DAY-NIGHT CYCLE IN THE HVSR OF SEISMIC NOISE

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Introduction

HVSR method (Nakamura, 1989) is one of the most efficient and widespread techniques to get useful information about seismic site effects. In more than 30 years of application many authors reported the effectiveness of this method in identifying the resonance frequency of the shallow geological structure in various geological context, particularly those characterized by horizontal soft layers (Mucciarelli, 1998; Bard, 1999; Bonnefoy-Claudet *et al*., 2006a). The method has been applied to seismic noise and to earthquake signals, giving similar results in the most of cases. During the last 20 years many questions arose about the stability of the results obtained from this analysis and theoretical considerations have been proposed to estimate the contribution of different seismic wave types to the HVSR result. While the interpretation of results is quite obvious in cases of flat topography and simple layered structures upon bedrock with high impedance contrast, it may become much more difficult for sites where raw topography and complex geological structure with lateral heterogeneity characterize the area. The effects of transient signals has been investigated by many authors and results indicate that their contribution to HVSR is minor in many cases (Mucciarelli *et al*., 2003; Parolai & Galiana-Merino, 2006). Thus many authors consider very stable the result of HVSR analysis, but some evidences of HVSR variability with time in particular geological contexts have been published recently (e.g. La Rocca *et al*., 2020). Since this method has found wide application in engineering-related fields (such as microzonation studies and structures monitoring), the questions about the consistency of the results and the limits of the method have gained more importance in recent years, and not only for purely scientific purposes. In this study we analyzed months of seismic noise recorded at many sites in Calabria in order to investigate the features of seismic noise, its day-night cycle, and the HVSR variations with time. We found that in some cases the HVSR curve can remarkably change its shape, especially in terms of the resonance peak amplitude, and such variations show a clear correlation with the day-night cycle that characterize the amplitude of seismic noise. Local and regional earthquakes were also analyzed at the same sites, and HVSR results were compared with those obtained from the analysis of seismic noise.

Data analysis and results

Data analyzed in this work come from the regional seismic network managed by Università della Calabria (Rete Sismica Unical, international code IY, doi:10.7914/SN/IY, http://doi.org/doi:10.7914/SN/IY, www.sismocal.org). We started our analysis computing HVSR on many weeks of continuous signals for more than 30 seismic stations. Among the stations that show the presence of site effects we selected 9 sites (CHC2, GIMI, LADO, MANE, MNGA, SCAI, SMIN, UC01, VBL2, www.sismocal.org) characterized by important variability of the HVSR peak amplitude. For the nine selected sites we performed further detailed analysis as described below.

We computed the HVSR of continuous signals in different periods of the year. In this analysis we included the months of March and April 2020, a period characterized by a lower contribution of antropic disturbances in background noise due to the major lockdown adopted by the government to contrast the COVID-19 pandemic. In fact, for some seismic stations usually affected by a high level antropic noise at frequency greater than 1 Hz, that period gave the opportunity to study signals less affected by human activities. Figure 1 shows the HVSR versus time and frequency for three permanent seismic stations where the day-night variation of the peak amplitude is particularly evident. A considerable increase of the peak amplitude occur during day hours, while the same peak almost disappear by night. This feature of the HVSR has been observed for several sites, and it is not affected by the reduced contribution of antropic noise that characterized the two months of March and April 2020. We computed the RMS (root mean square) versus time for continuous signals to follow the day-night variations of signal amplitude in time domain. The RMS was computed on a 300 s sliding window for the three components of ground motion on bandpass filtered signals to include only the frequency range shown by the peak of HVSR result. Then we computed the mean RMS among the three components, and the ratio between the RMS or horizonthal and vertical components. This last analysis, the H/V ratio in time domain (hereafter said H/V to distinguish from HVSR in frequency domain), allows to easily

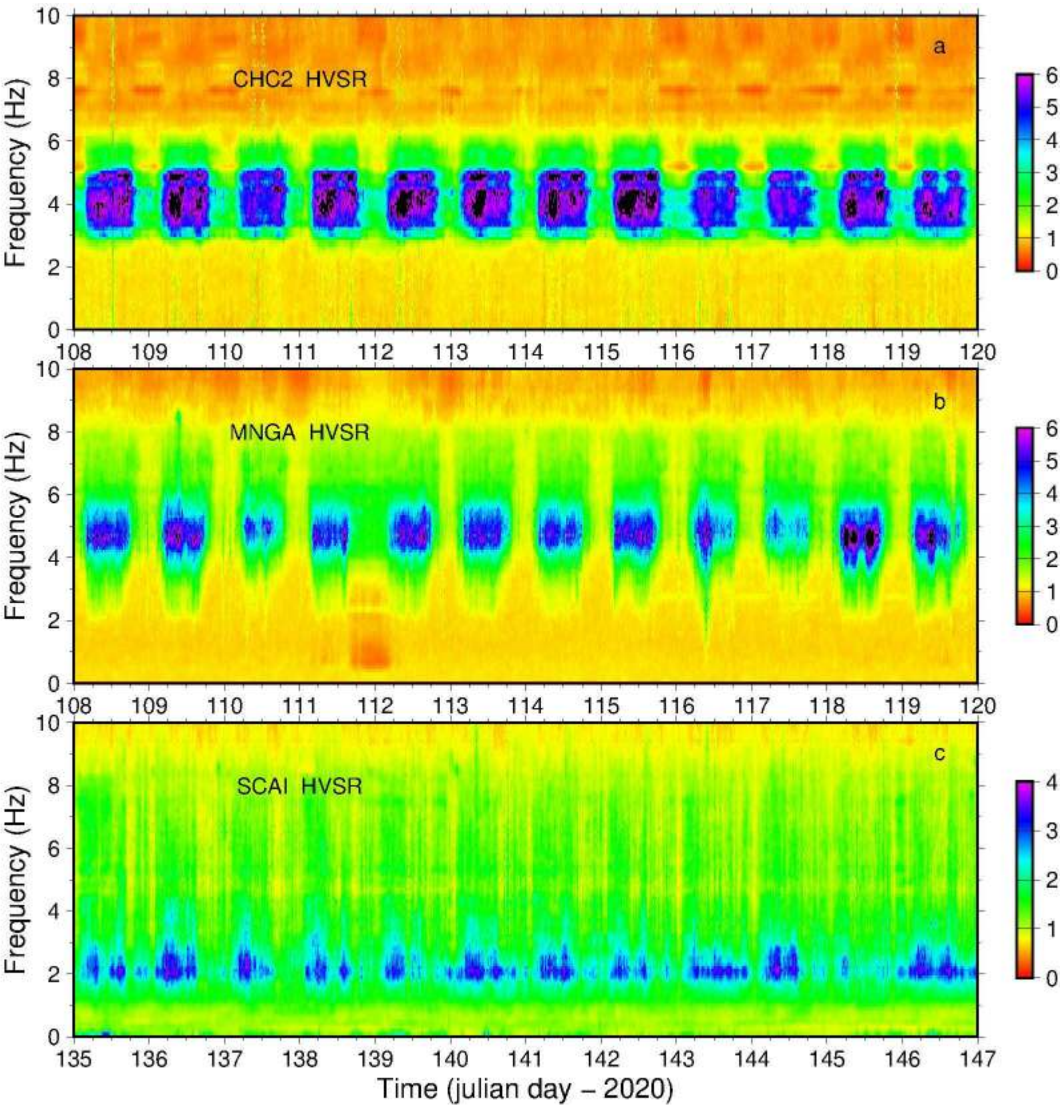

Fig. 1 - HVSR versus time and frequency at the three sites CHC2, MNGA, SCAI, for 12 days of data. A strong strong day-night variation of the peak amplitude characterizes these sites.

follow the variations of the HVSR peak amplitude versus time. For a better characterization of the wavefield properties the polarization analysis was performed on continuous signals filtered in a narrow frequency band centered at the HVSR peak frequency. This analysis was performed on 300 s sliding windows applying the covariance matrix method in time domain, obtaining the rectilinearity of particle motion, the polarization azimuth and the polarization incidence angle. Figure 2 shows, from top to bottom, RMS, rectilinearity, incidence (beta), polarization azimuth and H/V for 10 days of seismic signals recorded at the seismic station SCAI. Among these five parameters, only the polarization azimuth is quite stable, taking values in a narrow range around 200 degrees for most of the time, without any appreciable variations between day and night hours. The other four parameters are characterized by variations in time, with the highest values during day hours, and similar results have been found for other investigated sites. These features of the seismic noise are very interesting and require more in depth observations. Therefore we selected the results of HVSR analysis (versus frequency) for a specific hour of the day (11 am) and of the night (01 am) for tens of days to obtain two average HVSR curves representative of day and night hours respectively. The results of this selection are shown in Figure 3, top plots, for the same three sites shown in Figure 1.

The HVSR analysis was applied also to local earthquakes, selected for each station based on epicentral distance (<100 km), hypocentral depth (<40km), magnitude (>3), signal-to-noise ratio and backazimuth in order to have a distribution of sources as much uniform as possible. This analysis was performed on windows of few tens of seconds length, including the earthquake signal from the direct P wave to the middle coda waves. Thus we are sure that body wave contribution to the result is much greater than background seismic noise and than surface waves. Results of this analysis are shown in Figure 3, bottom plots, for three of the studied sites.

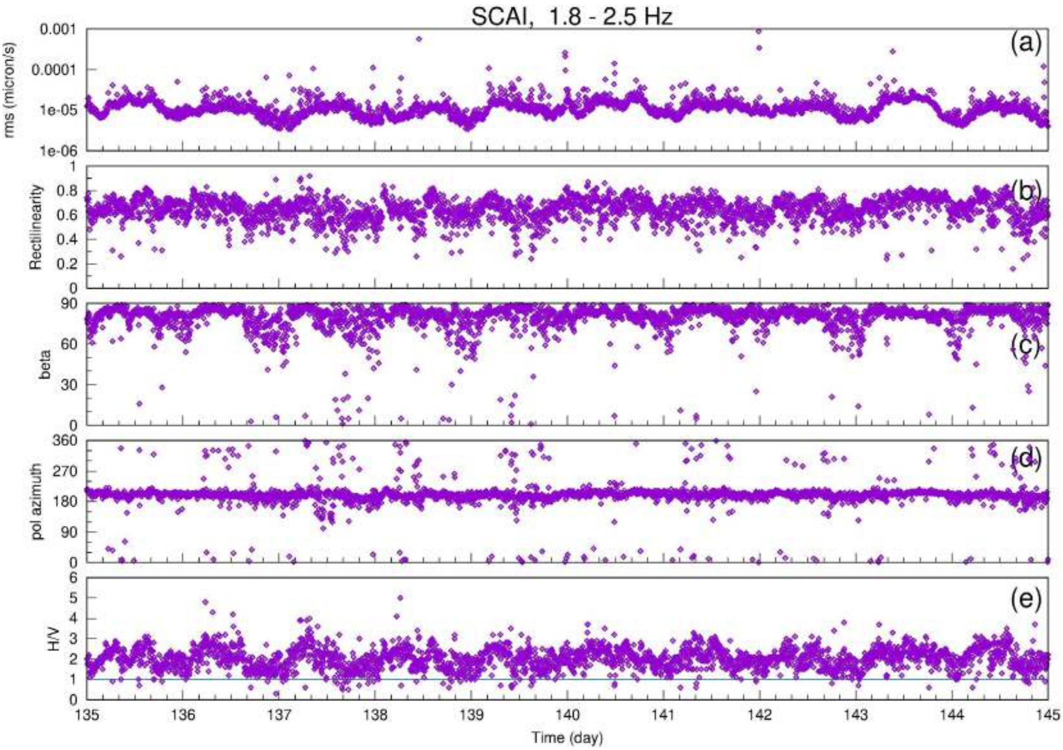

Fig. 2 - Results of amplitude and polarization analysis for 10 days of seismic signal recorded at SCAI site.

The three sites described in this paper, CHC2 (lat=38.6817, lon=16.4106), MNGA (lat=38.5174, lon=16.3222) and SCAI (lat=38.5343, lon=16.5177), are different among them with regards to the local geology, topographic features, and the resonance frequency of the HVSR peak. HVSR curve of CHC2 site is characterized by a well-defined peak at 4.0 Hz with average amplitude of 6 during the day that decreases to about 3 during night hours (Figs. 1a and 3a). All earthquakes analyzed at this site show a clear resonance peak at the same frequency but sharper and higher (always >7) than that observed for noise recordings (Fig. 3d). Similar results have been obtained at MNGA site. This site is characterized by a well-defined resonance peak at a frequency of 4.8 Hz reaching an amplitude greater than 5 during diurnal hours, but almost unidentifiable during the night (Figs. 1b and 3b). This is one of the most interesting results of our study. HVSR computed on local earthquakes shows a well defined peak at the same frequency and with a similar amplitude compared with that computed on diurnal recordings of seismic noise (Fig. 3e). Finally, results for SCAI site slightly differ from the previous two. In fact, here HVSR curves are characterized by values greater than 1 in a large frequency band with a broad peak at about 2.1±0.3 Hz reaching an amplitude of 3 during day hours and 2 during the night (Figs. 1c, 2e and 3c). Although the cyclic variation in the spectral ratio is not so remarkable as seen for MNGA and CHC2, we consider this result worth of attention because very stable in all time periods analyzed (many months of continuous signals). The results of amplitude and polarization analysis for 10 days of signals at this site are shown in Figure 2. The higher values of rectilinearity (plot b) are observed during day hours, in correspondence of higher RMS (plot a) and higher H/V (plot e). These features of the ground motion suggest a greater amount of body waves in the background noise during daily hours. About the analysis of earthquakes at this site, we see HVSR curves with main peak and average values very similar to those obtained from the analysis of diurnal seismic noise (Fig. 3f).

Discussion and Conclusions

For the selected sites we observe clear variations in HVSR curves well correlated with the day-night cycle. This is particularly evident for MNGA and SCAI sites, where the amplitude of the main HVSR peak is often smaller than 2 during night hours (Fig. 3b and 3c). This means that at these sites the estimation of site effects based on the HVSR analysis applied to a short recording of night hours seismic noise could lead to a misleading result and wrong conclusion. Our results suggest that those variations depend on the contribution of body waves on wavefield composition. This hypothesis is supported by the higher rectilinearity of the seismic noise observed during day

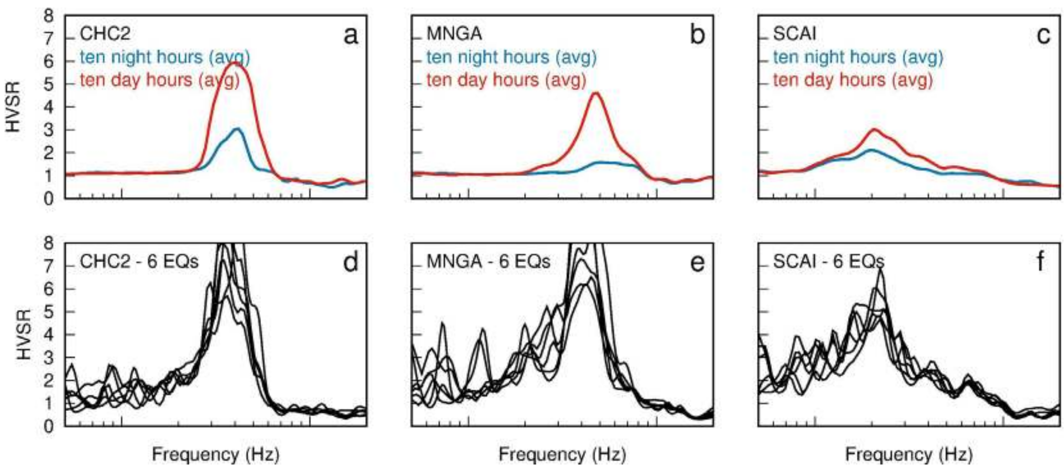

Fig. 3 - Day and night HVSR (top plots) and earthquake HVSRs for three sites.

hours compared with night hours. Higher rectilinearity of the particle motion corresponds to a greater amount of body waves, and perhaps Love waves, than Rayleigh waves. The HVSR of local earthquakes further support our assumption since in these signals the amount of body waves is far greater than surface waves, and HVSR results are very similar to the results obtained for day hour seismic noise. In many cases we found surprising results (CHC2, MNGA as described above) that need a deep investigation. For many years HVSR has been considered a stable feature of a given site. On the other hand, remarkable variations in HVSR shape or just in the peak amplitude have been observed and attributed to various factors, as topographic roughness and geological complexities (Burjanek *et al*., 2014; Napolitano *et al*., 2018; La Rocca *et al*., 2020) or even changes in groundwater level (Rigo *et al*., 2021). A large number of site effects studies are based on the assumption that the HVSR method is "fast and cheap" since half an hour of seismic noise recording is sufficient to get stable and reliable results. Our results demonstrate that in some cases the results of HVSR analysis computed on a short recording of ground motion can not be representative of the site features, and can lead to misleading interpretation of site effects.

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