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SYNOPSIS: We use synthetic calculations to investigate the spectral ratio between horizontal and vertical components (H/V ratio), derived from noise simulation, in order to appreciate the reliability of the so-called Nakamura's method for site effects applications. This ratio shows a peak whose position generally coincides with the fundamental resonance frequency. We show that this position is independent of the source function, whereas it is characteristic of the geological structure. We also compare these results with those obtained for vetical S waves and Rayleigh waves, in order to better understand the significance of this H/V peak. Finally, we show that the amplitude of the H/V ratio can not be used directly to derive the amplification for body waves, as suggested by Nakamura (1989), since it is very sensitive to parameters such as the Poisson's ratio and the source-receiver distance.

INTRODUCTION

Several recent studies of microtremor recordings have been made, in order to investigate the spectral ratio between horizontal and vertical components (e.g. Nakamura, 1989). In his study Nakamura (1989) suggests that this ratio is a good technique for site effect evaluation since it shows a peak which corresponds to the predominant frequency of the soil. This points to the fact that we could use microtremors for microzonation studies. Moreover, knowledge of the resonance frequency of the soil could be used in predicting the kinds of buildings which are likely to suffer greatest damage (Ohmachi et al., 1991). This method seems to be very suitable for site effect evaluation in urban areas, since it requires only noise recorded by one three component station. Some recordings made in Mexico City, Oaxaca and Acapulco (Lermo and Chavez-Garcia, 1993) and in France (Duval, 1992) provided encouraging results.

However, no reliable theoretical basis has yet been proposed to support this method. The aim of this numerical study is to check the influence of different parameters on the horizontal to vertical spectral ratio (H/V ratio). For example, it is necessary to check if the H/V ratio obtained from microtremor recordings is not too sensitive to the excitation function of the source. One of the main goals of this study is also to investigate the sensitivity of the H/V ratio to the local geological conditions.

We use a method of numerical simulation of urban noise, in order to understand the meaning of the H/V ratio and the influence of different parameters. For this, a multiple source model is used to make numerical simulation of urban noise. This work can be divided into two main parts. We first look at the position of the H/V peak, and its relation to the resonance frequency, for different source types and for varying geological structures. We also compare the results obtained with different types of incident waves. The second point of the study is to investigate the amplitude of the H/V peak. We try here to find which parameters have a control on this amplitude, in order to see if it is reliably possible to use the amplitude of the H/V peak for amplification studies.

METHODS OF INVESTIGATIONS

Noise simulation technique

The method developed by Nakamura (1989) is based on an estimation of the transfer function using ambient noise recordings, obtained with the spectral ratio between horizontal and vertical components. In order to investigate the influence of different parameters on the H/V ratio, we developed a model of numerical simulation of noise.

The noise recorded in towns can be considered as caused by a set of surface sources, randomly arranged and with varying amplitude. These sources are of different origin, for example wind, cars, trains, road works and factories, etc. It is therefore very difficult to simulate urban noise in a deterministic way. We choose to model the noise as a set of uniformly disposed surface sources, with random amplitude, placed around a central receiver, according to the model displayed in Figure 1. In this study we employed 240 or 480 sources, dividing the disk into 24 slices, with a radius varying from one hundred meters to one kilometer.

We use a program of numerical simulation giving the recordings obtained for a line of receivers and a point source, and make a summation for each of the three components, in order to obtain the signal recorded by the central receiver in our model. Four parameters must be taken into account in the calculation, in order to simulate the random nature of urban noise :

- different types of sources are used, such as explosion, unidirectional forces, with different source functions (step, Ricker, dirac);
- we introduce a random difference in phase between zero and the total duration of the seismogram for each source;
- the differences in amplitude are simulated by a random factor between 0 and 1;
- a coefficient A_i is used to take into account the probability of having a source inside each sector. This coefficient is proportional to the area of each sector. Clearly, the outer sectors of the disk are bigger than the inner ones, therefore there is a higher probability of a source in one of the outer sectors. We define A_i=(area of the i sector)/(average area of the sectors).

Then, considering the tangential, radial and vertical components from a source in any sector, we can write the three components of the central receiver.
This procedure is repeated ten times, by assigning random values to the difference in phase and the amplitude, in order to obtain several synthetic recordings.

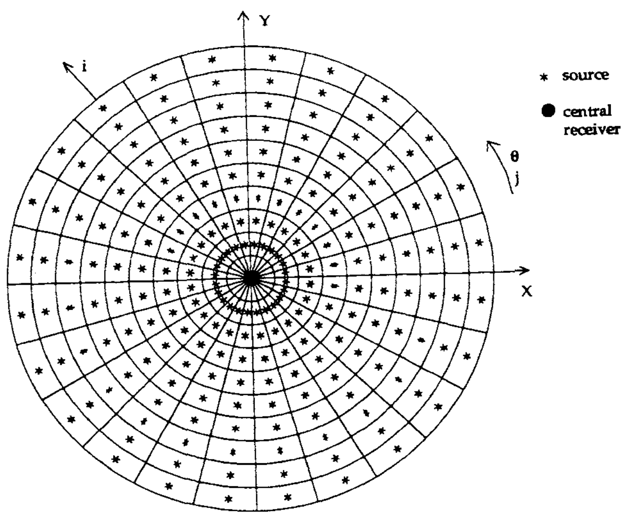

Fig. 1. Disposition of the multiple source model used for noise simulation.

Computation of the H/V ratio

Figure 2 displays schematically how we calculate here the H/V ratio from synthetic seismograms. The example shown is generated with the multiple source model described before, to obtain a three components synthetic noise recording.

We calculate the fast Fourier transform of the three components and smooth the spectra obtained. We have used two types of smoothing function. The first one was applied on a linear frequency scale. For different calculations with different geological structures, the maximum energy is situated at different positions in the frequency domain ; so we have to take different smoothing widths for each case. The second smoothing function is a triangle window applied on a logarithmic frequency scale. The advantage is that the smoothing width is a function of the frequency, so we can

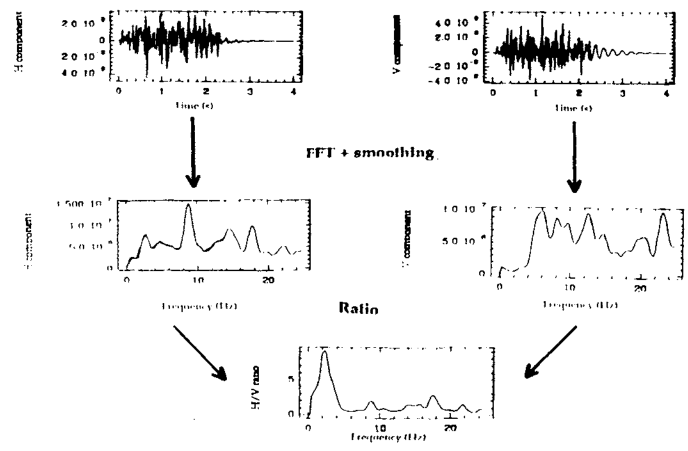

Fig. 2. Procedure used to calculate the H/V ratio from synthetic seismograms.

keep it constant (here equal to 0.1) for all the cases. Then we take one of the two smoothed horizontal spectra (or the average of the two, given by $Sh_i^l=(St_i^l+Sr_i^l)/2$) and the vertical one, and calculate their ratio.

H/V PEAK IN THE FREQUENCY DOMAIN

Influence of the source characteristics

The first part of this work consists of investigating the spectral shape of the H/V ratio. Nakamura (1989) suggests that this ratio peaks at the S waves resonance frequency of the layered structure (noted f_s), and that the location of this peak (fn) does not depend on the source characteristics.

We consider in this section a simple structure consisting of one sedimentary horizontal layer over an homogeneous half-space. The multiple source model described above is used to calculate the average H/V spectra for ten synthetic noise recordings. The simulation program used allows to choose different source types and functions. The same procedure is repeated for different source characteristics, so as to compare the H/V ratios obtained. The first source type used was an explosion (represented by a triple dipole), with two different functions, step and Ricker. However, another source type, a unidirectional force, given by its three directions (x, y, z), is probably more representative of the urban noise than sources such as double-couples or explosions. The H/V ratios are thus calculated for the same simple geological structure, with a source defined by a contribution of unidirectional forces (in the three directions), and three types of functions : step, Ricker and pseudo-dirac. The spectra obtained for these different sources are shown in Figure 3.

The H/V ratios obtained for different source characteristics, all clearly exhibit a peak, whose position is constant, whatever the source type and source function. In this particular simple case, it is situated at a frequency of approximately 10Hz. These results allow to conclude that

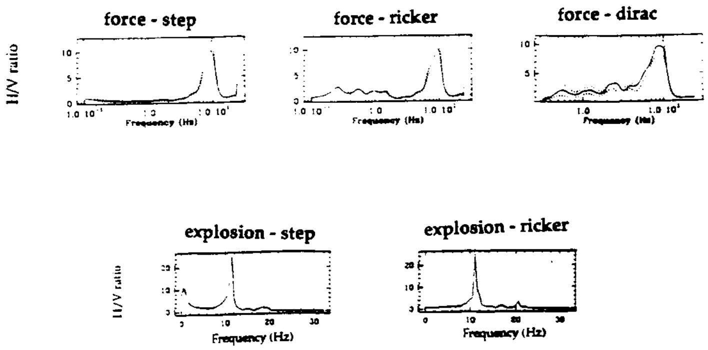

Fig. 3. H/V ratios for different source types.

for randomly distributed surface sources, the H/V peak position is independent of the source characteristics.

Variation of the geological conditions

We now investigate the influence of the geological structure on the H/V peak position. Synthetic seismograms are thus computed with the multiple source model, for a number of different soil structures. A constant source type is chosen for this set of calculations, characterized by unidirectional forces (radial, tangential and vertical) and a pseudo-dirac function. Two types of structures are considered. Figure 4 displays the S wave velocity profiles for all the structures.

In the first step six simple theoretical models are studied, with varying velocity contrast and thickness of the layers. In the second step a similar procedure is applied for a few (more complex) real geological structures, from three different regions : Ashigara Valley (Japan), Turkey Flat (California) and coastal sites located in SE France. Geotechnical surveys carried out in several sites in these areas give precise physical characteristics of the geological structures.

The H/V ratios obtained in these various cases present a clear peak situated at a varying frequency fn, from one site to the other. A comparison between the results obtained for the different sites, points out clearly the influence of the geological structure on the H/V peak position.

Comparison with vertical S waves

The next step is to compare fn with the "resonance frequency" fs, corresponding to vertical S waves resonance. These frequencies f_S were computed for each of the geological structures with a simple 1D program based on the reflectivity method (Kennett, 1979). Figure 5 provides a summary comparison between fs and fn for all the geological structures presented before. It shows an overall good agreement between the peak positions obtained for noise and those obtained for vertical S waves, from which we conclude that the fn frequency derived from H/V spectra is a probably reliable indication of the fundamental resonance frequency f_S of a horizontally layered structure.

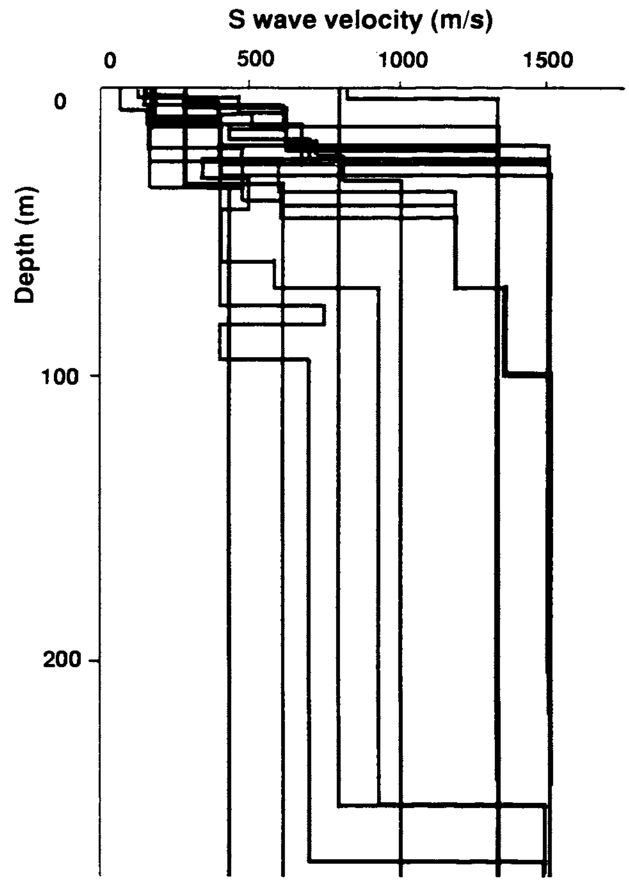

Fig. 4. S wave velocity profiles for all the geological structures considered.

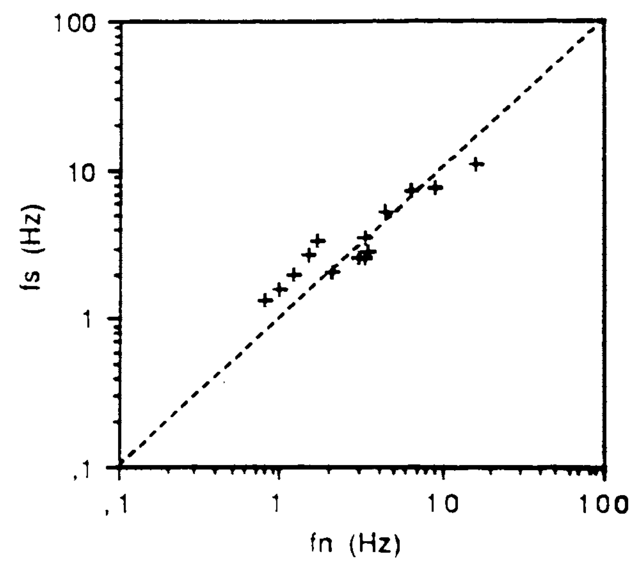

Fig. 5. Plot of the H/V peak frequency for each site; fn: H/V peak frequency for noise simulation, fs: H/V peak frequency for vertically incident S waves. The dashed line is the f_S=f_n line.

Comparison with Rayleigh waves

As described above, urban noise is believed to be generated by surface sources and should therefore mainly consist of surface waves. In layered media like those considered in this study, two main kinds of surface waves may exist, Love waves and Rayleigh waves. Love waves are polarized only in the horizontal direction and therefore lead to infinite H/V ratios. Rayleigh waves however, are polarized in both horizontal (radial) and vertical directions, so that the peak observed in the H/V ratio may be related to the polarization curve of Rayleigh waves. The polarization of Rayleigh waves was therefore investigated for each of the models considered. These polarization curves exhibit several peaks corresponding to a vanishing of the vertical component.

It is interesting to compare the polarization curves obtained for each of the sites considered with the H/V ratios calculated from noise simulation, for these same sites. Figure 6 displays a comparison between f_n and the frequency of the first peak on the polarization curve, noted f_p : the H/V peak position in noise simulation generally corresponds to the first peak in the polarization curves. In other words the shape of the H/V ratio is widely controlled by fundamental Rayleigh waves, which in turn are closely related with resonance phenomena.

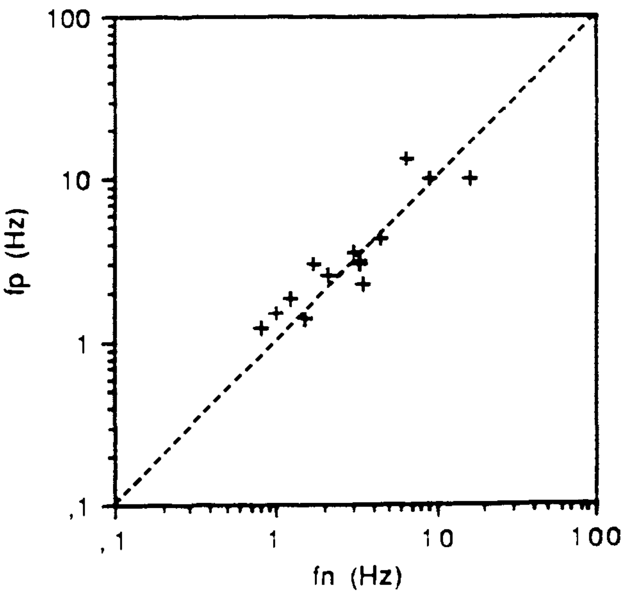

Fig. 6. Plot of the H/V peak frequency for each site; fn: H/V peak frequency for noise simulation, fp: frequency of the fundamental peak in the polarization curves of Rayleigh waves. The dashed line is the f_p=f_n line.

AMPLITUDE OF THE H/V PEAK

The second objective of this numerical study is to investigate the amplitude of the H/V peak (An). Nakamura (1989) suggests that we can estimate the amplification of seismic motion, due to resonance of surface layers, simply from the maximum spectral amplitude of the H/V ratio. A first raw test of this - strong - assumption is provided by comparing the amplitude (An) of the H/V peaks obtained from noise simulation with the maximum amplitude of the transfer function for vertically incident S waves (As). This is done in Figure 7, where An and As are plotted for each of the geological structures described above. Obviously there does not exist a good agreement between the H/V peak amplitude and that for vertical S waves. For some cases, the H/V peak amplitudes are far larger than the vertical S wave amplification. As these sites correspond to large Poisson's ratios at the surface, we investigate the influence of the Poisson's ratio and source location in order to see if they have a control on the H/V peak amplitude, derived from noise simulation.

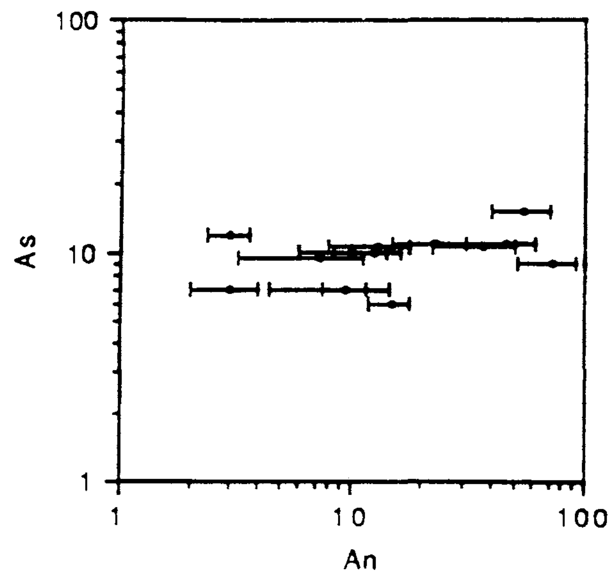

Fig. 7. Plot of the H/V peak amplitude for each site. With An being the H/V peak amplitude for noise simulation and As the amplitude of the horizontal component for vertically incident S waves.

The influence of the Poisson's ratio in the sedimentary layer is first studied by varying the P wave velocity while fixing the S wave velocity. The results obtained show significant variations (between 4.75 and 17.5), as a function of the V_p/V_s ratio (related with the Poisson's ratio). In the second step, the sites with a large Poisson's ratio were modified to set their Poisson's ratio to the value 0.25, at the surface. For this, a four meter thick layer, with a 0.25 Poisson's ratio, was introduced at the surface of each site. In the case of a 0.25 surface Poisson's ratio the amplitude is much smaller, indicating the large influence of the Poisson's ratio in the surface layer on the H/V peak amplitude; although there is no clear relation between these two quantities (Lachet and Bard, 1994).

The results may also depend on the relative location of source and receivers, namely on the ratio between the structure characteristic thickness and the maximum source-receiver distance, and also on the source depth which may influence the excitation of the various surface waves (especially the higher modes). The effects of these parameters are also investigated by changing the maximum source-receiver distance, that is to say the radius of the multiple source disk. As we have seen before, the H/V peak generally corresponds to the fundamental peak of the polarization curves of Rayleigh waves. It is therefore likely that the greater the source-receiver distance, the bigger the Rayleigh wave contribution, and thus the higher the H/V peak amplitude. This shows that the source-receiver distance has some effect on the H/V peak amplitude (which vary between 4 and 9), but with no particular correlation between the two parameters (Lachet and Bard, 1994).

These results allow to conclude that the H/V peak amplitude can not be used in a straightforward way for amplification studies, since it undergoes considerable variations with respect to parameters such as the Poisson's ratio in the sedimentary structure and (to a lesser extent) the source-receiver distance.

CONCLUSIONS

This numerical study has allowed to investigate some aspects of the properties of the horizontal to vertical spectral ratio applied to noise simulation. The main conclusions inferred from these synthetic calculations may be summarized as follows :

- the H/V ratios obtained from noise simulation show a peak whose position is independent of the source excitation function;
- there is a good agreement between the H/V peak positions derived from noise simulation and those obtained for vertical S waves. This shows that the H/V ratio gives a reliable indication of the resonance frequency of a horizontally layered structure;
- the shape of the H/V ratio is largely controlled by the polarization curve of fundamental Rayleigh waves;

On the opposite, the amplitude of the H/V peak was shown to be very sensitive not only on the velocity contrast, but also on parameters such as the Poisson's ratio in the sedimentary structure and the source-receiver distance. Its use for determining the amplification of horizontal motion for incident S waves, is therefore, in our mind, still premature from a strictly theoretical point of view.

This numerical study allows a better understanding of the H/V ratio and shows this technique to be of great interest for site effect and microzonation studies, in an urban context. This method represents a relatively cheap way of determining the resonance frequency of a site, that is the frequency of the motion that buildings are likely to undergo in the site considered.

This study is concerned with the use of urban noise recordings, but it is interesting to notice that the H/V method might also give good results in the case of weak or strong motion recordings, since the ratio is also stable for body waves : this theoretical result is supported by various experimental observations (Lermo and Chavez-Garcia, 1993; Theodulidis and Bard, 1994). Finally it is clear that the H/V ratio method has to be tested on several real noise recordings, in order to check the theoretical results obtained here, and to find out its limitations.

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