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A critical review of 10 years of microtremor HVSR technique

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Abstract - In the last 10 years, Nakamura's technique (HVSR) has gained a widespread popularity as a low cost tool to estimate site amplification of seismic ground motion: a large amount of site amplification studies is described in the grey literature. 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. This paper provides a review of its theoretical background, as well as a description of its applications: there is, seemingly, a wide consensus on the possibilities offered by HVSR, however, no clear theoretical background has yet been established, and the literature offers contradictory views about several key points of the method.

1. Introduction

"Nakamura's technique is able to predict the resonance frequency of soils but fails to correctly estimate the amplification of ground motion". This sentence is reported in many publications and appears to be the general consensus about the possibility of this technique. However, a more close scrutiny reveals quite a different reality. The foundations of the method itself are not so clear to everyone, if the same author of the starting work (Nakamura, 1989) comes back ten years later (Nakamura, 2000) with a paper entitled "Clear identification of fundamental idea of Nakamura's technique and its applications". It could be interesting for future science historians, as well as for those who dictate the values of citations or impact factors, to study the case of this technique: one of the most cited papers in seismology in the past 10 years appeared in Japanese on a poorly known corporate bulletin. Most of the papers

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referring to the first work of Nakamura are simply interested in its practical application for microzoning purposes; the theoretical background, as well as the limitations of the method are of no interest to the authors and are taken up by the few, well-known papers dealing with these topics. The problems that will be discussed in the following can be briefly summarised:

- there is no general agreement about a standard for data collection and processing. Most papers do not even mention which equipment was used;
- there are multiple views about which seismic phases we are dealing with and interested in, nevertheless we can obtain a satisfactory estimate of elastic soil behaviour in the presence of direct S waves;
- there is very poor statistical treatment of data. The first test proposed to discriminate spurious peaks in microtremor HVSR is in press just at the date of the preparation of this review;
- the method gives very stable results in time. Even if not yet completely modelled, HVSR is related to a permanent feature of the investigated sites;
- the method seems to work better (especially in amplitude) when applied to buildings, where the original hypotheses on the theory behind it do not apply, and gives interesting results when applied as a prospecting technique.

2. The method

"Take whatever instrument you think is able to measure very weak ground motion, let it work on the site of your choice for the time you want, at the sample rate you prefer. Whatever A/D converter is fine. Aim for stationarity during quiet periods at night-time or, if you prefer, record heavy road traffic. Taper or not, filter or not, base-line correct or not, then perform an FFT, or some other time-domain/frequency domain transform on separate components, then add averaging to your taste. Before or after this last operation take the ratio of horizontal to vertical spectra, select the average of all ratios (or the average plus the standard deviation) et voilà, site amplification is ready". This is the vague recipe of the HVSR method most people are applying. The problem is that we do not have a better one or a general agreement about a standard for data collection and processing. When we speak about comparing the HVSR technique with other methodologies or with models we are facing this problem: there is no *one* HVSR technique but several variations of it.

3. Applications

Everybody should agree on one point: the aim of our effort is to estimate the amplification of ground motion over as broad a frequency range as possible, for the elastic (low-deformation) soil behaviour. Here is the first question that needs to be addressed: is the amplification intended with respect to a rock outcrop or to the underlying bedrock? Neglecting the free-surface effect can lead to an underestimation of a factor two in amplitude. Second question: Are we interested in the amplification of all phases or just in the most destructive ones, like direct SH arrivals?

Nakamura (1989, 2000) claims that we are measuring and interested in S-waves only. This position is in agreement with Zhao et al. (2000). Parolai et al. (2000) propose a model based on the summation of different phases of body waves. Most papers, and the most famous among them (Field and Jacob, 1993, 1995; Lachet and Bard, 1994) model HVSR using Rayleigh surface waves. Arai and Tokimatsu (2000) also include Love waves in their model. On the other hand, for weak motion recordings Castro et al. (1997) showed that when surface waves are present, HVSR is not able to reproduce the results obtained using other techniques like the Generalised Inversion (GIT). Again the presence of Rayleigh waves and subsequent vertical amplification was attributed to the discrepancy between HVSR and other methods observed, by Raptakis et al. (1998, 2000) analysing the wealth of data produced by the EUROSEISTEST experiment. For the Garner Valley Array, Volant et al. (1998) showed that HVSR is related to upgoing S-waves and not to Rayleigh ones. Lermo and Chávez-García (1993) evaluated site effects using HVSR with S-waves, and Lermo and Chávez-García (1994) studied the applicability of microtremor measurements to evaluate site response in three cities of Mexico (Mexico City, Oaxaca and Acapulco) interpreting Fourier amplitude spectra, spectral ratio relative to a firm reference station and, finally, HVSR of Nakamura's technique. Dravinski et al. (1996) use Nakamura's spectral ratio, evaluated from the steady-state surface response for different incident waves, and sediment-to-bedrock spectral ratio (Kagami's ratio) to investigate deep sedimentary basins. Rovelli et al. (1991) compare the soft-to-hard site microtremor spectral ratios with the corresponding acceleration spectral ratios and Ogawa et al. (1998) estimate peak horizontal ground velocity based on microtremors. Seekins et al. (1996) compare microtremor data to weak-motion S-wave and coda recordings at sites in San Francisco in order to clarify the range of applicability of microtremor data to ground-motion prediction. Zaré et al. (1998) characterised 26 Iranian sites with different techniques. Malagnini et al. (1996) collected explosion, earthquake and ambient noise recordings to infer seismic response properties by reference and non-reference techniques in a sediment-filled valley. Chávez-García et al. (1996) applied this technique not only to the 1-D model it is intended for, but also to the study of amplification due to topographic effect. Tokeshi and Sugimura (1998) compared Fourier phase spectral, the HVSR technique and the 2D horizontal Fourier spectral analysis with the 1D fundamental resonance frequency of SH waves. The most extensive comparison among HVSR and other methods is given by Satoh et al. (2001). In conclusion, the evidence seems to point out that we are not sure which kind of waves we are using in the HVSR technique, nevertheless we can obtain a satisfactory estimate of elastic soil behaviour in presence of direct S-waves.

4. Field measurements

Then let us move on to the practical point of field measurements. The same concept of measuring what is called ambient noise is upsetting. Quoting from Mucciarelli (1998) "When using Nakamura's technique one should bear in mind that the data he is collecting is actually disregarded as an annoyance by fellow seismologists. Thus, it is difficult to understand how and when a "good" noise sample has been collected. It is clear that the equipment used has a paramount importance, since one must be sure that no spurious noises are added (electronic noise, motion induced by wiring between equipment parts, noise that is not coupled with the ground like wind on the sensors)". The same paper reviewed some case studies, giving contradictory results about HVSR and, after some controlled condition experiments, came to the conclusion that: "The use of accelerometers should be avoided, since they could not have enough resolution power to resolve noise on a broad frequency band in all the components. Seismometers should be used instead, coupled with a high gain acquisition system and avoiding long external wiring to prevent mechanical and electronic noise; when in the field, one has to be careful about weather conditions and, in particular, avoid wind gusts; a temporary rigid shelter should be used wherever possible. Ground floors or basements of buildings can provide good measurement points since they can protect instrumentation from the weather and are well-coupled with the ground. However, the soil-structure interaction should be accounted for and measurements should be taken at the upper floors also, in order to identify frequencies induced by buildings' vibration; search for undisturbed ground conditions and try to obtain the best possible coupling between sensors and soil. Avoid coverings and, in particular, asphalt; while reinforced concrete gives only a small attenuation leaving the frequency pattern unchanged, the presence of asphalt may induce spurious peak of noticeable amplitude. Traffic is not a problem; the absolute value and frequency of the amplification peaks remain substantially unchanged. Moreover, higher energies in the ground could help to better resolve the behaviour at low frequencies; below 1 Hz… it has been observed that the addition of noise with, for example, a seismic sledgehammer, increases the amplitude of the peaks leaving the frequency pattern unaltered… no changes are observed due to daytime/night-time variation of the microtremors". The problem of sufficient energy and wave penetration as a key point for good HVSR results is also claimed by Volant et al. (1998) for the Garner Valley Vertical Array data.

5. Stability of the method

A striking feature of the HVSR method is its stability: the same result is obtained if one repeats measurements for a week (Volant et al., 1998), after a month (Mucciarelli and Monachesi, 1998) or after a year (Bour et al., 1998). As Gallipoli et al. (2000a) pointed out, HVSR converge to weak motion amplification in average, and the interpretation of the results has to be carried out in a statistical sense: comparing a single event with microtremors may lead to unsatisfactory results. The most recent evidence in this sense is given by Trifunac and Todorovska (2000) for the 1994, Northridge event. There are, however, papers claiming a satisfactory comparison between the damage of a single earthquake and HVSR measurements, like Gueguen et al. (1998) for the 1996 Ecuador event. Other comparisons for a single event were made by Lachet et al. (1998) for the 1995, Kobe earthquake, by Kameda et al. (1991) for the Loma Prieta earthquake, by Finn et al. (1994) for the 1994 Northridge earthquake, by Ohmachi and Nakamura (1992) for the 1990 Philippine earthquake, by Suzuki et al. (1995) for the Kushiro-Oki earthquake.

One of the main problems related to the HVSR method is the statistical reliability of measurements: a way of identifying spurious, non-significative peaks in the amplification function has only recently been proposed: Albarello (2001) first suggests a simple *T*-test between the peak values and the average, then a more complex, frequency-dependent test based on a binomial distribution. Stojkovic (1998) presented some methodological aspects of investigation of stationary characteristics of microtremors depending on their random stationary characteristics and stochastic nature.

6. Seismic zonation case histories

Notwithstanding the above-mentioned uncertainties, HVSR has been used alone or combined with other methods for the seismic zonation of a large number of cities and urban areas. In most of these studies the authors are generally happy with the similarity among HVSR results and the one obtained with other techniques like weak-motion measurements or numerical simulations. We report a selection from the available literature: Navarro et al. (1998) microzonation of Almerìa City (Southern Spain); Goula et al. (1998) microzonation of Barcellona (Spain); Duval et al. (1998) microzonation of Caracas; Ramìrez-Centeno and Martin del Campo (1998) microzonation of Guadalajara, Mexico; Midorikawa (1998) microzonation of Odawara City, Japan; Romdhane et al. (1998) microzonation of Tunis; Chavez-Garcia and Cuenca (1998) microzonation of Acapulco; Lachet et al. (1996) microzonation of Thessaloniki (Greece); Chávez-García et al. (1995) microzonation of Puebla City, Mexico; Love et al. (1995) microzonation of Adelaide; Ghayamghamian et al. (1995) microzonation of Tehran; Ohmachi et al. (1995) microzonation of Yokohama city; Bouckovalas and Krikeli (1991) microzonation of Kalamata, Greece; Alva Hurtado et al. (1991) microzonation of Lima City, Peru; Kobayashi et al. (1991) microzonation of Mexico City.

7. Other uses of HVSR

The main use of HVSR outside the field of microzoning is its application to the study of sedimentary basins to identify the variation of resonance frequency with depth. Examples of this use are given in Al Yuncha and Luzon (2000), in Chàvez-Garcìa et al. (1998) for the Parkway basin (New Zealand), in Zama (1992) for Tokyo Bay, in Seo (1998) for the Fukui basin, in Lee et al. (1995) for the Taipei basin, in Dravinski et al. (1995) for San Fernando valley, in Kagami et al. (1991) for the Perth basin, western Australia, in Di Pasquale et al. (1995) for the Rieti basin, in Ansary et al. (1995) for the Hualien site, Taiwan, in Seo et al. (1995) for the Los Angeles area, in Lu et al. (1992) for Chiba, Japan, in Duval et al. (1994) for Nice (France), in Clitheroe and Taber (1995) for Wellington City (New Zealand), in Zaslavsky et al. (1995) for Israel, in Teves-Costa et al. (1995) for Lisbon, in Morales et al. (1992) for Granada basin (Spain), in Ohmachi et al. (1991) for San Francisco, in Ojeda et al. (1998) for Pereira (Colombia), in Iwatae et al. (1995) for Zushi City, in Goula et al. (1998) for Barcelona, in Gosar et al. (2001) for the Soca Valley (Slovenia).

Some recent attempts are aimed at using the HVSR as a geophysical prospecting technique, to estimate first-order geometry of main seismic reflectors, like the interface between a basin alluvial filling and the underlying bedrock. Yamanaka et al. (1994) were the first to suggest this use. Other examples are Bodin and Horton (1999) for the Mississippi Basin, Delgado et al. (2000) for the Segura River valley (Spain), Giampiccolo et al. (2001) for Catania, Ibs-von Seth and Wohlenberg (1999) for the Rhine Graben. This last paper is the first to address the problem of the gradient of velocity with depth, while the others are assuming a constant wave velocity (Vs) and derive the thickness of the basin (H) from the measured frequency (F) using the well known relationship $F = Vs/4H$.

HVSR combined with other geophysical methods like high-resolution geoelectric tomography, is applied to the study of landslide detachment surface by Gallipoli et al. (2000b). HVSR allows the study also of the behaviour of a cavity as shown by Lombardo and Di Paola (2000). The presence of waves trapped in fault gauges can be also detected using the HVSR technique, as shown by Mucciarelli et al. (1999a). The same technique has been applied to validate the possible presence of site effects in a set of localities in the Val d’Agri area (Southern Italy). For these sites the enhancement of Probabilistic Seismic Hazard (SHE) has been the first indication of geological characteristics potentially responsible for amplification effects, in fact the analysis of HVSR seismic amplification functions suggests a correlation between the SHE and the amplification peaks in the range of frequency of interest for the building (Gallipoli et al., 2000c). D’Amico et al. (2000) provide similar results for the Garfagnana area (Tuscany, Italy).

Another chapter of the HVSR use is relevant to buildings. Nakamura himself (2000) claims that this technique be applied to the estimation of a sort of instrumental vulnerability index. Mucciarelli et al. (2001), proposed an alternative approach which takes more directly into account the importance of input seismic spectrum. While the application of HVSR to vulnerability estimates requires further extensive validation, it is more accepted that it is a feasible technique for determining a fundamental building frequency without the need for simultaneous measurement at each floor (Irie and Nakamura, 2000). The main result expected is the determination of the fundamental frequencies of the investigated building and of its foundation soil, to put in evidence resonance phenomena capable of compromising the building stability during an earthquake. The expected results cannot have the complexity and the richness of information on the dynamic behaviour in the time domain of a whole study which can also involve the installation of permanent instruments and the performance of surveys. Nevertheless, it is reasonable to consider that we can obtain, in the frequency domain, a faithful representation of the linear elastic behaviour.

The importance of resonance between civil buildings and soil frequency was investigated by Ganev et al. (1995), by Mori and Asada (1992), by Mucciarelli e Monachesi (1998, 1999) during the Umbria-Marche and Slovenia earthquakes, respectively and, by Mucciarelli et al. (1999a) for the 1998 Southern Italy earthquake. The possible resonance between buildings and frequency induced by traffic was studied by Mucciarelli et al. (1999b), the determination of the main frequencies of our cultural heritage, such as the determination of the dynamic characteristics of the Tower of Pisa and the roman Colosseum using microtremor by Nakamura et al. (1999, 2000).

8. Conclusions

The Nakamura technique has a large number of applications: besides its well-known use for microzonation purposes, it is now applied to geophysical prospecting and studies of buildings' dynamical behaviour. Notwithstanding the widespread agreement on the usefulness of this technique for estimating fundamental soil frequency, large discrepancies exist in other aspects. First, the theoretical justification is still disputed. Some authors maintain that it should be used only in simple 1-D situations while others are satisfied with the results obtained in 2-D cases. Some suggest that it gives better results when the impedance contrast is high (Trifunac and Todorovska, 2000) while others invoke it just for low-impedance contrast (Al-Yuncha and Luzòn, 2000). It appears that more studies are needed both from a theoretical standpoint as from an experimental one, under controlled conditions. Surprisingly, the method seems to work better (especially in amplitude) when applied to buildings, where the original hypotheses on the theory behind it do not apply.

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