HVSR VARIABILITY AT SITES NEAR AND UPON TOPOGRAPHIC HEIGHTS

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Introduction. The horizontal to vertical spectral ratio (HVSR, Nakamura, 1989) is one of the most efficient techniques available for the analysis of site effects, especially in the estimation of the resonance frequency in case of a soft surface layer upon a bedrock (Mucciarelli, 1998; Mucciarelli and Gallipoli, 2001; Bonnefoy-Claudet *et al*., 2006a). The layer seismic resonance produces a well defined peak in the HVSR curve, and its frequency is strictly related to the layer thickness (Bonnefoy-Claudet *et al*., 2006a). Interesting site effects are produced by the interaction of seismic waves with the topography. Topographic effects generally produce an amplification of the horizontal ground motion and a polarization in the same direction of the maximum slope, or normal to the ridge crest, thus mountain places are commonly affected by such effects in case of earthquake (Pedersen *et al*., 1994; Spudich *et al*., 1996). The analysis of seismic noise provides useful information about the topographic effects (Chavez-Garcia *et al*., 1996; Panzera *et al*., 2011).

Results obtained from HVSR analysis are generally considered as a stable feature of a given site, infact a number of experiments have shown that the frequency of the resonance peak is almost the same among weak stationary noise, transient noise, traffic noise, calm or windy days, and even earthquakes (Mucciarelli, 1998; Mucciarelli *et al*., 2003; Parolai *et al*., 2004; Guillier *et al*., 2007; Cara *et al*., 2010). Actually, the most of these observations were carried out on sites characterized by quite simple geological structures where a well-defined resonance peak occurs, while evidences of non-stability of the HVSR curves are very few (Benkaci *et al*., 2018). In this paper we show some examples of sites where the HVSR shape may change considerably with the appearence of one or more occasional peaks when the amplitude of background noise increases due to weather conditions.

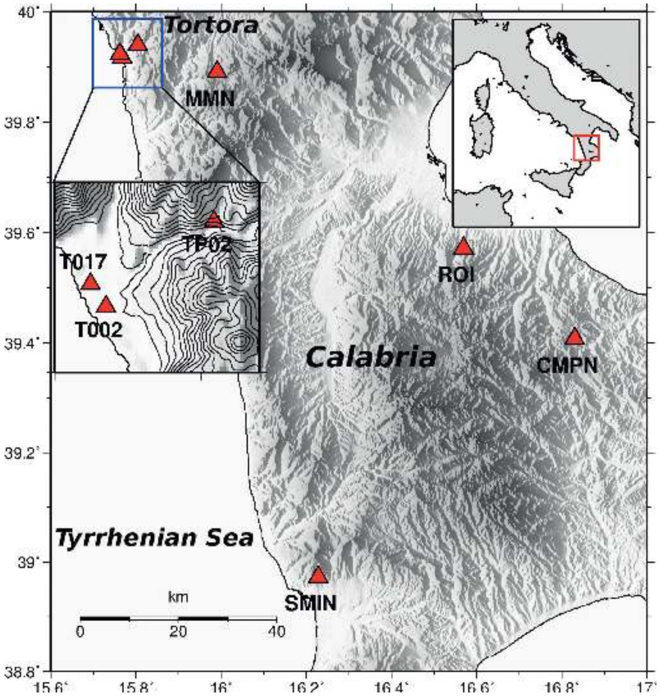

Fig. 1 - Topography map showing the position of seismic stations used in this paper. MMN, ROI, CMPN and SMIN are permanent stations of the Università della Calabria Seismic Network, while T002, T017 and TP02 shown in the inset are temporary stations.

Data analysis and results. We recorded a large amount of data at many different sites in Calabria (Italy) through three component seismic stations (Fig. 1). Then we performed standard HVSR analysis on selected data using the software GEOPSY (www.geopsy.org). Spectra were computed on 120 s sliding window, applying an anti-triggering algorithm if necessary to remove transients related to vehicles and other human activities, and they were used to compute the average HVSR and its standard deviation. Through the same software we computed also the HVSR versus azimuth to study the polarization of the HVSR peaks, which generally is a consequence of the amplification of horizontal ground motion in the slope direction or perpendicular to the ridge crest (Spudich, 1996; Paolucci, 2002). During periods of higher amplitude background noise, generally related to weather conditions, we observe the most relevant variations in HVSR curves. To establish a relation between the noise amplitude and the variations of the HVSR curves we computed the rms of continuous signals over 4 minute sliding window, after an appropriate bandpass filtering. Hereafter we use "weak noise" expression to indicate low amplitude seismic noise during good weather periods, and "strong noise" expression to indicate higher amplitude seismic noise during low-pressure periods. From these observations we obtain a first important result: the most striking variations of HVSR occur during strong noise periods, in fact at all the sites considered the HVSR shows the appearance of one or more peaks of relevant amplitude during strong noise periods, that are not present during normal weak noise periods.

The most interesting results, that means the most variable HVSRs, have been observed at the seven sites shown in Fig. 1. Here we give a detailed description for only two sites for shortness reasons. Fig. 2 shows the results of data recorded at site TP02 by a temporary seismic station (equipped with Lennartz 1 Hz seismometer and 24 bit data logger) installed for some months in the basement of a church in the historical center of Tortora village. This site is located on a narrow N-S ridge where few meters of Pliocene sands and conglomerates overlie the

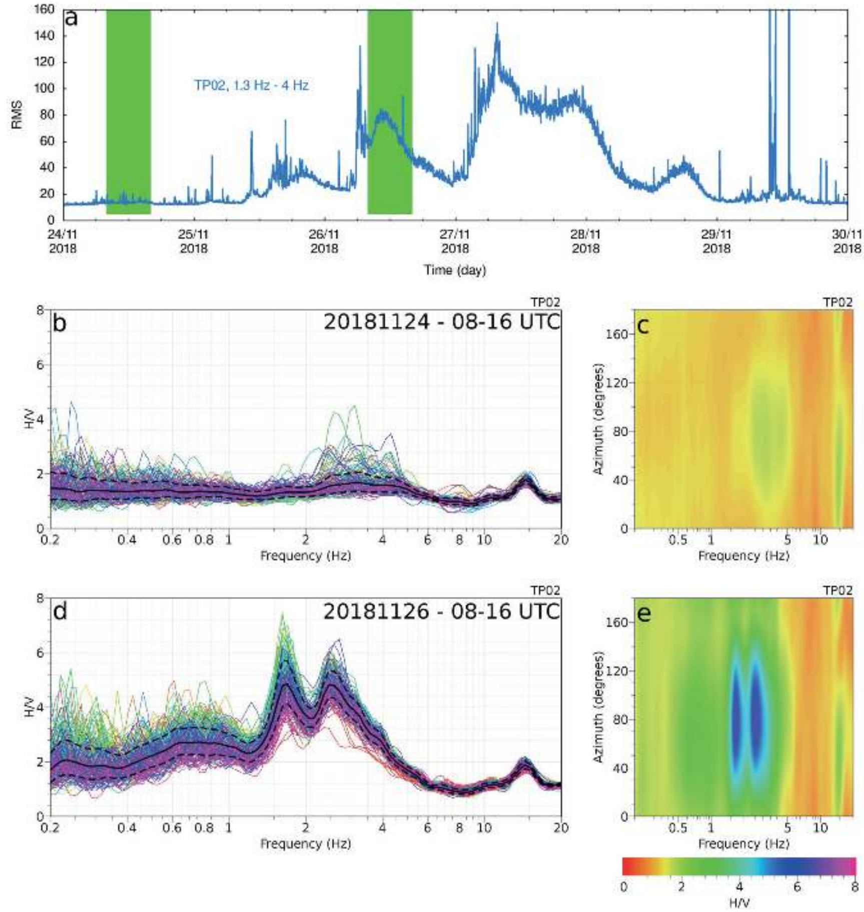

Fig. 2 - Results of the analysis of seismic noise at site TP02. Plot a shows the rms computed for 6 days of signals bandpass filtered in the frequency band: 1.3 - 4 Hz. Plots b and c show the plain and directional H/V spectral ratio of weak signal computed in the 8 hours time window shown by background color in plot a. Plots d and e show the plain and directional HVSR of strong signal.

well-bedded Triassic dolomitic bedrock through an unconformity surface. The analysis of weak noise for TP02 shows a flat HVSR curve and no significant peaks according to Sesame project criteria (Sesame, 2004) in a broad frequency band (Fig. 2b, 2c). Such result was expected because of the outcropping bedrock. Only a peak at about 15 Hz is very stable, but its average height is just below 2, while some peaks between 2 Hz and 5 Hz appear only occasionally. On the contrary, the analysis performed on strong noise shows very different HVSR curve, which is characterized by two peaks at frequency of 1.6 Hz and 2.5 Hz, height more than 4, both well polarized (about 80 degrees, Fig. 5d, 5e). The origins of these peaks, their frequency value and their E-W polarization agree with a topographic amplification of the horizontal ground motion in the direction normal to the N-S oriented crest.

Fig. 3 shows the results of the analysis of seismic data recorded with a Lennartz LE3Dlite seismometer at site ROI that is a permanent station of the RSU (Rete Sismica Unical). This site is located on a N-S ridge, characterized by a complex of Paleozoic acidic intrusive rocks (granodiorite and granite) often deeply weathered and tectonized, widely outcropping in the surrounding area. The analysis on weak noise shows HVSR curves characterized by irregular shape with a broad double peak between 6 Hz and 10 Hz of height 3 (Fig. 3b). Instead, in the HVSR curves of strong noise the double peak between 6 Hz and 10 Hz increases its height up to 7, and another well defined peak rises at frequency of 3.3 Hz with an average height of 5.

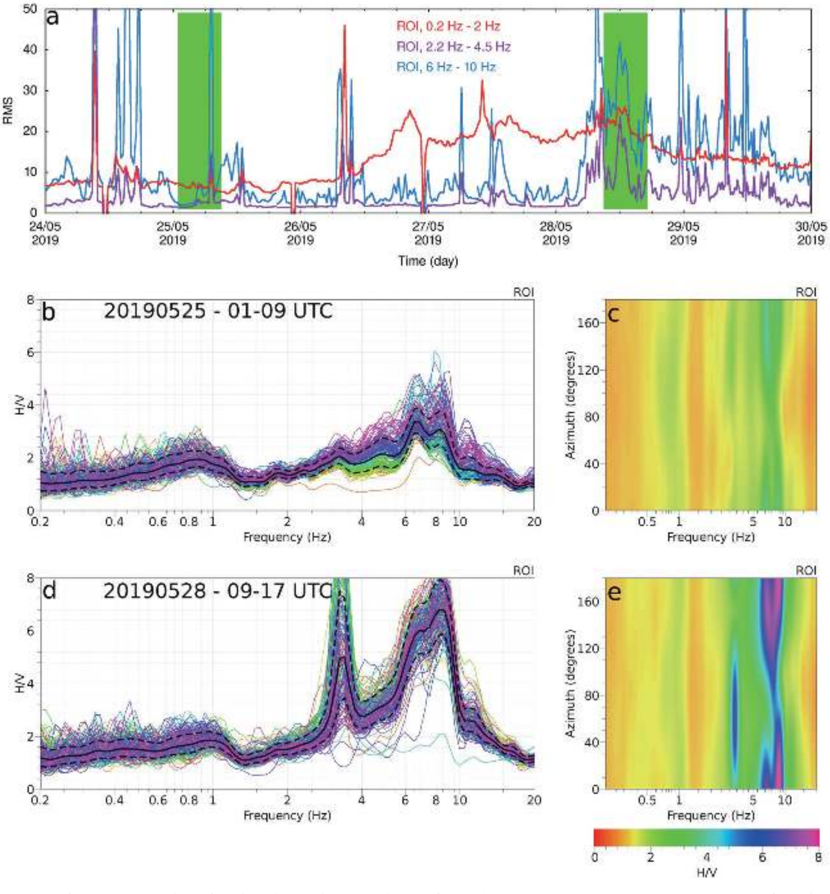

Fig. 3 - Results of the analysis of seismic noise at site ROI. Plot a shows the rms computed for 6 days of signals bandpass filtered in three different frequency bands: 0.2 - 2 Hz (red line), 2.2 - 4.5 Hz (magenta line) and 6 - 10 Hz (blue line). Plots b and c show the plain and directional H/V spectral ratio of weak signal computed in the 8 hours time window shown by background color in plot a. Plots d and e show the plain and directional HVSR of strong signal.

The completely different polarization between the broad peak (ranging from 6 Hz and 10 Hz) and the occasional peak (at 3.3 Hz), respectively 160 degree and 60 degree, is another very interesting feature of this site.

Discussion. For the seven analyzed sites the HVSR curve obtained from the analysis of seismic noise is not a stable feature. In fact the typical shape of the HVSR curve obtained for each site in case of strong noise differs quite a lot from that obtained in case of weak noise. Five sites are located on hill slope (MMN and SMIN) or ridge crest (TP02, ROI, CMPN), in places where the soft soil thickness can be neglected. In the HVSR curves of these sites computed on weak noise we expect contributions from both geology and topography (Burjanek *et al*., 2014), not easily discernible from each other. For all these five sites the occasional contribution to the HVSR yields peaks in a broad frequency range, from 1.7 Hz to 14 Hz. The two sites at Tortora Marina, T002 and T017, located in between the sea and the mountain, show always a well defined persistent peak at 2.15 Hz and 1.4 Hz, respectively. The occasional peak that appear in case of strong noise have lower frequency, 1.3 Hz and 0.95 Hz. We believe that at these two sites the occasional peak is likely the result of a shear head wave produced by the sea waves as they approach the coast. The HVSR peak associated with shear head waves has been theoretically described by Bonnefoy-Claudet *et al.* (2006a). Unfortunately, our single station data are not sufficient to confirm or reject this hypothesis. All the persistent HVSR peaks observed in the seven sites are well polarized in the horizontal plane. In mountain environments where topographic effects occur, the polarization is parallel to slope direction (MMN, SMIN) or normal to ridge crest (TP02, ROI, SMIN), while along the coast (T002, T017) the polarization of the peaks, due to resonance of soft layer, is parallel to the presumed layer dipping direction.

All analyzed data were acquired by seismic stations installed inside a building (house basement, cellar, vault, and similar locations) with the seismometer covered by a shelter and thermally insulated in case of broad band sensor, therefore the direct action of any external factors upon the instruments (wind, rain etc..) cannot be responsible of the observed HVSR variations.

We suppose that the composition of the seismic wavefield has a greater amount of body waves in case of strong noise compared to weak noise. The interaction of body waves with local geology and topography is expected to produce different effects compared with the interaction of surface waves. The contents of surface and body waves in the background signal are not constant and depends on the noise sources, their features and distance from the recording site. In the hypothesis that strong noise has a contents of body waves greater than weak noise, we can explain the occasional low frequency peak that rise up in the HVSR at the two sites near the coast, T002 and T017, as produced by shear head waves, as suggested by some theoretical analyses (Bonnefoy-Claudet *et al*., 2006a). Furthermore, the interaction of body waves with the local topography could explain the different HVSR curves observed for sites located on hill slope or upon a ridge. The important contribution of body waves to topographic effects has been recognized in many studies (e.g. Chavez-Garcia *et al*., 1996), therefore we believe it is the most likely source of the occasional effects observed during strong noise periods.

Conclusions. While the stability of HVSR results in simple geological contexts is well supported by many papers, our study demonstrates that in some cases the HVSR results are not stable in time and their interpretation is not obvious, especially at sites characterized by rough topography and complex geological structure. The results of HVSR analysis computed for different time periods may be very different, with a tight relationship with the amplitude of the incoming waves. Understanding how the composition of the seismic signals, in particular the amount of body waves in the background noise, affects the HVSR is fundamental in places where different site effects may occur. However, a better comprehension of the seismic wavefield, for example from the analysis of array data recordings, and a good knowledge of the local geological structure which include a 3D velocity model, are necessary to explain the occasional HVSR peaks.

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ASSESSMENT OF SEISMIC VULNERABILITY OF SMALL EARTH DAMS IN PIEDMONT REGION: FROM A SIMPLIFIED METHOD TO ADVANCED TOOLS

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Introduction. The project “ReSba” (Resilienza degli Sbarramenti) is aimed at improving the knowledge regarding the risks of small dams and the related resilience of the community. The Italian Code for Dams (NTD, 2014) defines “small dams” those up to 15 m high and a reservoir lower than 10^6 m^3. Despite the small cubage of the reservoir volume, the risk associated with their potential rupture can be considerable. Indeed, they are often located along slopes close to populated areas. For these reasons, the evaluation of their associated seismic risk is of paramount importance. In this respect, the activity conducted at the Politecnico di Torino is to