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THE HVSR TECHNIQUE FROM MICROTREMOR TO STRONG MOTION: EMPIRICAL AND STATISTICAL CONSIDERATIONS

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SUMMARY

The Horizontal to Vertical Spectral Ratio technique is a widespread tool for the study of ground motion amplification. It applies to a wide range of ground motion amplitude, from microtremor to strong motion. Sometimes it becomes a mandatory choice, when there is no available outcrop for the Reference Site technique and a borehole is unfeasible. There has been a wide debate on the theoretical limitations of the methodology, especially when applied to microtremors. On the other hand, very few studies have been devoted to the experimental validation of the hypothesis underlying the different theoretical models. In addition, the basic rules of practice for noise recording and processing claimed for little attention.
This paper presents the results of three studies that aim jointly to the comprehension of the possibility and limitation of the HVSR technique. The first study is relevant to the analysis of the recordings provided by a seismic network purposely installed for site amplification studies. The four stations involved are located in the Southern Apennines, Italy. Two stations are on soft sediments, one on bedrock and one above a strong velocity inversion. In the past four years, these stations provided hundreds of earthquake recordings (down from a maximum acceleration of 1%g) as well as thousand of triggered noise records. These last records are mainly man-made noise exceeding the STA/LTA setting of the seismometers. They provide a large database (>2000 events) for comparing HVSRs obtained from low amplitude, stationary noise with non-stationary noise, weak motions and strong motion. The main result is that non-stationary noise gives the same HVSR with respect to weak motion, with the notable exception of the velocity inversion where microtremor show a band of de-amplification. The second study aims to the experimental validation of two main assumptions of the Nakamura technique: the equivalence of vertical and horizontal components at the bedrock and the Rayleigh wave's nature of the microtremor wave field. Finally, the third study investigates the probability of occurrence of sharp peaks in the microtremor HVSR at randomly selected sites. We analyzed a database of more than 500 HVSRs, each from a different site, all obtained with the same instrumentation and processing. Then, we compare this distribution of HVSR peaks occurrence with data coming from post-earthquake field survey, when damage drives the interest. The result highlights the difference of the two statistical distributions, calling the attention on the actual probability of occurrence of high HVSR peak.

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INTRODUCTION

In the last 10 years, the HVSR technique has gained a large popularity as a low cost tool to estimate site amplification of seismic ground motion both when applied to ambient noise [1, 2] and weak motion recordings [3]. A large amount of site amplification studies is described in the gray literature and recently this technique has been used for different purposes, like studies of sedimentary basins, faults, cavities and finally to estimate the fundamental frequency of buildings. There is seemingly a wide consensus on the possibilities offered by HVSR, however no clear theoretical background is yet established, and the literature offers contradictory views about several key points of the method. A recent review of the methods and its application is given in [4; 5]. Our group is mainly interested in the reliability [6] and repeatability of HVSR measurements [7]. This paper tries to provide some answers to three main questions regarding the HVSR technique: 1) Is the HVSR obtained with stationary and non-stationary noise comparable with the one relevant to earthquake recordings? 2) The two main theoretical assumptions on the noise HVSR technique are that at the bedrock, the horizontal and vertical component must have equal amplitude spectra and that ambient noise is mainly composed by Rayleigh waves. Are those two assumptions verified and necessary for the method? 3) Which is the probability of observing high HVSR values by chance?

HVSR FROM NOISE AND EARTHQUAKES

We started in 1999 a long-term experiment to study HVSR stability problem and the effect of other variables (such as signal amplitude, time, rainfall) installing a network of 3D digital seismometers in the Basilicata Region, Italy. The four stations are: TIT, located at the surface of a lacustrine valley in the Lucanian Apennines, with 30 m of soft sediments overlying the bedrock. VDA, located in the seismic area of the Val D'Agri, with 15 m of debris and alluvium above limestone. VEN, with 5 meters of landfill imposed over 15 m of well-cemented conglomerates, then a velocity inversion leading to about 300 m of clays overlying the bedrock. MAT, located directly on the Tertiary limestone of the Apulian platform. We purposely installed the instruments in noisy areas (except MAT), so that we can have several noise events triggered at the same threshold used for detecting weak motion earthquakes (triggered noise). The reason for this choice is that most authors tend to exclude from their measurements the non-stationary noise, thus considering only the low amplitude part of noise (see [8] for a recent example). On the contrary, [6] showed that the use of non-stationary, high amplitude noise improves the capability of microtremors HVSR to mimic the response obtained with weak motion recordings of earthquakes. All the analyzed data were recorded with a 24 bit PRAXS A/D converter attached to a tri-directional 1 Hz seismometer (Mark L4C for TIT, Lennartz 3d Lite for the other stations). Sampling ratio was 125 Hz. We used the full-length records that were de-trended, baseline corrected, tapered and band pass filtered between 0.1 and 25 Hz. Then we performed FFT on 15 log-equispaced bands per decade, applying the processing methodology proposed by Castro et al. (1990), and finally calculated HVSR. As a comparison, we perform also a standard 10 min. noise measurement with a compact digital seismometer (we cannot provide further details because it is a patent pending prototype we had from the manufacturer to beta-test it). For MAT we analyzed 300 earthquakes and 400 triggered noise signals, for TIT 132 and 674, for VDA 150 and 170, for VEN 26 and 15. Fig. 1 shows the results. There is a good agreement between the different sets of data for each station. Some notable patterns are: 1) it is not true that ambient noise always underestimates the amplitudes; 2) triggered noise is very close to earthquakes HVSR, except that for VEN. This lend support to the idea that the stronger the noise, the best is the fit with earthquakes. VEN is the only site with a velocity inversion, suggestion that complex geology controls the misfit more than the nature of the wave field.

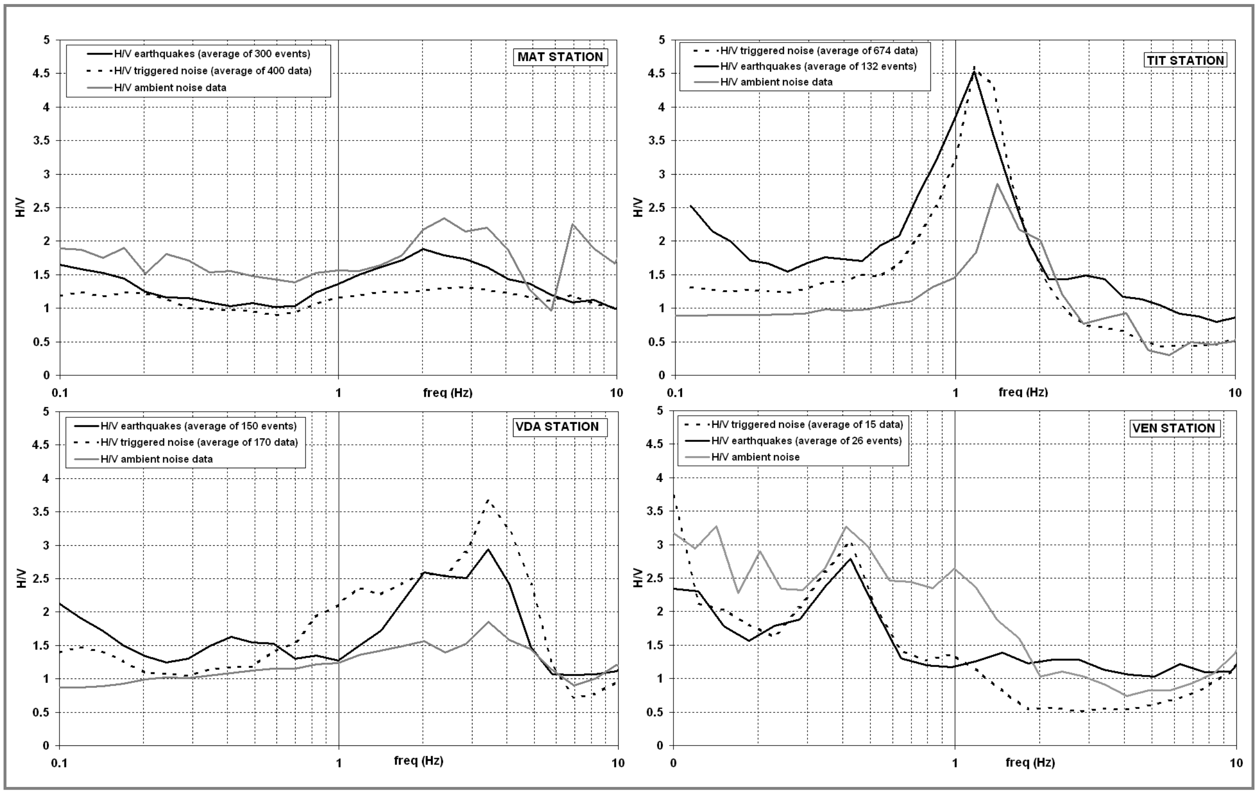

Fig. 1. H/V by earthquakes, triggered noise and microtremors obtained for the four stations.

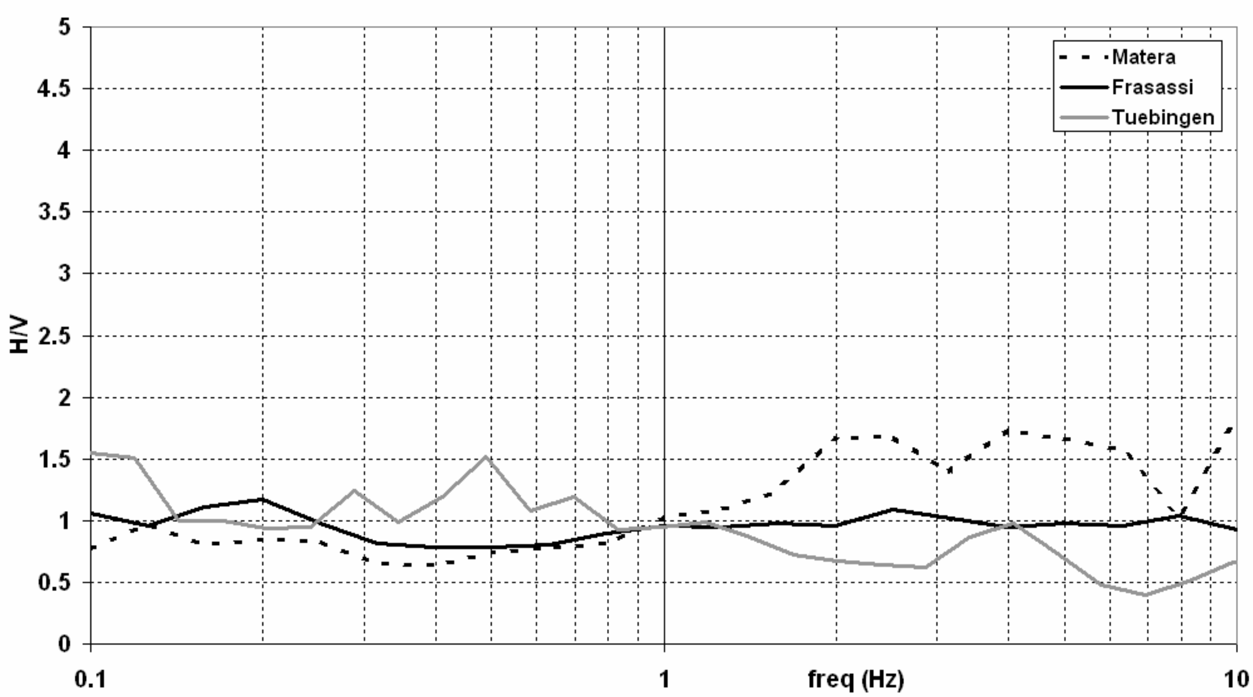

Fig. 2. H/V by noise at bedrock: Frasassi, Italy (cave at 1000 m depth); Tuebingen, Germany (borehole at 100 m below the surface); Matera, Italy (cave at 10 m depth).

VALIDATION OF THEORETICAL ASSUMPTIONS

Noise at bedrock

The fundamental assumption of HVSR is that at the bedrock the amplitude of vertical and horizontal component is equal. To test this hypothesis we used recordings in cavities at different depth below the surface. We performed two noise measurements on limestone: in the deep Frasassi cave, Italy and in a shallow cave in Matera, Italy, with a depth of the order of 1000 and 10 meters respectively. We then took advantage of the availability over the Internet of the continuous recording of a borehole seismometer at Lennartz factory in Tübingen, Germany. This last instrument is located 100 m below the surface.

Fig. 2 shows the results of the HVSR for cavities measurements: increasing the depth, the HVSR tends to reach unity. Fracturing and weathering at 10 meters depth is enough to obtain a non-flat HVSR. It seems that for a thick layer, the assumption of equivalence of components at the base is reasonable.

About Rayleigh waves

Many authors have lent a theoretical support to the hypothesis that seismic noise is mainly made of Rayleigh waves [9, 10]. Following this approach, recent works provided a framework for deriving Vs profiles from noise measurements [11, 12]. However, there are also papers maintaining that HVSR works on body waves [2, 11]. To find empirical evidence, we used what is acknowledged as the best source available for locally generated, short period Rayleigh waves: a SASW test.

We acquired tri-directional velocigrams during a SASW test, and checked with polarization analysis that the impact of a 2-tons concrete cube produced a Rayleigh wave's main pulse. We then processed the data using Horizontal-to-Vertical Mowing Window Ratio (HVMWR). Fig. 3 shows the result. It is possible to see that during the main pulse there is a strong HVSR peak characterized by a deep through at higher frequency: this is the mark of the behavior due to the ellipticity of Rayleigh waves. However, it is worth noting that the coda of the main pulse (likely due to reflected and refracted body waves) as well as the pre-trigger noise shows a different fundamental frequency and no de-amplification at higher frequencies.

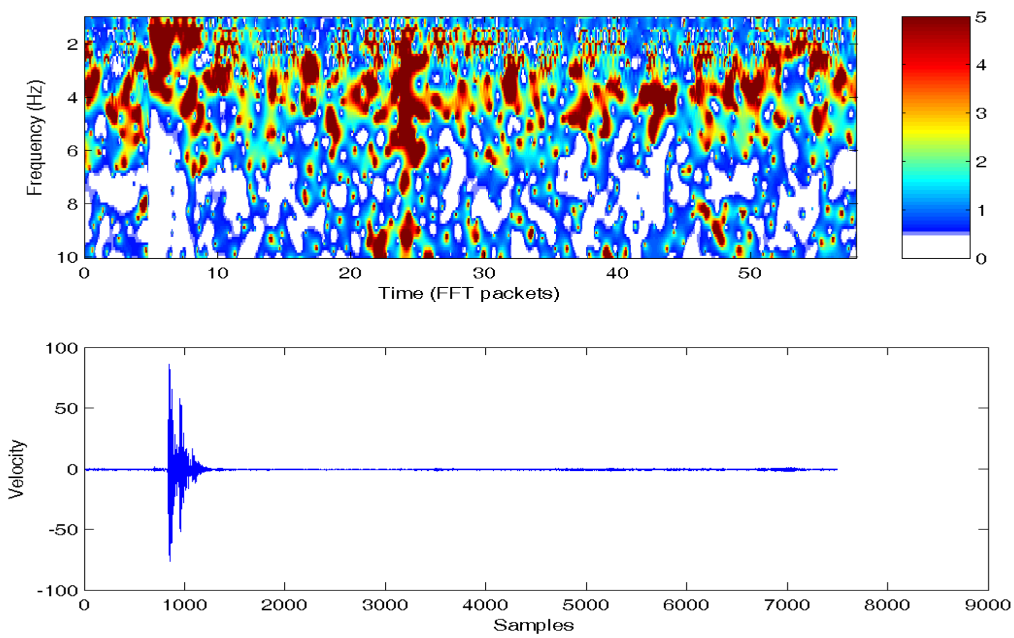

Fig. 3. Moving window HVSR during a SASW test. The main pulse, composed by Rayleigh waves, shows a strong de-amplification at frequencies higher than the fundamental mode.

This suggests that noise is actually made of an unpredictable brew of different wave fields, and not by Rayleigh waves alone. The suggestion that higher modes of Rayleigh waves could mask by summation the expected de-amplification faces two problems: 1) in a real medium with anisotropy and attenuation, it is unlikely that the participation to higher Rayleigh modes is larger than the one to the fundamental body-wave mode. 2) HVSR from noise has the same frequency of HVSR from earthquakes S-waves (see Fig. 1) and, if the noise is strong enough, also the same amplitude.

A zero-level model

We suspect that when dealing with noise, data sampling and processing artifacts could be deceiving. Before testing the fit between data and proposed theoretical models, one should check the absence of such artifacts. We implemented what we call a zero-level model, since it has no direct reference to seismic noise and no assumptions about the nature of the wave field. It is more an exercise of signal processing. Fig. 4 shows the Matlab Simulink block model that we used. It has composed by three parts: the bedrock, the soil and the surface. Two time-series of uncorrelated Gaussian white noise, composed by signals with the same amplitude (this assumption is justified by our analysis on noise in cavities), represents the input signal. A filter simulating a spring-mass-damper device processes this input. In particular only the “horizontal” component interacts with the system while the “vertical” one is unaffected by filtering. At the “surface”, we add a variable amount of random noise before calculating the spectral ratio between the two components.

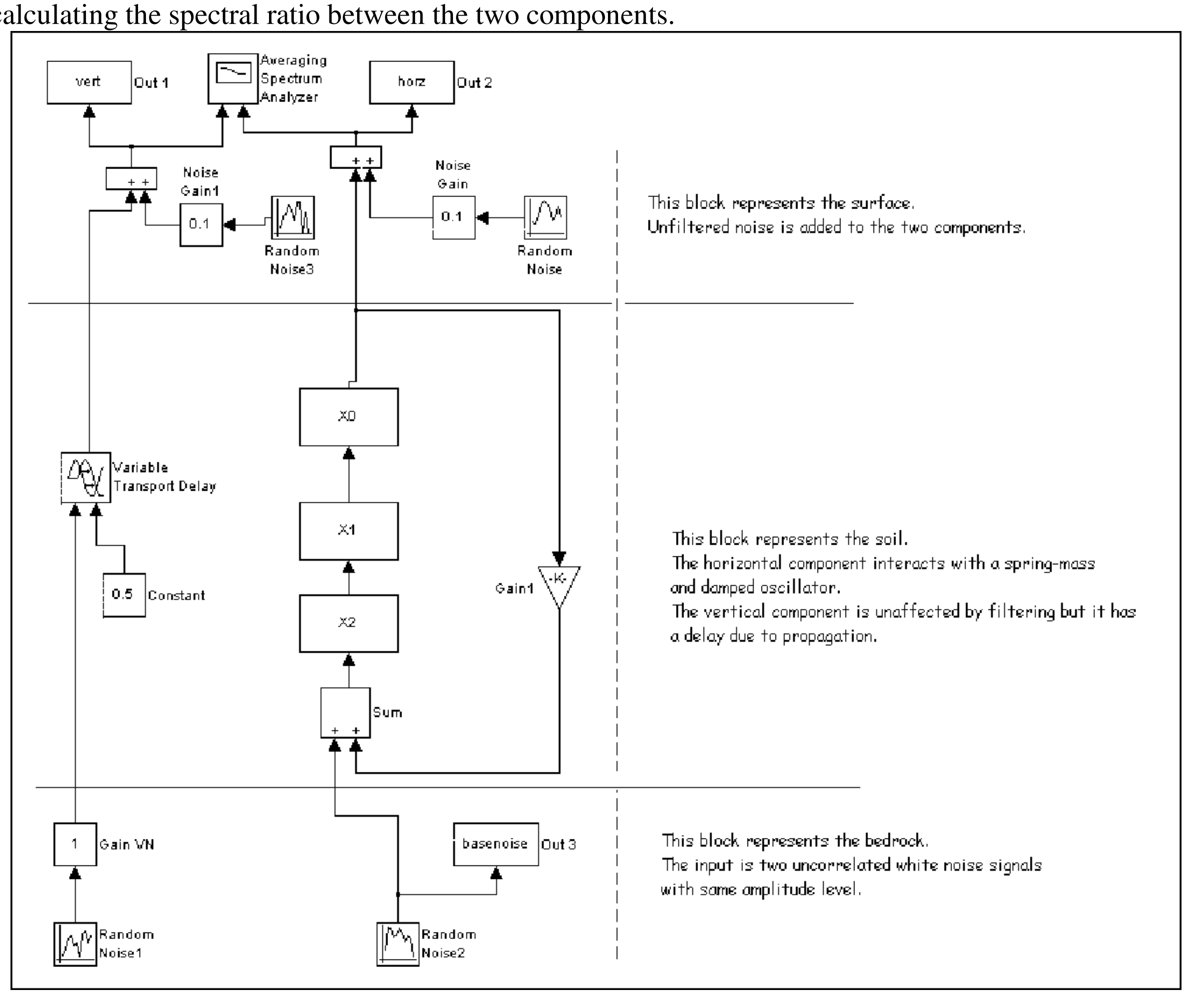

Fig. 4 Matlab Simulink block model: uncorrelated Gaussian white noise is processed by a filter simulating a spring-mass-damper device.

Fig. 5 shows how this elementary model is able to reproduce two features of seismic noise HVSR [6]: 1) When the input noise level decreases, the filter properties (frequency, amplitude) are less resolved. 2) When the unfiltered noise (e.g., wind at the surface) increases, the departure from the expected model also increases, with a remarkable over-estimation in the low frequency range.

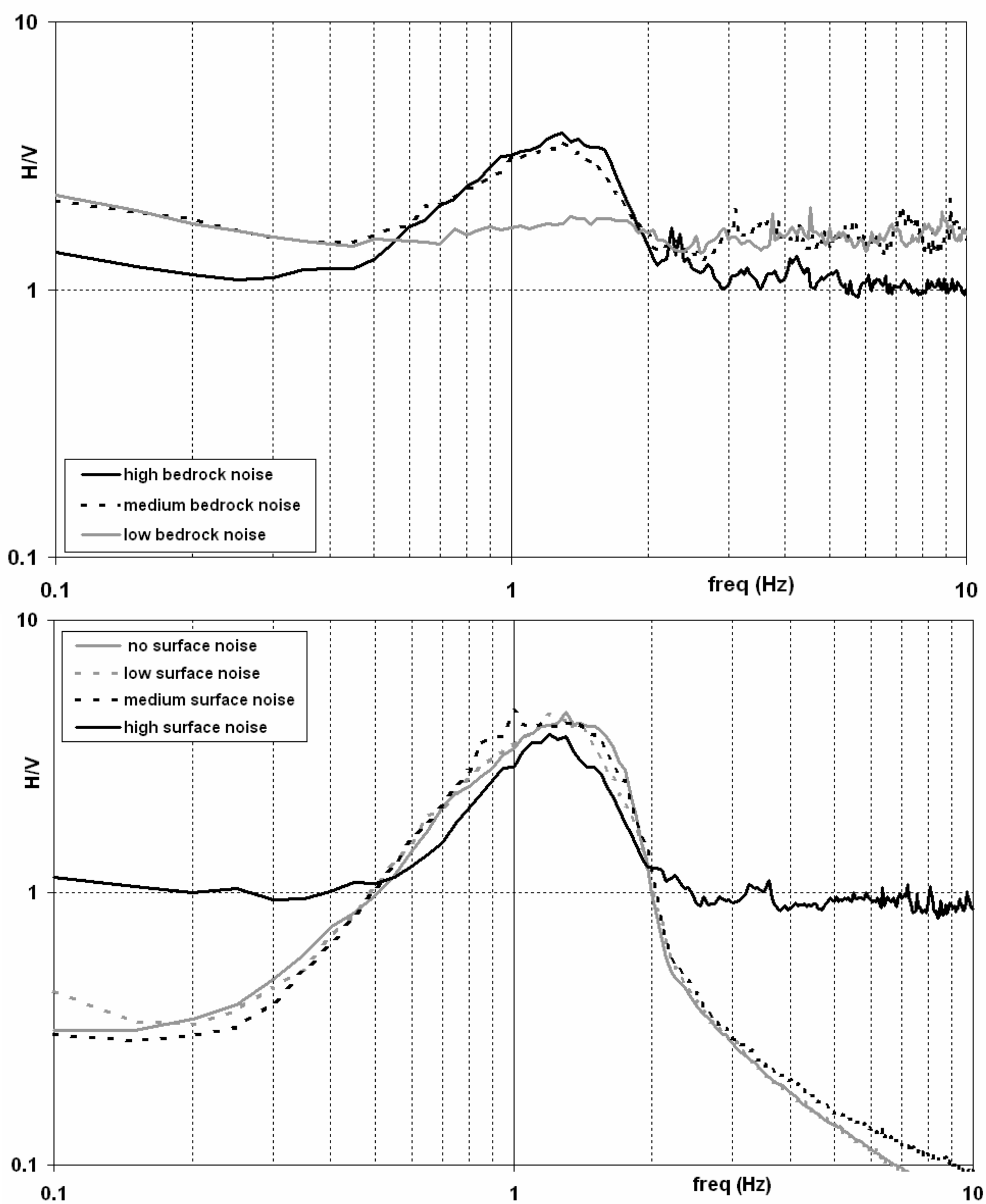

Fig. 5 (top) effect due to the input noise level; (bottom) effect on HVSR when the unfiltered noise at the surface (e.g., wind) increases.

STATISTICS ON HVSR MEASUREMENTS AT VARIOUS SITES

During the past 7 years, our group conducted two kinds of HVSR campaigns: microzonation studies and post earthquake surveys. The aim was different: in the first case, we sampled all the municipalities or sites within the study area without *a priori* selection; in the second case, we performed measurements aimed at investigating possible resonance phenomena between the fundamental frequency of the soil and the one of damaged buildings. Thus in this second case we performed a selection driven by the observed damage. The existence of hidden selection criteria in a sample may introduce unwanted bias in the outcome (see Ref. [12] for a description of the consequence of pre-selection in seismological studies). We performed all the measurement using the same instrumentation and processing technique. Now we have a database of 540 HVRS measurements, and compared three samples: 407 measurements from microzonation studies in different Italian regions, 79 from post-earthquake surveys [13,14,15,16] and 54 from our latest post-earthquake survey [17]. In this last case, we performed measurements not only at the most damaged sites, but also more uniformly in the investigated area. The variable we have considered for our statistics is the higher HVSR value in the frequency range 0.5-10 Hz, which is the frequency range of interest for most of the buildings. It is clear (Fig. 6) that the data from microzonation studies and post-quake survey have similar distributions but very different parameterization. This difference is due to the selection criteria used in post-quake surveys. This means that even if microtremors HVSR do not have amplitude exactly matching amplification from other techniques, there is a monotonic correlation between HVSR and damage. Another observation derived from Fig. 6 is about the probability of observing high HVSR values at randomly sampled sites. The sampled data from microzonation studies has a lower probability than the one resulting from post-quake studies. This means that there are few sites with strong local amplification, and they are those that claim for attention when the damage is driving our researches. The distribution observed after the Molise 2002 event [17] shows that a study conducted after an earthquake yield the same distribution of earthquake-independent studies, provided that the sampled location are not pre-selected but the whole area is investigated.

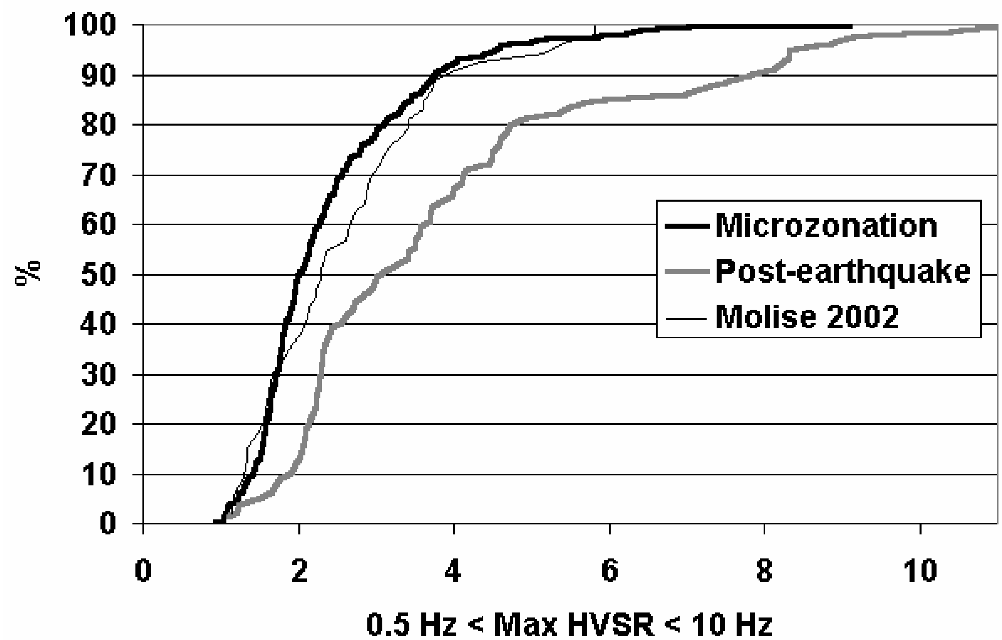

Fig. 6. Comparison between the CDFs of different sets of HVSR, as a function of the largest value observed in the frequency range 0.5-10 Hz.

CONCLUSIONS

This work aimed to provide some empirical and statistical considerations on the HVSR from noise ad earthquakes. We believe that a satisfactory theory explaining HVSR results should span from ambient noise to strong ground motion passing through high intensity noise and weak motion. For instance, it is difficult to reconcile the view of noise as composed only by Rayleigh waves with the results reported in [18] that shows how the presence of surface waves in strong-motion recordings flattens the HVSR by S-waves. We perform several experiments to investigate empirical aspect of the HVSR technique providing constraint and verification of assumption for theoretical models. The results are summarized in the following.

Analyzing 608 earthquakes time histories (up to 0.1g) and 1280 triggered noise signals recorded at four different stations, we obtained very similar HVSRs from the two data sets. The major differences are at the station VEN and MAT. VEN has a complex geological setting with a velocity inversion. MAT is the only station we did not install in a noisy urban environment, thus lending support to the hypothesis that higher noise amplitudes provide a better agreement with earthquakes HVSR.

Noise recordings in cavities provide direct evidence that at depth vertical and horizontal components of seismic noise do have equal spectral amplitude. When increasing the depth, the HVSR better approaches a flat, unity response.

HVMWR analysis of SASW data highlights that the shape and amplitude of Rayleigh waves HVSR substantially differs from the one of later phases and pre-trigger noise. In particular, only Rayleigh phases show a de-amplification at frequency higher than the fundamental one.

A very simple model based on signal processing considerations, show that no a priori hypothesis on the nature of the wave field are required to reproduce some characteristics of real HVSR. The good or bad estimates of the expected response, the increase of low frequency HVSR and the presence or not of de-amplification are due to the amplitude of input noise and to the ratio between the amplitude of noise filtered by the structure and external noise.

Finally, we compared the distribution of the highest HVSR between 0.5 and 10 Hz observed in two separate data sets of measurements. We compared the measurements for microzonation purposes with those performed during post-earthquake surveys. The first ones are located on the territory without any *a priori* choice, while the second ones were performed where most damage occurred. Both empirical CDFs are well fitted by a log-normal distribution, but the parameters are significantly different (K-S test reject equality at 99.99% confidence level). This suggests that: 1) HVSR correlates monotonically with damage and 2) damage-driven survey may suggest a spatial rate of occurrence of site amplification higher than the real one.

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