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

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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.

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 set 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 seismic 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.

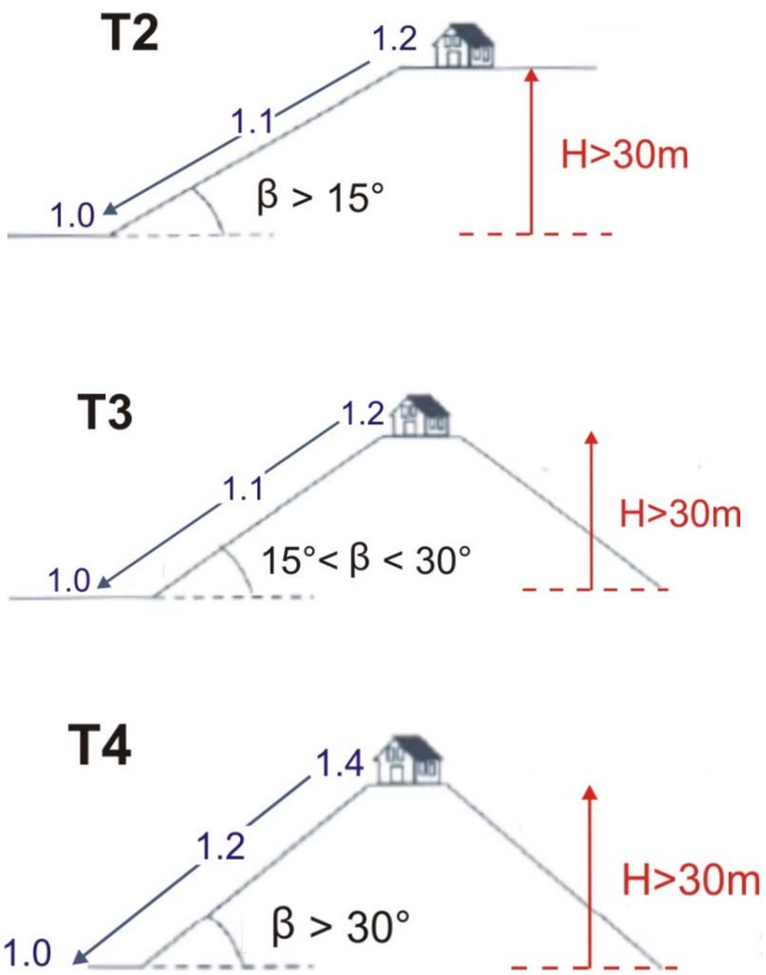

Figure 1. Scheme of the topographic categories and coefficients for the Italian seismic code

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 x 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.

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 3000 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) 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 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.

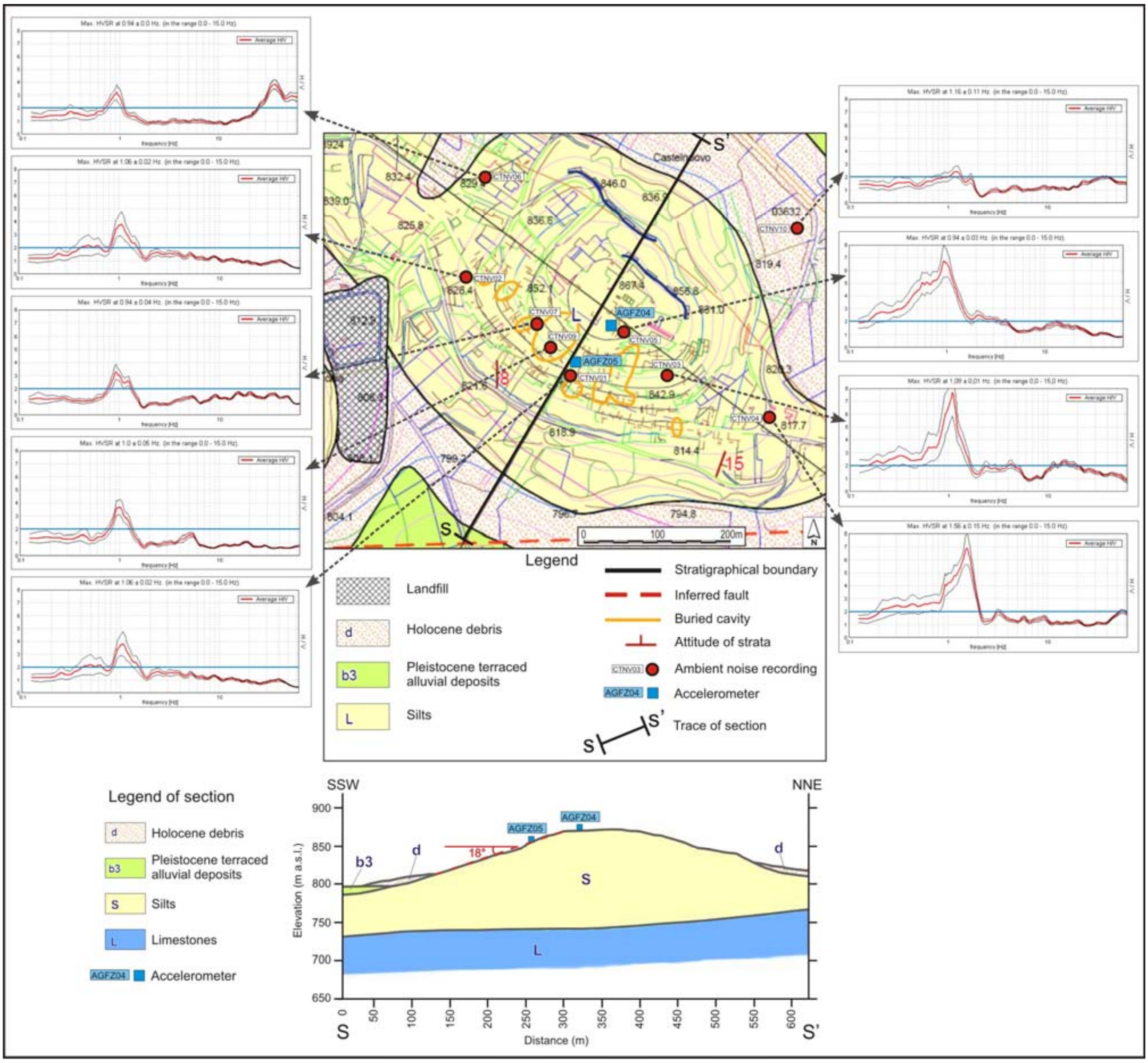

Figure 2 Geological map and section for Castelnuovo (mod. from Gallipoli et al., 2011)

To validate the ambient noise HVSR, in the framework of the above mentioned joint experiment with INGV and GFZ (Ameri et al., 2010) two ETNA-Kinematrics 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 2.0-5.1 Ml have been recorded. Fig. 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 of 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≥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. (2010). 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).

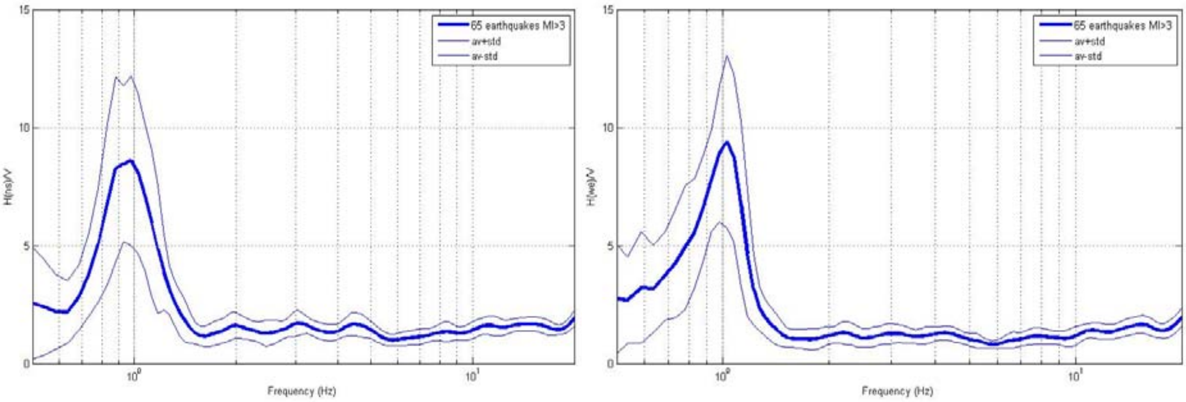

Figure 3. HVSR curves for the two components (NS on the left and WE on the right) of AGFZ05-Castelnuovo by 65 earthquakes with Ml>3.

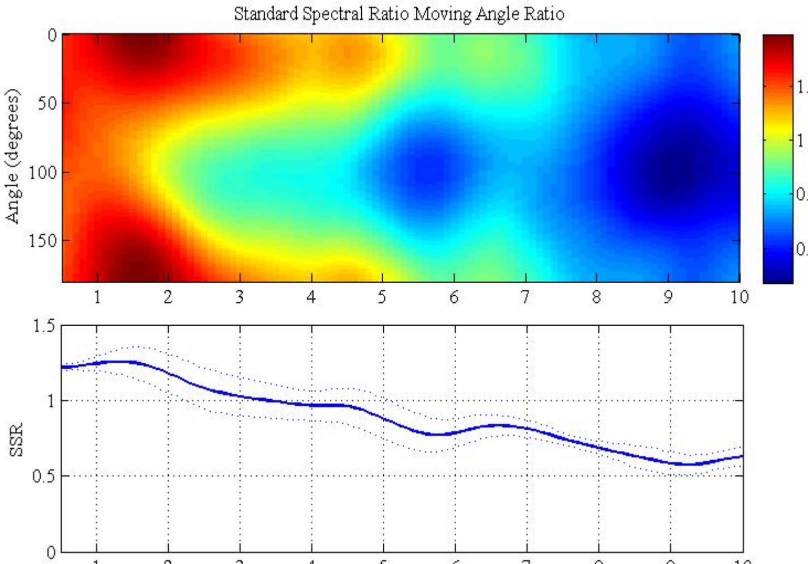

Figure 4. Rotational Standard Spectral Ratio by 19 Ml≥4 earthquakes recorded on the top of the hill (AGFZ04) and on the site considered as a reference (AGFZ05).

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

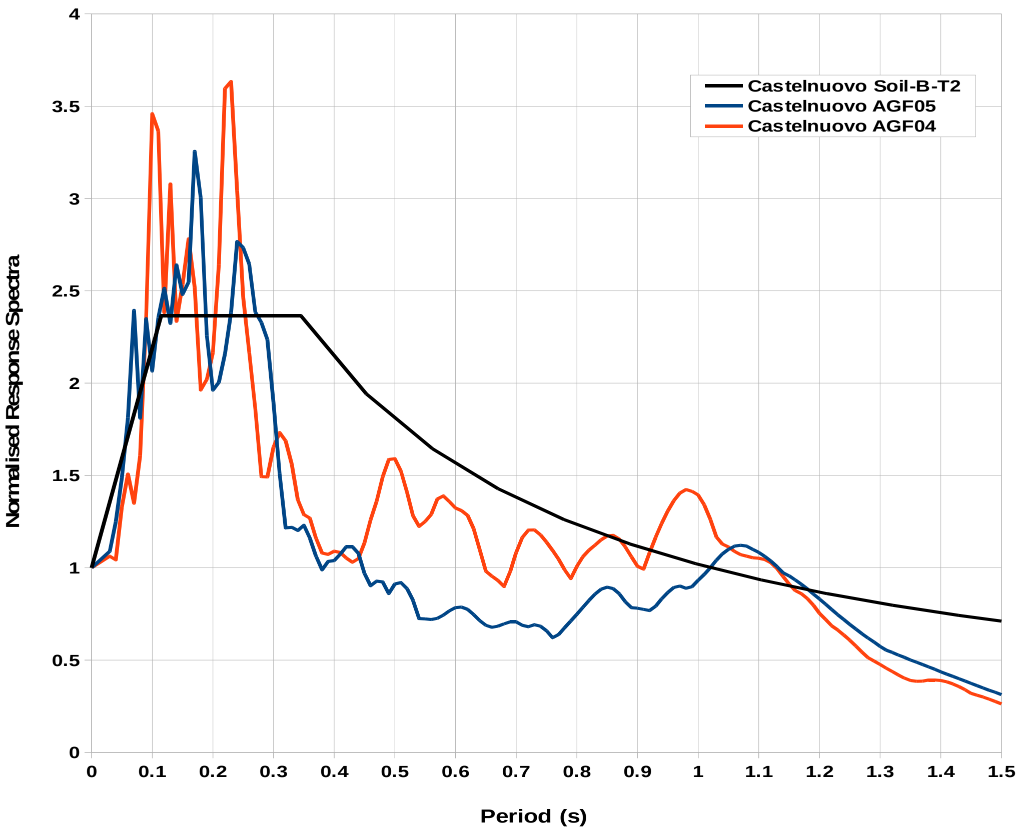

Figure 5. Normalised Response spectra of the M 5.1 event of April 9, 2009 recorded at two sites in Castelnuovo compared with code provision.

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. Fig. 6 shows the comparison between code provisions and observed amplification ratio. The code on average 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 suggest that the overestimation is due to larger-than-expected spectra on the top than 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.