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ORIGINAL RESEARCH PAPER

Topographic versus stratigraphic amplification: mismatch between code provisions and observations during the L'Aquila (Italy, 2009) sequence

M. R. Gallipoli · M. Bianca · M. Mucciarelli · S. Parolai · M. Picozzi

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Abstract During the L'Aquila seismic sequence (Italy, 2009) we had the opportunity to install temporary accelerometric stations to study the role of seismic site amplification in damage enhancement. Two of the monitored sites, Castelnuovo and Navelli were also a good test for the recently introduced Italian seismic code (NTC08 2008) that prescribes an aggravation factor for slopes and ridges. Castelnuovo was an ideal situation to check the rule proposed for the distribution of amplification as a function of the position along a slope, while Navelli provided the possibility to test the almost equivalent factors that NTC08 sets for stratigraphic and topographic amplification (respectively up to 40 and 60 %). In neither case the observation matches code provisions. For Castelnuovo, there is a frequency dependence that shows as the code is over-conservative for short periods but fails to predict amplification in the intermediate range. For Navelli, the code provision is verified for long periods, but in the range around the site resonance frequency the stratigraphic amplification proves to be three times more important than the topographic one.

Keywords Topographic effects · Site amplification · Seismic code · L'Aquila earthquake

M. R. Gallipoli
Institute of Methodologies for Environmental Analysis-CNR, Tito Scalo, PZ, Italy

M. Bianca
Department of Structures, Geotechnics, Engineering Geology, University of Basilicata, Potenza, Italy

M. Mucciarelli
OGS-CRS, National Institute for Oceanography and Experimental Geophysics, Udine, Italy

M. Mucciarelli (✉)
School of Engineering, University of Basilicata, Potenza, Italy
e-mail: marco.mucciarelli@unibas.it

S. Parolai · M. Picozzi
Deutsches GeoForschungs Zentrum GFZ, Section 2.1, Helmholtzstraße 7, 14467 Potsdam, Germany

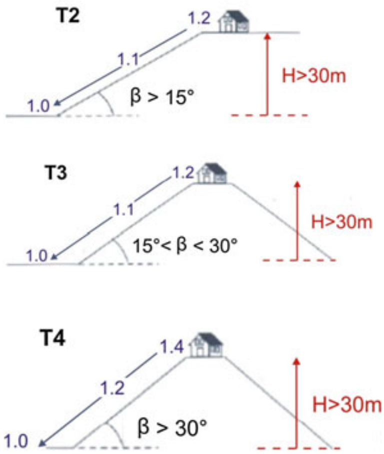

Fig. 1 Scheme of the topographic categories and coefficients for the Italian seismic code

1 Introduction

After the L'Aquila, 2009 mainshock (Mw = 6.3), a joint European effort allowed for the immediate installation of several temporary stations to record the ongoing seismic sequence (Bergamaschi et al. 2011). The cooperation between GFZ-Potsdam and Basilicata University mainly aimed to study the causes for damage enhancement observed at some localities. Examples of these joint engineering and seismological studies are given in Mucciarelli et al. (2011a) for the town of Navelli and in Mucciarelli et al. (2011b) for San Gregorio.

In the mean time, the analysis of all the available recordings using both spectral ratio and generalised inversion techniques showed that most of the amplification observed was due to stratigraphic causes (Ameri et al. 2011). Among the few localities claiming for topographic causes of amplification, the case of Castelnuovo stands out for the severity of damage, reaching IX degree MCS. The cases of Navelli and Castelnuovo are appealing for the possibility of verifying the recently introduced Italian seismic code (NTC08 2008). This code sets four topographic categories (Fig. 1: T1, flat surface, or slopes with less than 15° inclination; T2, hillsides sloping more than 15°; T3, ridges much narrow at the top with respect to the base, sloping between 15° and 30°; T4 Ridges sloping more than 30°). These category are relevant to 2-d configuration and must be considered if more than 30 m high. The values of topographic amplification coefficients range from 1 to 1.4. The topographic amplification factor S_T is 1 for T1, 1.2 for T2 and T3 and finally 1.4 for T4. If the site is not at the top of the topographic feature, the coefficient is proportionally scaled, ranging to the class value at the top and 1 at the base.

These coefficients are almost the same provided for stratigraphic amplification S_s following a Vs30 classification that range from 0.9 to 1.8. The total amplification S is given by the product $S = S_T \times S_S$. It is important to note that while S_T is constant for all the spectral ordinates, S_S is period dependent, because of the introduction of an amplitude and frequency dependency aimed to simulate the effect of soil non linearity. The effectiveness of Vs30 as a proxy for site amplification as well as the contribution of non-linearity is out of the scope of this paper. Considerations on these topics for the Italian territory can be found in Gallipoli and Mucciarelli (2009) and Puglia et al. (2011), while a paper by Rai et al. (2012) provides an updated state of the art of theoretical and empirical studies worldwide.

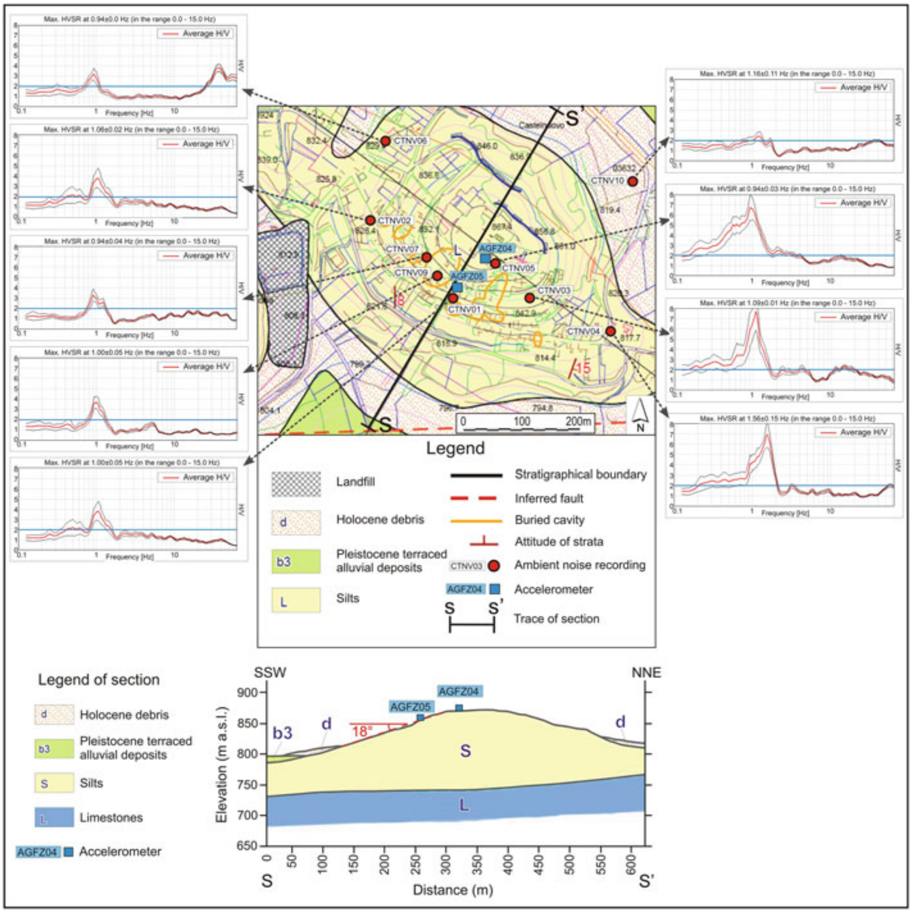

Fig. 2 Geological map and section for Castelnuovo (modified from Gallipoli et al. 2011)

Both Navelli and Castelnuovo showed damage enhancement due to site effects, and are then a couple of valid test site to check the relative importance of stratigraphic vs. topographic amplification.

In the geologic framework of the Abruzzo region, the sites are located in the sector of the Apennine fold-and-thrust orogenic belt, where mountain ranges reaching 3,000 m a.s.l. are separated by alluvial valleys that fill basins generated by normal faulting. The rock outcropping are manly limestones or cemented breccias. The sediments filling the valleys range from coarse gravel to lacustrine clay. After the 2009 L'Aquila seismic sequence, new field surveys based on a 1:5,000 scale topographical map have been carried out for these two sites.

2 Castelnuovo case study

The village of Castelnuovo (Fig. 2) is located on the top of a NW-SE-trending hill made up of Pliocene-Pleistocene silty alluvial deposits (Aielli-Pescina Unit in the geological sheet 359)

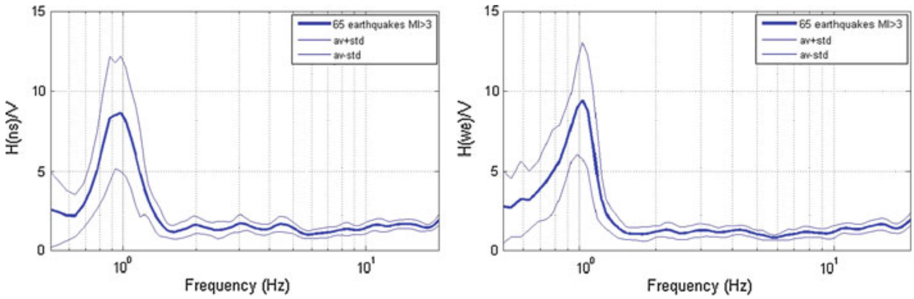

Fig. 3 HVSR curves for the two components (NS *on the left* and WE *on the right*) of AGFZ05-Castelnuovo by 65 earthquakes with Ml $>$ 3

that unconformably overlie the Mesozoic limestones belonging to different geological units (see sheet 359 for details). The limestones do not outcrop in the map shown in Fig. 1 but are represented only in the geological section.

Gallipoli et al. (2011) performed nine ambient noise recordings, estimating a clear resonance peak at about 1 Hz. Although the thickness of the resonance stratum varies from 80 m on the top to 20 m at the base of the hill, the peak frequency remains at 1 Hz moving from site to site while the amplitude value changes (see Fig. 2). The Horizontal-to-Vertical Spectral Ratio (HVSR) curve estimated on the top of the hill has higher amplitude values than those at the base of the hill. This variation in amplitude with stationarity in frequency of resonance peak could be a clue of 2–3D effect attributable to a structural effect of the whole hill, as modelled in Costanzo et al. (2010).

To validate the ambient noise HVSR, in the framework of the above mentioned joint experiment with INGV and GFZ (Ameri et al. 2011) two ETNA-Kinemetrics accelerometers have been installed the day after the main shock, one on the top of the hill (AGFZ04 in Fig. 2) and the other halfway on the south-western slope, about 100 m far from the first one (AGFZ05). Hundreds of events with a magnitude ranging between 2.0 and 5.1 Ml have been recorded. Figure 3 shows the AGFZ04 Horizontal-to-Vertical Spectra Ratio (HVSR) obtained by 65 earthquakes with Ml $>$ 3, confirming the peak at 1 Hz in both horizontal components. The difference in HVSR of the two components could be a clue directional variations of seismic site response under specific geological and topographical conditions, as reported by several previous studies (Bonamassa and Vidale 1991; Vidale et al. 1991; Spudich et al. 1996; Martino et al. 2006). We performed Rotational Standard Spectral Ratio (RSSR) calculating the ratio between the amplitudes of the Fourier spectrum of horizontal (longitudinal and transversal) components recorded on the top of the hill (AGFZ04) and the same components recorded on the site considered as a reference (AGFZ05) for 19 Ml $\geq$ 4 earthquakes (Fig. 4). The RSSR provides some more interesting clues. The HVSR at high frequency is conditioned by the amplification of vertical component as shown by the GIT performed by (Ameri et al. 2011). Around the resonance frequency, the RSSR considering only the horizontal components, better describes the kind of variation of ground motion that the code provision should try to capture. For any angle and any frequency the ratio of Fourier spectra seems in the range of the coefficients provided by the NTC (see introduction), but the ratio has variations above and below unity while the NTC supposes that the spectra at the top should be greater that the one halfway on slope for any frequency (Fig. 4).

To further investigate the relationship between code provision and observed values, we calculated the acceleration response spectra at the two stations. We selected earthquakes

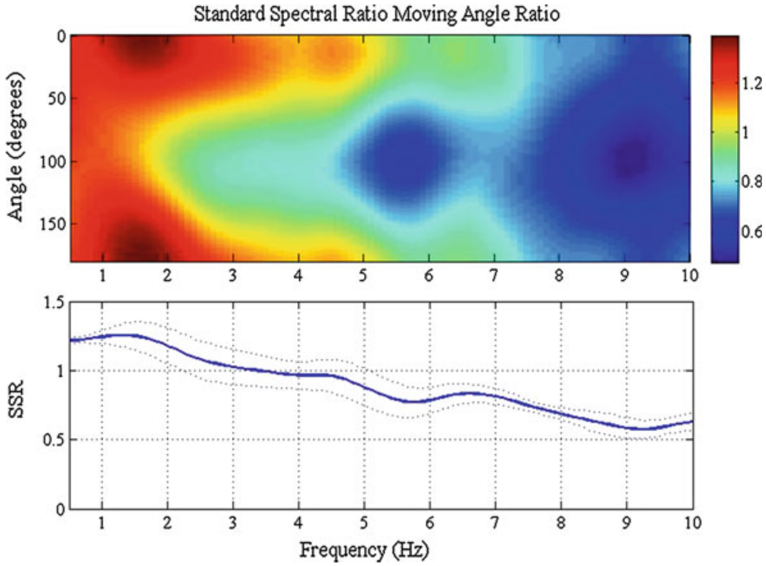

Fig. 4 Rotational Standard Spectral Ratio by 19 Ml ≥ 4 earthquakes recorded on the top of the hill (AGFZ04) and on the site considered as a reference (AGFZ05)

with the best signal to noise ratio and higher acceleration: the data analysed comprise 19 earthquakes occurred from 8 to 9 April, with magnitude ranging from 3.5 to 5.1 and distance from 10 to 40 km.

As known from previous studies both from the experimental (Gallipoli et al. 2011) and the theoretical standpoint (Lanzo et al. 2011), the top of the hill shows larger amplification with respect to the slope and this is confirmed at a first glance of the response spectra. As an example, Fig. 5 shows the comparison between the 5 % damped, normalised response spectra of the N–S component at the two sites and the NTC08 spectra for the magnitude 5.1 event occurred on April 9, 2009.

The spectra are quite similar for short period where the source effect is important, while they differ mostly for longer periods and around the resonance frequency (1 s) where they overcome again the code provisions.

The mean slope angle of the hill calculated along the alignment of the accelerometric stations is 19° and this value allows us to ascribe this slope to the topographic category T2 of NTC08. The code provides that for T2 sites, the maximum topographic amplification factor multiplying the whole input response spectra (1.2) is assigned to the top of the feature. The points along the slope are assigned factors that are a linear interpolation from the value at the top to a factor 1 at the base. Being halfway to the top, the accelerometric station on the slope has thus a code amplification factor equal to 1.1. The ratio between the two topographic amplification factors, constant for all periods is thus 1.09.

Both sites are on the same lithology, so the stratigraphic amplification factor assigned by the NTC08 code on the basis of a Vs30 classification disappears when the ratio between the two is considered. At this point we calculated the mean and the standard deviation for the ratio between the response spectra obtained from the 19 earthquakes at the two stations and compared them with the theoretical ratio provided by the code. Figure 6 shows the comparison between code provisions and observed amplification ratio. The code on average

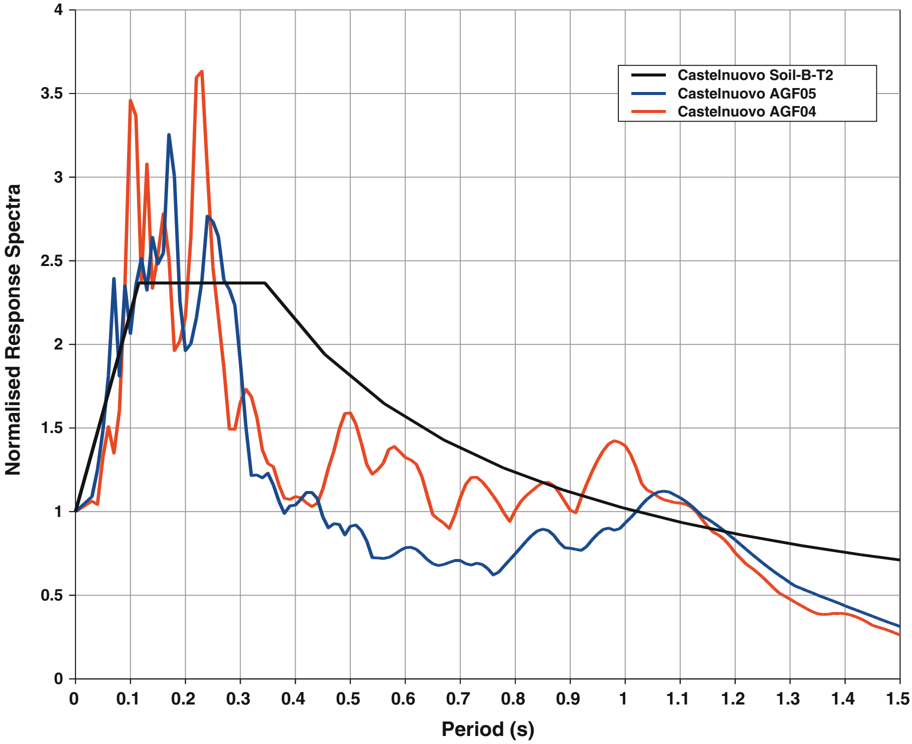

Fig. 5 Normalised Response spectra of the M 5.1 event of April 9, 2009 recorded at two sites in Castelnuovo compared with code provision

overestimates the observed amplifications for period slightly lower than 0.5 s; then, and up to 1.5 s, the ratio between the observed amplification on the top and the slope is higher than code provision of a factor greater than 1.2 that reaches 1.4 around 0.6 s. The observational data can provide just a relative factor, but the examination of spectra in Fig. 5 suggests that the overestimation is due to larger-than-expected spectra on the top rather to lower-than-expected spectra halfway on the slope.

The Castelnuovo case is actually a peculiar kind of amplification which cannot be simply described as topographic or stratigraphic. It is rather a structural-like behaviour, with a modal shape of the fundamental mode with a minimum at the base and a maximum at the top of the hill, which is also uniformly made of a soft material in sharp contrast with the underlying bedrock.

3 Navelli case study

Figure 7 shows that the historical centre of Navelli is located along the south-western slope of the NW-SE-trending narrow ridge of Mt. S. Nico, which is lithologically characterized by the outcropping Jurassic crystalline limestones (Crystalline Limestones with Echinoderma and Corals formation in the sheet 360 of the new Geological Map of Italy). The new part of the village extends upon the adjacent morphological plain representing the erosional top of

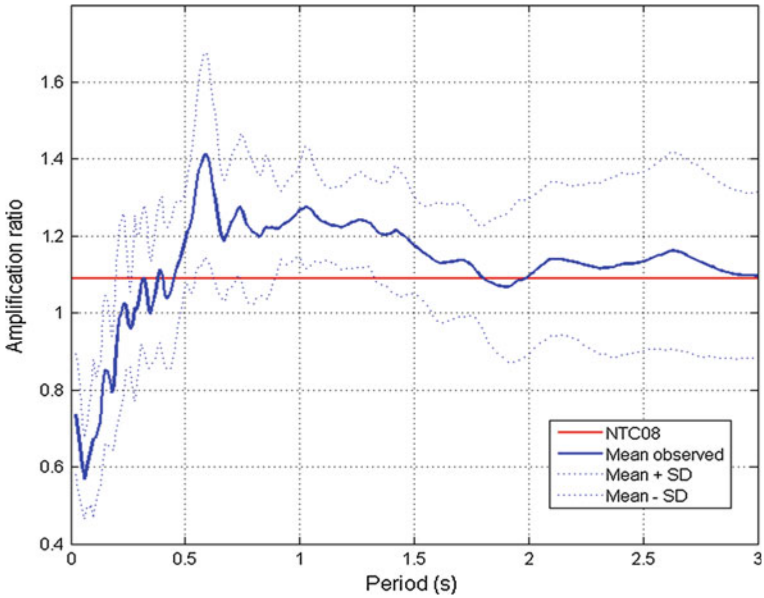

Fig. 6 Comparison between code provisions ratio (*red*) and observed amplification ratio (*blue*) in Castelnuovo

a stratigraphical succession of Late Pleistocene lacustrine sand-silt-clay deposits (Majelama Valley Unit in the geological sheet 360) that unconformably overlie the Mesozoic limestones, as shown also in the geological section (Fig. 7). The surface boundary between the Pleistocene lacustrine deposits and the Mesozoic limestones of the slope is morphologically marked by the net change of slope angle between the plain and the south-western slope of Mt. S. Nico, and it is covered by a few-metres-thick wedge of calcareous gravel-sandy debris created by the erosional processes which have affected the limestone slope during the Quaternary. A geognostic borehole has been drilled close to the town hall building down to a depth of 30 m below the ground level, and its stratigraphic log, which points out that the borehole crosses only the sand-silt-clay lacustrine deposits and therefore it does not reach the top of the seismic bedrock represented by the Mesozoic limestones (Mucciarelli et al. 2011a).

Two days after the main shocks and until the 29 April two accelerometers have been installed in Navelli downtown: one in the historical centre (AGFZ01 in Fig. 7) and the other in the town hall building at the ground floor (AGFZ02). Figure 8 shows the HVSR obtained by 9 earthquakes with Ml $>$ 4 earthquakes at the town hall site: the shape reveals a clear resonance peak at 2 Hz. This peak is due to resonance contrast at 75 m depth between sand-silt-clay lacustrine deposits over limestone (Mucciarelli et al. 2011a). The availability of a near reference site (AGFZ01) allows us to estimate the RSSR (Fig. 9).

Both SSR and RSSR reveal a quite large amplification, exceeding a factor 4, much larger-than-expected from NTC08 (Fig. 9). From the temporary network we selected 21 recordings with the best signal-to-noise ratio, with magnitude of earthquakes ranging between 3.5 and 5.1 and with epicentral distance between 20 and 50 km.

As for Castelnuovo, after the standard correction procedure of accelerograms we calculated the acceleration response spectra at the two stations. As an example, Fig. 10 shows the comparison between the normalised response spectra of the M 5.1 event occurred on April 9, 2009 and the code provisions. The biggest difference between the spectra values is observed around the resonance frequency (0.5 s): for AGFZ01 (the site in the historical centre) the

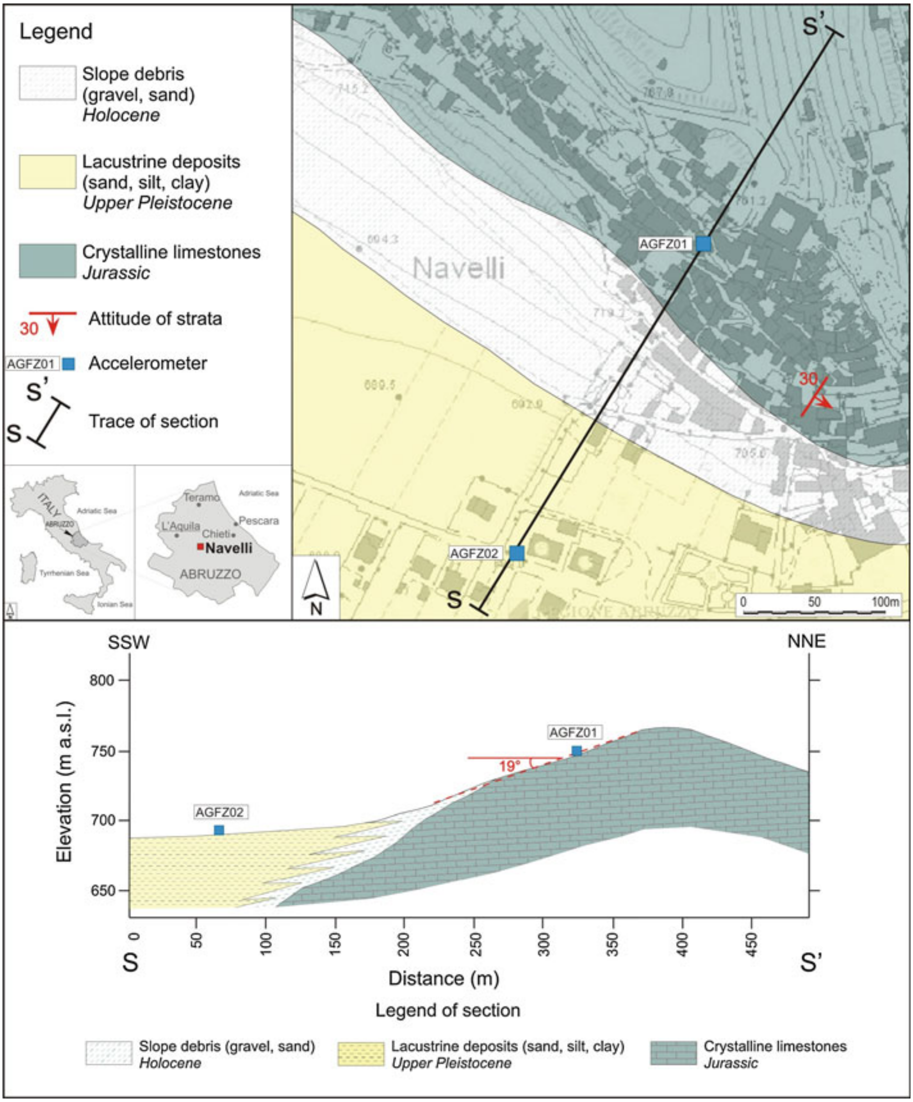

Fig. 7 Geological map and section for Navelli

spectrum provided by the code for topographic effect overestimates the estimated one, while for AGFZ02 site (at the town hall) the spectrum provided by the code for stratigraphic effect underestimates the estimated one.

The mean slope angle calculated between the crest and the top of the slope along the alignment of the accelerometric stations is 19° (Fig. 7), and considering that this morphological ridge is much narrow at the top with respect to its base, the Navelli historical centre can be ascribed to the topographic category T2 of NTC 2008. So the NTC08 code would assign a topographic amplification and no stratigraphic amplification to the historical centre, while the opposite holds for the alluvial valley, where the spectrum has to be modified for stratigraphic amplification but not for topography, being on a flat surface.

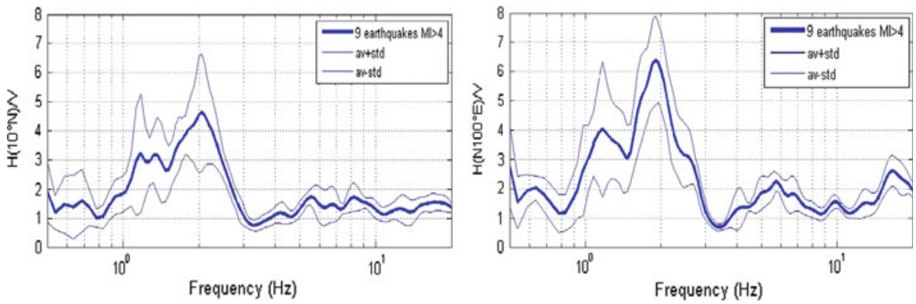

Fig. 8 HVSR curves for the two components (10°NS *on the left* and N100°WE *on the right*) of AGFZ02-Navelli by 9 earthquakes with Ml > 4

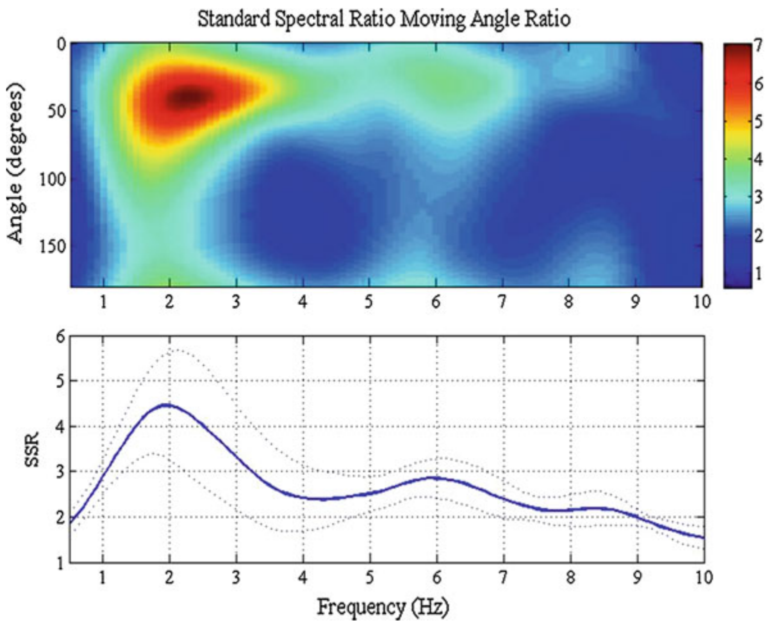

Fig. 9 Rotational Standard Spectral Ratio by 9 Ml ≥ 4 earthquakes recorded at Navelli on the hill (AGFZ01) and on the alluvial valley (AGFZ02)

Here the code spectra ratio starts from unity and then reaches 1.3 at 3 s period. This is due to the assumption on non-linear behaviour of soils that reduces amplification factors at long periods for the stratigraphic factor, while the topographic one remains constant for all the periods. What is worth to be noted, however is a problem with the NTC08 code. As mentioned for Castelnuovo, the Italian code provides that the maximum amplification factor is assigned to the top of the feature, while the points along the slope are assigned factors that are a linear interpolation from the value at the top and a factor 1 at the base. But which is the base of the slope? As it can be seen from Fig. 7, the rocky slope continues well below under the flat surface provided by the present level of sediments. Down-hole measurements and geo-electrical tomography (see Mucciarelli et al. 2011a) suggest that under the town hall the bedrock is more than 70 m deep and continues downwards. We adopted a conservative approach, assuming that since the accelerometer on the hill flank is almost at the top, a full 1.2

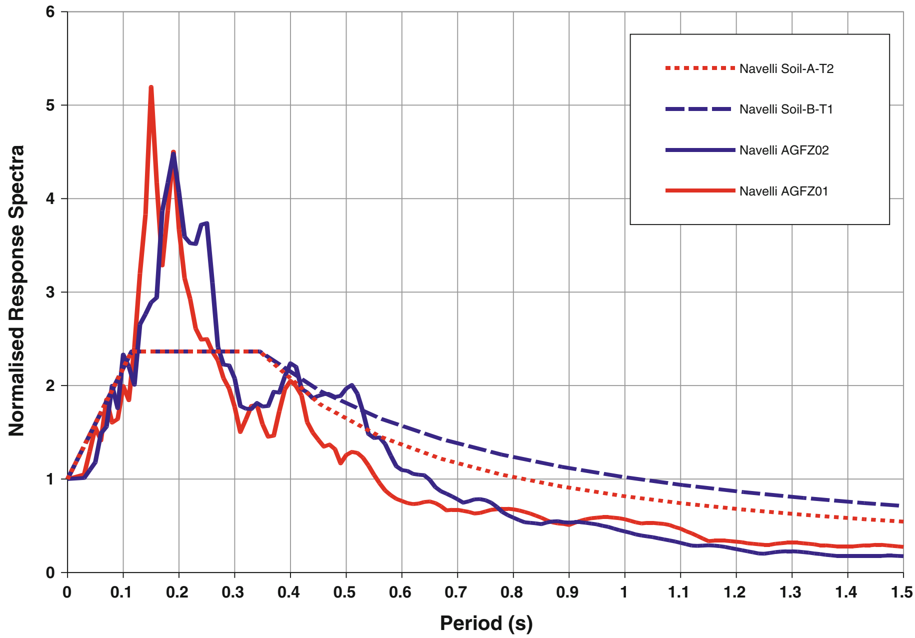

Fig. 10 Normalised Response spectra of the M 5.1 event of April 9, 2009 recorded at two sites in Navelli compared with code provision

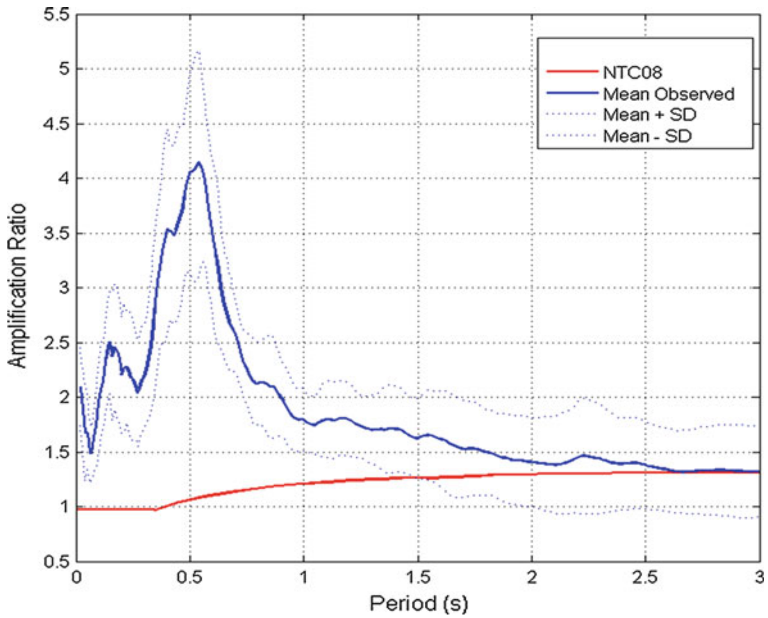

Fig. 11 Comparison between code provisions (*red*) and observed amplification ratio (*blue*) in Navelli

factor could be given for topographic amplification at that site. Notwithstanding this, Fig. 11 clearly shows the very large underestimation of code provisions, with observed amplification ratio exceeding the expected one by a factor 4 at resonance frequency (0.5 s) and reaching the same level only for periods larger than 1.5 s.

4 Conclusions

The occurrence of the L'Aquila, 2009 seismic sequence allowed us to test the Italian anti-seismic provisions about topographic amplifications. The temporary installation of accelerometric networks during the sequence provided data for two morphological situation suitable for the test: Castelnuovo, where two accelerometers were located on the same lithology at the hill top and halfway along the slope, was the ideal case to test the proposed rule of linear increment of amplification along the slope; Navelli, where the combination of topographic and stratigraphic amplification factors was near unity, given a station on a rocky slope and one on a flat alluvial valley.

In both cases, the ratio between the observed response spectra exceeded the ratio between the amplification factors provided by the code. In Castelnuovo the underestimation was of the same order of the code amplification factor (1.4) while the most upsetting situation is in Navelli, with the code missing of a factor 4 the observed data. Even if we can provide relative and not absolute evidence, given the difficulty of finding a reference site for topographic amplification, the general impression is that the code causes unnecessary conservatism on slopes and largely fails to take into account the real amount of stratigraphic amplification for strong impedance contrast. Our result confirms previous findings in Italy, such as in Massa et al. (2010), where the NTC08 topographic coefficients are discussed versus empirical analysis, observing that the empirical amplification involves a narrow frequency band and is not constant at all frequencies.

References

Ameri G, Oth A, Pilz M, Bindi D, Parolai S, Luzi L, Mucciarelli M, Cultrera G (2011) Separation of source and site effects by generalized inversion technique using the aftershock recordings of the 2009 L'Aquila earthquake. Bull Earthq Eng 9:717–739. ISSN: 1570–761X. doi:10.1007/s10518-011-9248-4

Bergamaschi F, Cultrera G, Luzi L, Azzara R, Ameri G, Augliera P, Bordoni P, Cara F, Cogliano R, Dalema E, Di Giacomo D, Di Giulio G, Fodarella A, Franceschina G, Galadini F, Gallipoli MR, Gori S, Harabaglia P, Ladina C, Lovati S, Marzorati S, Massa M, Milana G, Mucciarelli M, Pacor F, Parolai S, Picozzi M, Pilz M, Pucillo S, Puglia R, Riccio G, Sobiesiak M (2011) Evaluation of site effects in the Aterno river valley (Central Italy) from aftershocks of the 2009 L'Aquila earthquake. Bull Earthq Eng 9:697–715. ISSN: 1570–761X, doi:10.1007/s10518-011-9245-7

Bonamassa O, Vidale JE (1991) Directional site resonances observed from aftershocks of the 18th October 1989 Loma Prieta earthquake. Bull Seism Soc Am 81:1945–1957

Costanzo A, D'Onofrio A, Silvestri F, Martelli L, Gallipoli MR, Piscitelli S, Mucciarelli M (2010) The seismic response of the Castelnuovo hill (Central Italy) after the 2009 Abruzzo earthquake. In: Proceedings of the 5ICEGE (international conference on earthquake geotechnical engineering) (in press)

Gallipoli MR, Mucciarelli M (2009) Comparison of site classification from VS30, VS10, and HVSR in Italy. Bull Seismol Soc Am 99:340–351

Gallipoli MR, Albarello D, Mucciarelli M, Bianca M (2011) Ambient noise measurements to support emergency seismic microzonation: the Abruzzo 2009 earthquake experience. Bollettino di Geofisica Teorica e Applicata 53:539–559. ISSN: 0006–6729. doi:10.4430/bgta0031

Lanzo G, Silvestri F, Costanzo A, d'Onofrio A, Martelli L, Pagliaroli A, Sica S, Simonelli A (2011) Site response studies and seismic microzoning in the Middle Aterno valley (L'aquila, Central Italy). Bull Earthq Eng 9(5):1417–1442

Martino S, Minutolo A, Paciello A, Rovelli A, Verrubbi V (2006) Evidence of amplification effects in fault zone related to rock mass jointing. Nat Hazards 39:419–449

Massa M, Lovati S, D'Alema E, Ferretti G, Bakavoli M (2010) An experimental approach for estimating seismic amplification effects at the top of a Ridge, and the implication for ground-motion predictions: the case of Narni, Central Italy. Bull Seism Soc Am 100:3020–3034. doi:10.1785/0120090382

Mucciarelli M, Bianca M, Ditommaso R, Gallipoli MR, Masi A, Milkereit C, Parolai S, Picozzi M, Vona M (2011a) Far field damage on RC buildings: the case study of Navelli during the L'Aquila (Italy) seismic sequence, 2009. Bull Earthq Eng 9:263–283. ISSN: 1570–761X. doi:10.1007/s10518-010-9201-y

Mucciarelli M, Bianca M, Ditommaso R, Vona M, Gallipoli MR, Piscitelli S, Rizzo E, Picozzi M (2011b) Peculiar earthquake damage on a reinforced concrete building in San Gregorio (L'Aquila, Italy): site effects or building defects? Bull Earthq Eng 9(3):825–840. ISSN: 1570–761X. doi:10.1007/s10518-011-9257-3

NTC08 (2008) Nuove Norme Tecniche per le Costruzioni, Gazzetta Ufficiale n. 29, Suppl. n. 30

Puglia R, Ditommaso R, Pacor F, Mucciarelli M, Luzi L, Bianca M (2011) Frequency variation in site response as observed from strong motion data of the L'Aquila (2009) seismic sequence. Bull Earthq Eng 9:869–892

Rai A, Rodriguez Marek M, Yong A (2012) Topographic effects in strong ground motion. In: Proocedings 12 world conference on earthquake engineering, Lisbon 2012, electronic edition

Spudich P, Hellweg M, Lee WHK (1996) Directional topographic site response at Tarzana observed in aftershocks of the 1994 Northridge, California, earthquake: implications for mainshock motions. Bull Seism Soc Am 86(1B):S193–S208

Vidale JE, Bonamassa O, Houston H (1991) Directional site resonances observed from the 1 October 1987 Whittier Narrows, California, earthquake and the 4 October aftershock. Earthq Spectra 7:107–125