For each site averaged rotational HVSR and, if possible, SSRs were calculated.
All data used to perform the spectral analyses are downloadable from the Italian Accelerometric Archive, ITACA, http://itaca.mi.ingv.it).

3. SITE RESPONSE DUE TO TOPOGRAPHY FROM IN FIELD DATA

Considering that the application of the single station technique (Horizontal to Vertical Spectral Ratio, HVSR) can not accurately predict the amplification levels of a site (often resulting in underestimated values) and, at the same time, it could lead to false interpretation of the results (i.e HVSRs calculated on strong motion phase of near source data do not allow to clearly separate the contributions of the source and of the site), for each investigated station, HVSRs were calculated considering the same earthquake also recorded by another station, showing similar epicentral distance, similar propagation path and absence of topography (when it was possible rock sites are selected).

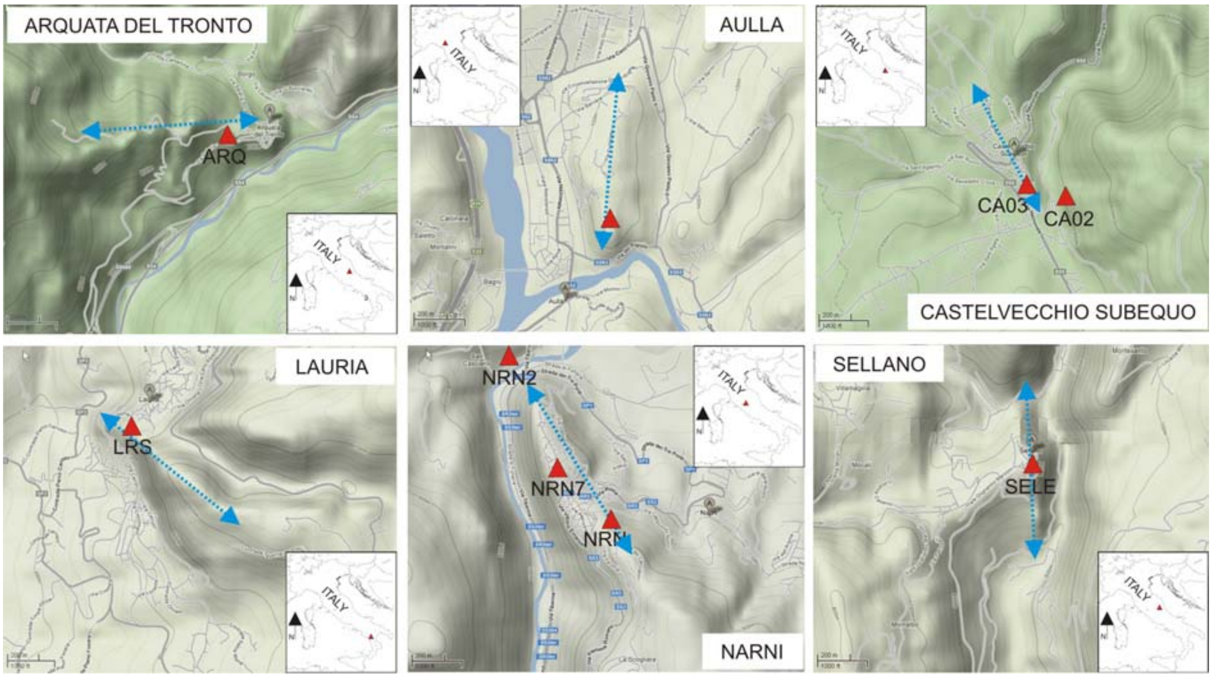

Figure 1. Topographies studied in the paper. The blue arrows indicate the main elongation of the studied ridges.

At the same time HVSRs were calculated considering both the strong motion phase and the coda. Figures from 2 to 4, summarize the results of HVSRs obtained for the considered sites.

In general, even if with the exception of Narni (Massa et al., 2010) and Castelvecchio Subequo (Marzorati et al., 2011) where a reference site is available, for the other sites only qualitative considerations are possible. In spite of this, the choice to compare HVSRs obtained considering the same event recorded (if possible) at comparable distances with respect to the considered stations and, at the same time, the choice to compare HVSRs obtained from strong motion phase and coda, allows in some case to suppose what could be the causes of each observed peak.

In general as highlighted from the case of CA03 and CA02 (Figure 3), but also from NRN and TRN case (Figure 2), it is possible to note it seems that the coda is more able to evidence the site features with respect to HVSR on S-phase where surely many peaks due to source effects are present, in particular for events recorded at distance comparable to the source dimension (e.g. the case of LRS station, figure 2): in almost all case in the analyses performed on coda some peaks with respect to S-phase tend to disappear, while the other ones remain constant. Moreover, comparing different stations recording at similar distances (and if possible with similar path) HVSRs on S-phase allow to detect the same peak in both stations (probably due to source or path effects) while, in any cases, the results on coda differ with the exception of peaks probably due to site response. On the basis of these considerations, in each figure the peak interpreted as topographic effect is highlighted by a gray inset. These statements are however confirmed by the analyses on CA02 and CA03 (Castelvecchio Subequo, figure 3) where it is possible to observe as the coda, also considering the reference station, is able to maintain some characteristic of the morphology oscillation around 3 Hz, that is completely lost by observing the S-phase HVSR, where, for both stations, the peak around 1Hz (probably non depending from the site) is more evident (considering the dimension of the morphology it is possible to exclude, from an analytical point of view a so low resonance frequency of the ridge).

Figure 5 shows examples of averaged rotational SSRs computed at Castelvecchio Subequo (left) and Narni (right) sites, considering as a reference the stations CA02 and NRN2 respectively. The results well highlight for both sites amplification strongly polarized in the direction perpendicular to the main elongation of the ridges (see blue arrows in figure 1). In this case, the SSR results confirm the amplified frequencies around 3 Hz and 4 Hz previously obtained (at CA03 and NRN respectively) performing the rotational HVSRs. In particular, considering CA02 and CA03, it is possible to observe that the peak around 1.5 Hz, detected at both stations by HVSRs (figure 3), probably reflects a peculiar characteristic of the analysed earthquakes.

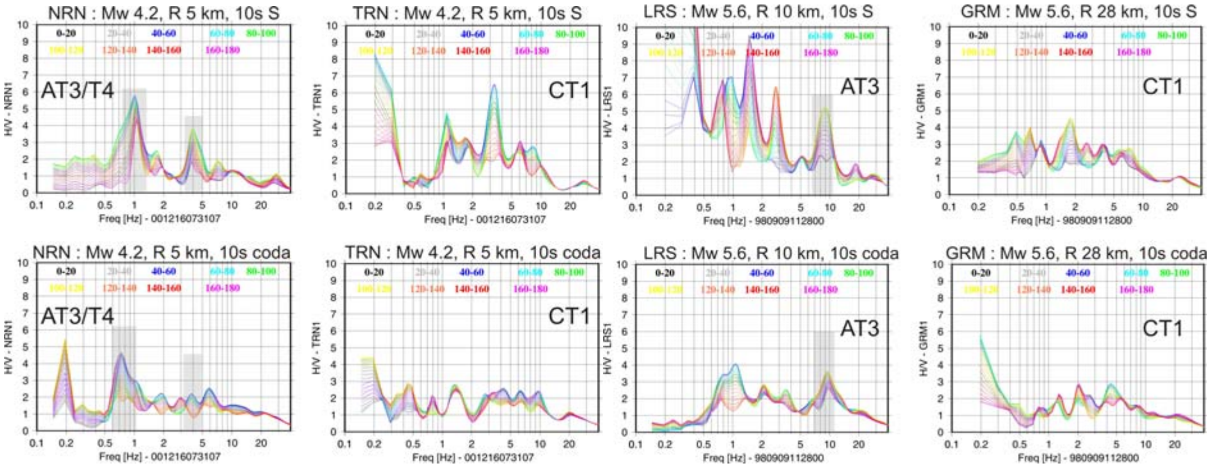

Figure 2. Top: rotational HVSR calculated on 10 s of S phase at Narni (NRN) and Terni (TRN) for the 20001216073107, Mw 4.2, event and at Lauria (LRS) and Grumento Nova (GRM) for the 19980909112800, Mw 5.6, event. In each panel, magnitude, epicentral distance, NTC08 soil category and NTC08 topography category are reported. Grey bars indicate the hypothesized topographic amplifications. As indicated in the legend each colour groups the analysed directions in interval of 20°. Bottom: the same as on top, but considering coda.

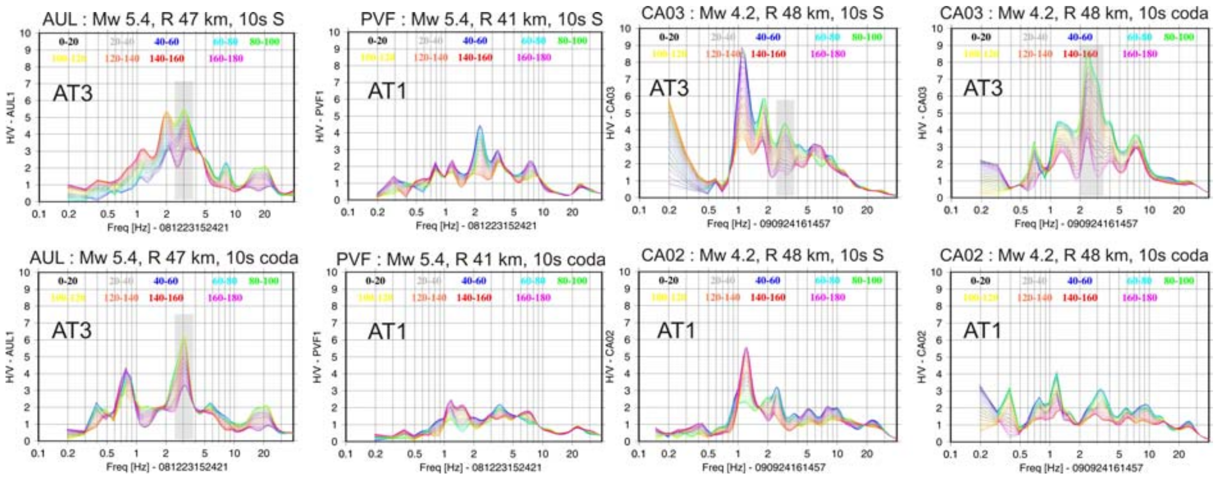

Figure 3. The same as in figure 2: Aulla (AUL) and Pavullo del Frignano (PVF) for the 20081223152421, Mw 5.4, event and Castelvecchio Subequo (CA03, top, CA02, base) for the 20090924161457, Mw 4.2, event

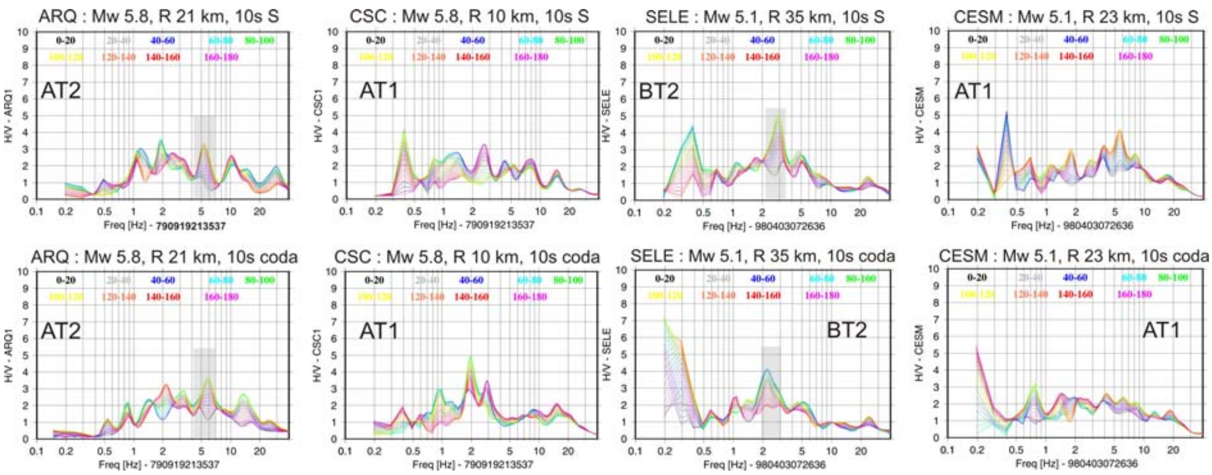

Figure 4. The same as in figure 2: Arquata del Tronto (ARQ) and Cascia (CSC) for the 19790919213537, Mw 5.8, event and Sellano (SELE) and Cesi Monte (CESM) for the 19980403072636, Mw 5.1, event.

The results in figure 5 (left) show that the peak around 1.5 Hz disappears while the amplification around 3 Hz, that reflects the real site response, is again evident using both S-wave and coda (non reported here) recordings. This example has to be a warning about possible misinterpretations of site effects, particularly whether they are deduced from HVSRs only.

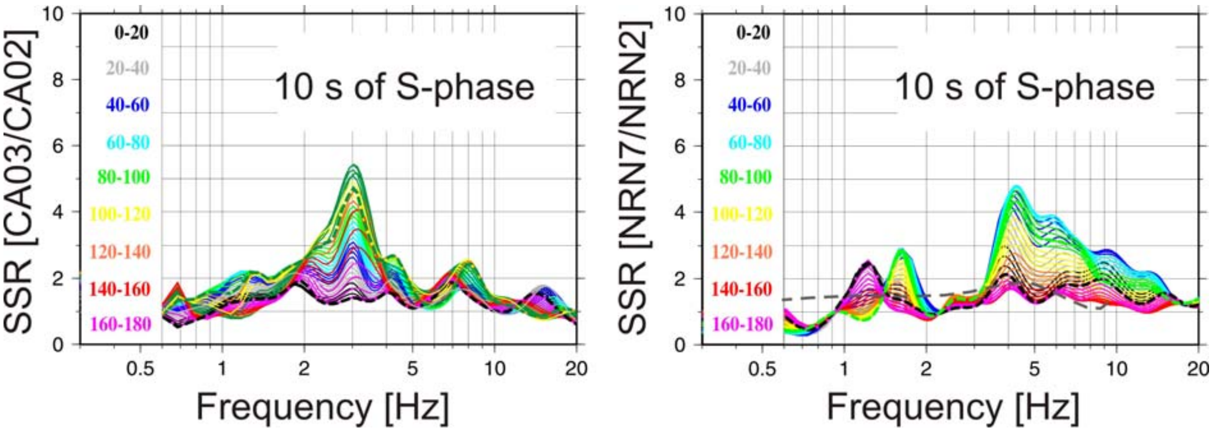

Figure 5. SSRs calculated for Castelvecchio Subequo (left) and Narni (right). The panels show averaged rotational SSR calculated from weak-motions (Mw up to 4.2) collected during the field experiments described in Marzorati et al., 2011 and Massa et al., 2010, respectively.

An important evidence for a peak caused by a topography is the high degree of polarization detected during the spectral analyses: this feature is present in all highlighted peaks related to the investigated sites. Also considering the time histories of the events analysed in figures from 2 to 4, it is possible to observe the relevant difference in the peak ground accelerations recorded on the two horizontal components. Table 2 highlights the percentage difference between horizontal PGA related to the stations installed on topography (up to 64% for Aulla station, figure 3) with respect to those classified in T1 category. Even if, in general, the frequency that characterizes the PGA can be different with respect to the fundamental frequency of the morphology, table 2 could represent a warning about possible anomalous site response of a topography. It is worth noting as, on the basis on geological maps, all investigated ridges, with the exception of Castelvecchio Subequo, could be considered in the first approximation as homogeneous geological bodies. In the case of Castelvecchio Subequo, as well stated in the paper of Marzorati et al. (2011), the ridge, on the basis of detailed geological field surveys, appears to be affected by significant anisotropies able to strongly modify the ground motion in the case of an earthquake: in this case it is not right to talk about "classical topographic effect".

Table 2. Horizontal PGA percentage difference obtained for the analysed stations.

yyyymmddhhmmss	staz	T category	comp	PGA (cm/s/s)	comp	PGA (cm/s/s)	diff %
20001216073107	NRN	T3/T4	NS	27	EW	55	50.9
20001216073107	TRN	T1	NS	64	EW	68	5.8
19980403072636	SELE	T2	NS	13	EW	19	31.5
19980403072636	CESM	T1	NS	14	EW	15	6.6
19790919213537	ARQ	T3	NS	54	EW	75	28
19790919213537	CSC	T1	NS	144	EW	143	0.7
20081223152421	AUL	T3	NS	8	EW	22	63.6
20081223152421	PVF	T1	NS	2	EW	1.9	5
19980909112800	LRS	T3	NS	161	EW	154	8.2
19980909112800	GRM	T1	NS	33	EW	34	2.9

Figure 6 shows the horizontal waveforms related to the 20090924161457 event (Mw 4.2) recorded at the top (CA03) and at the base (CA02) stations of Castelvecchio Subequo. The bottom panels figure highlight the relevant difference both in amplitude and duration of the ground motion recorded at the top (red) with respect to the same recorded at the base (green), in particular considering the filtered seismograms between 2 and 4 Hz (on the right). In the top panels, the acceleration response spectra (SA) for the two considered stations is calculated: the blue line indicates the difference between top and bottom. It is worth noting as for the EW component, perpendicular to the main elongation of the ridge, the difference between top and base reaches the value of 6 at a period around 0.33 s (3 Hz). It is worth mentioning as Castelvecchio Subequo during the April 6, 2009 L'Aquila earthquake (Mw 6.3), underwent an anomalous and relatively high degree of damage (i.e. Is 7 MCS scale) even considering the relevant distance (about 40 km) from the mainshock epicenter.

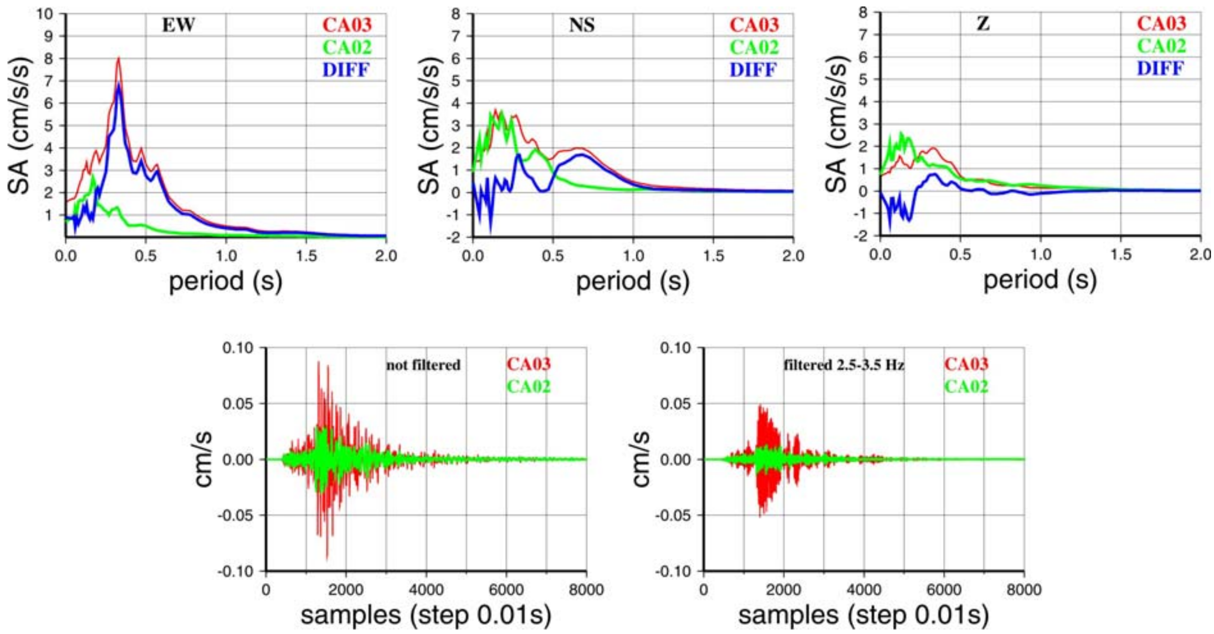

Figure 6. Top: acceleration response spectra for the 20090924161457 event (Mw 4.2, R 48 km) recorded at the top (CA03, red) and at the base (CA02, green) of Castelvecchio Subequo. In blue the difference between the spectra. Bottom: EW filtered (right) and unfiltered (left) waveforms recorded at the top and at the base.

4. CONSEQUENCE ON PREDICTIVE MODELS AND RULE FOR SEISMIC DESIGN

In order to check the reliability of the Italian ground motion predictive models recently proposed by Bindi et al., 2010, for each analysed site, 5% damped acceleration response spectra were calculated considering the earthquakes downloadable from ITACA with Mw higher than 4 and epicentral distance lower than 100 km (i.e. respectively the lower and the higher limit of M and R used in the GMPE calibration),and then compared to those predicted by the empirical relation. Figure 7 shows examples for representative events recorded at Aulla and Sellano sites. In each panels the acceleration response spectra (SA) calculated considering NS (blue), WE (red) and vertical (green) components are compared to the median of Bindi et al. (2010) in the period range 0-2 s. In general, the recorded SAs show a relevant polarization properties, typical of site response in presence of topography and in general overestimate the median of GMPE even if they are however included into the $\pm 1\sigma$ bounds. Also for the other sites (non reported in figure, we obtain very similar behaviour).

In order to identify anomalous site response (e.g. alluvial basins or topographies) in terms of deviation from the behaviour predicted by an empirical model an approach implemented in the framework of INGV-DPC S4 Project by Bindi et al. (2011) was used. For each selected station, the residuals between the recorded and predicted logarithmically-transformed spectral accelerations SA(T) for period up to 2s were calculated. The analysis allow to study the dependence of variability of earthquake ground motion on the considered spectral range. The residual $r_{p,q}$ for the p^{th} station and the q^{th} event is defined as:

$$r_{p,q}(T) = Log\left[SA_{p,q}^{obs}(T)\right] - Log\left[SA_{p,q}^{GMPE}(T)\right] \qquad \text{for } p = 1...N_S \text{ , } q = 1...N_E \tag{1}$$

where $SA^{obs}_{p,q}$ (T) and $SA^{GMPE}_{p,q}$ (T) are, respectively, the observed and predicted spectral acceleration for the station *p* and earthquake *q*. Subsequently, it was decided to normalize the residuals computed as follows:

$$r_{p,q}^{N}(T) = \frac{r_{p,q}(T)}{\sigma^{GMPE}} \tag{2}$$

σ^{GMPE} is the logarithmic standard deviation of the selected GMPE: in this case the inter-station error σ^{STA} (i.e. the difference between the median obtained considering all data and the same one obtained considering only the recordings related to one station) was considered. Correction of residuals for local site conditions is particularly useful because it allows to highlight the stations for which the recorded SA (T) is remarkably different from the median value expected for their class (either rock or shallow alluvium or deep alluvium), rather than a relative amplification/deamplification with respect to rocklike conditions. It has become common practice when deriving GMPEs to divide the aleatoric variability (σ) into the inter-event (σ^{EVE}, i.e. the difference between the median obtained considering all data and the same one obtained considering only the recordings related to one event) and intra-event variability. Starting from the consideration, residuals have to take into account the results coming from the inter-event error calculated considering the events used in the examples. The inter-event error allows to quantify the error associated to each event of the dataset and hence to investigate the dependence of errors on magnitude. Once determined the inter-event error it is possible to make consideration about the normalized residuals (i.e. if a peak of residuals is at the same period where a peak in the inter-event error exist, probably the deviation from the median is related to a feature of the analysed earthquake and not caused by the site response).

In the bottom panels of figure 7 examples of residuals between observed and predicted values, normalized using the total standard deviation of GMPEs are shown for SELE and AUL. In this case if the residuals deviate from the zero line in a positive sense it means that the predicted values underestimate the real data, in these case also up to +2σ bound. However, as stated above, to make consideration, we have to consider the inter-event errors: while SELE, AUL (but also NRN) there is an effective correspondence between the trend of the residuals and the supposed topographic effects deduced from the spectral analyses, for LRS the residual behaviour more reflects the features of the events recorded by the considered station.

Figure 8 is dedicated to a comparison between the acceleration response spectra calculated for a set of selected events recorded at the investigated stations and the design acceleration response spectra calculated at the same site on the basis of the Italian seismic rule for building (NTC 2008). The NTC spectra represent an envelop of the probabilistic uniform hazard spectra calculated for 16.000 Italian sites (2004-2006 DPC-INGV S1 Project, http://esse1.mi.ingv.it/) in terms of 10% of probability to exceed the expected PGA and SA in the next 50 years (return period of 475 yrs). Being the validity of NTC spectra in near source (design spectra at site), in order to make comparison to the available events, both recorded SA and design spectra were normalized to their PGA (spectral ordinate at zero period). In this comments only about the shape of the spectra are possible. It is worth noting that, being the design spectra an approximation of probabilistic spectra a direct comparison between NTC spectra and a spectrum of a single event represents however an approximation. Considering the results reported in figure 8, with particular attention in the range of periods where the topographic effect is expected (see the grey bar), it is evident that, independently from the amplitude, for some sites like in particular AUL, the flat part of design spectra (dark lines) does not cover all periods of interest. On the contrary, in other case, like NRN, the shape of the design spectra well envelop the real acceleration spectra (i.e. the site has a behaviour that well reflects the soil category in which it is included: in the case of NRN the class A of NTC 2008).

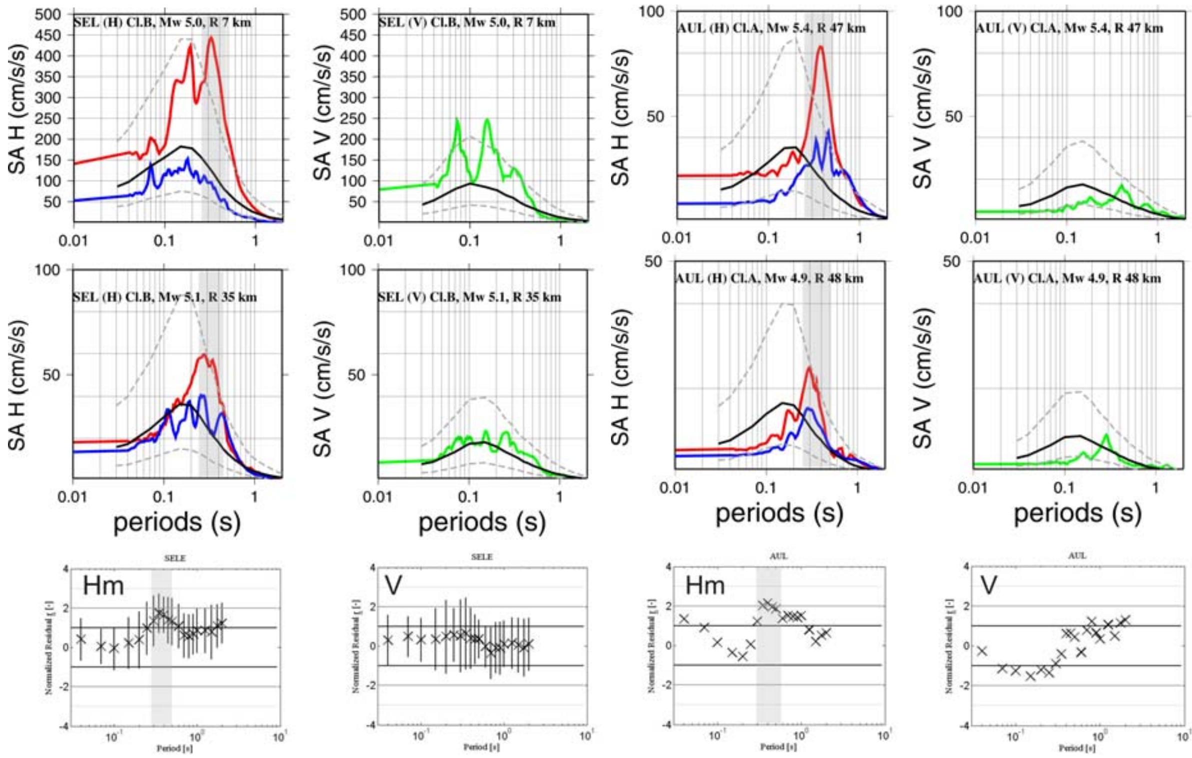

Figure 7. Left: Comparison between SA calculated for the 19980403072636 (Mw 5.1) and 19980321164509 (Mw 5.0) at SELE station and those predicted by Bindi et al. (2010). Blue lines indicate NS components, red the EW ones and green the vertical components. Black solid and dotted grey lines are the median ±1σ of Bindi et al. 2010. GMPE. Right: the same as for Sellano, but considering the 20081223152421 (Mw 5.4) and 20081223215825 (Mw 4.9) events recorded at AUL station. Bottom panels: normalised logarithmic residual between observed and predicted data. The dark vertical bars indicate the dispersion around the mean value (if non present it means that only one event is available). The grey inset indicates where the topographical site response is supposed.

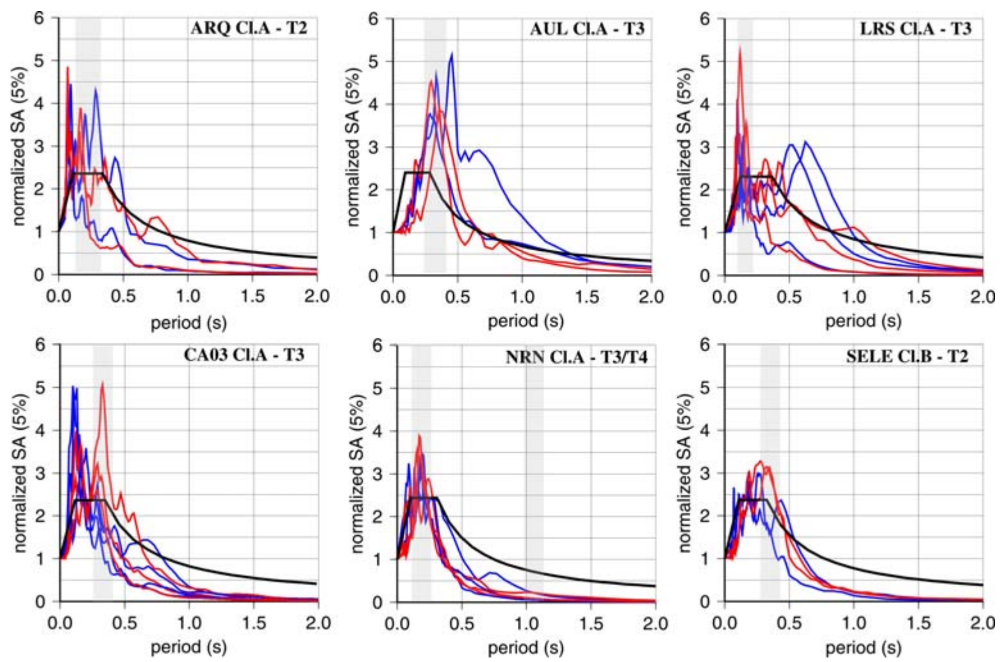

Figure 8. Normalized acceleration response spectrum (blue the NS components and red the WE ones) calculated for the events recorded at the investigated sites. Dark line represents the NTC normalized design acceleration response spectra. In each panel the soil and topography categories are indicated.

Considering the only case of Narni, in order to evaluate the performance of NTC design response spectra also in term of amplitude, we deaggregate the Italian seismic hazard map (return period of 475 ysr, Stucchi et al., 2011) at Narni site for period of 0.2 (5 Hz), considering that 5 Hz is the frequency that showed the highest experimental amplification factors. As showed in figure 9 (left panel), the more probable energetic event for Narni site has a magnitude around 5 and an epicentral distance around 10 km. Considering these values of M and R, Bindi et al. (2010) GMPE predicts for a rock site the spectrum reported in the right panel of figure 9 (blue line). In order to evaluate the NTC design spectrum for a T3 topography category, in which Narni is included, the Bindi et al. (2010) median values were multiplied by corrective coefficients estimated in Massa et al. (2010) as a logarithmic difference between the averaged SA calculated at the top of the ridge (NRN7 station) and the same one obtained at the reference station NRN2. The results, represented in term of grey squares compared to the T3 NTC design response spectrum (solid red line), highlight as in the narrow range of periods around 0.2 s the design spectrum underestimates the real amplification of ground motion detected at the top of the ridge.

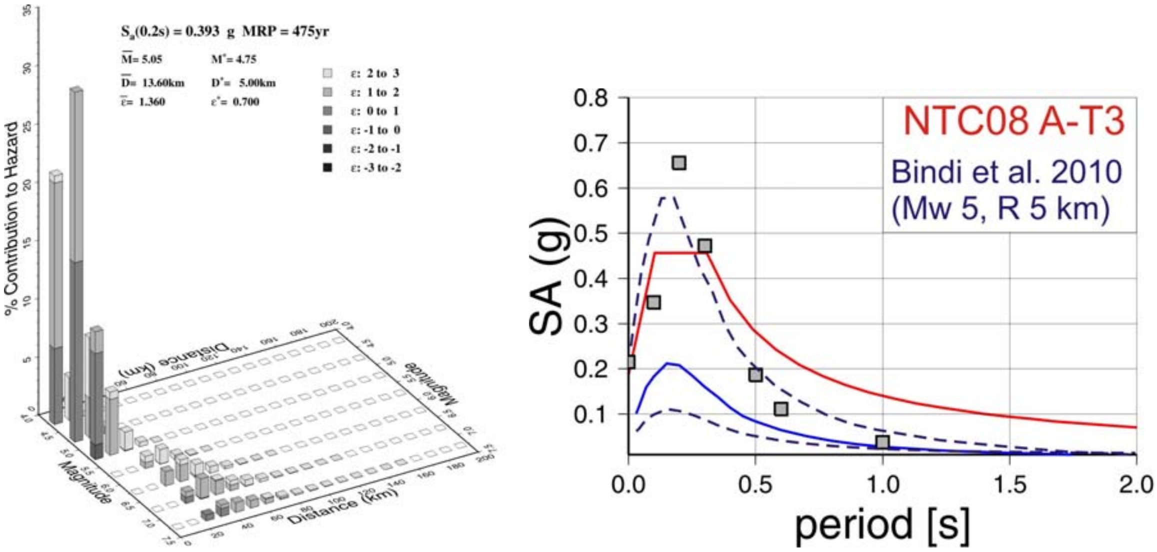

Figure 9. Left: deaggregation of Italian seismic hazard map (return period of 475 yrs) for period of 0.2 s in performed at Narni site (Barani et al., 2009). Right: the T3-NTC design spectrum (red) (i.e. a design spectrum for a rock site then multiplied by a factor of 1.2, period independent); predicted acceleration response spectra by Bindi et al. (2010) (solid and dotted blue lines for median ±1σ); Bindi et al. (2010) GMPE multiplied (at 0.0s, 0.1s, 0.2s, 0.3s, 0.5s, 0.6, 1.0s) by the corrective topographic coefficient calibrated in Massa et al., 2010.

5. CONCLUSIONS

The paper debates the issue of seismic topographic effects from different points of view. The presented analyses were performed in correspondence of six Italian ridges, where a seismic station is installed at the top of the topographies (figure 1).

Considering the results coming from the spectral analyses, and in particular the agreement in term of resonance frequency between HVSRs and SSRs, it is possible to state that the ground motion in correspondence of a steep topography undergoes relevant modifications, showing amplifications strongly polarized in the direction perpendicular to the main elongation of the ridge. It is worth noting as in the case of a non homogeneous geological body, the amplification could not be due to the topography alone, but more likely to a coupling between topographic and stratigraphic effects (Marzorati et al., 2011). This confirms the quantitative disagreement observed in many cases between theoretical and observed amplifications, at first noted by Géli et al. (1988) and then confirmed by many authors (e.g. Spudich et al., 1996; Le Brun et al., 1999; Lovati et al., 2011).

The paper then investigates the possible consequences of topographic effects on GMPEs determination and regulation for seismic design. Considering that each topography has its peculiar conditions,

concerning GMPEs calibration, it is not easy to generalize the discussion. However, it is clear that a hard-rock steep topography shows a more complicated seismic response if compared to an ordinary rock site (class A of EC8 or NTC 2008). As demonstrated in figure 7, the actual Italian GMPEs calibrated by Bindi et al. (2011) for rock sites tend to underestimate the ground motion recorded at the top of topographies, even if in a narrow range of periods.
The last consideration regards the actual Italian seismic code for building that provides for steep topographies corrective period independent coefficients that range from 1.0 to 1.4, on the basis of the geometrical features (table 1). As demonstrated in the paper, the topographic amplification often influences a very narrow band of the spectra, usually at period lower than 1.0 s. Of consequence the use of period independent topographic coefficients, as proposed by NTC 2008, leads to have underestimated design spectra in the narrow periods band of interest and conservative values for the other periods.

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