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H/V technique for site response analysis. Synthesis of data from various surveys

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Abstract - "H/V" techniques are very attractive tools for estimating local site effect characteristics. They consist in computing the spectral ratio between the horizontal and the vertical components of a signal. For the "receiver function", or RF method, the signal is an earthquake, whereas it is composed of ambient noise for the NN method. The classical transfer function method, called SR here, is based on the spectral ratio of an earthquake recording between one site and a reference. The aim of this paper is to collect experimental results (44 sites) and compare values worthy of note obtained from the H/V and the SR techniques. For several typical sites, we first illustrate that, when a clear peak arises on an SR curve, it also exists, at the same frequency for RF or NN curves. But there is no correlation between the two kinds of curves except for the low frequency part (below the first peak) where a fuzzy relationship seems to exist. Finally,we show that NN and RF techniques determine, very accurately, the fundamental frequency of alluvial sites, below which there is no amplification. In most cases, they also provide a lower bound (in amplitude) and bandwidth (in frequency) estimates for peak amplification.

1. Introduction

In the past few years site effect surveys have become very common in earthquake engineering. Each new destructive earthquake gives further proof of site amplification severity. It is obviously necessary to anticipate the damages due to these phenomena. This can result in prospecting before the disaster, to determine how and where seismic signals are modified by

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local geological or morphological conditions. The classical method for describing such site effects consists in recording earthquakes at several sites and comparing each record with the corresponding one at the reference site (e.g. Borcherdt and Gibbs, 1970; Field and Jacob, 1995a; Bard, 1998). This method can require considerable material and time (Duval et al., 1994, 1995; Duval, 1996; Lebrun, 1997). Numerical modelling can also provide satisfactory results, with the requirement that the geotechnical model is well constrained, which can also be very expensive for routine use in microzoning studies (see for instance Semblat et al., 2000). This is why the so-called "Nakamura" technique - first proposed by Nogoshi and Igarashi (1970) - based on inexpensive noise recordings, has spread so rapidly throughout the world in recent years (see review in Kudo, 1995; and Bard, 1998). It consists in recording a few minutes of noise (microtremor) with a tri-directional sensor and computing the horizontal to vertical (H/V) spectral ratio. The theoretical explanation for this method is not yet totally established, although phenomenum begin to be more understood than it was some years ago. The results of the numerous surveys recently published (Lermo and Chavez-Garcia, 1993; Field et al., 1995; Lachet et al., 1996; Bonilla et al., 1997; Riepl et al., 1998; Fäh et al., 2001 for instance) lead, globally, to accepting the fact that the natural frequency of soft soil could on the one hand be very precisely determined by this method, while, on the other, the amplitude of the spectral ratio from microtremor is supposed to have no relation with the site transfer function in case of an earthquake (Field and Jacob, 1993; Lachet and Bard, 1994). The engineering interest of such an agreement would be considerable. That is why so many surveys are performed with this technique today, to determine, at least, the soil's natural frequency, but without any clear certainty as to the meaning and usefulness of the amplitude of H/V curves (see review in Bard, 1998). So, despite the absence of any satisfactory physical explanation for this amplitude issue, and since the modelling of noise is no easy task, we decided to perform a strictly empirical check of this very appealing method. We proceeded by comparing, for as many sites as possible, the results of the standard spectral ratio method (with respect to a reference site), and the results of the H/V techniques. This paper presents preliminary results from this comparison, for a significant set of sites located in different areas of Europe and the Antilles. The experiment presented here can be considered as representative of many surveys performed in a low seismic rate context, where earthquake data are rare. That is why is it interesting to check, empirically, several methods that could allow us to quantify local seismic hazard from these few data.

2. The techniques

2.1. The standard spectral ratio technique (SR)

This method, denoted as SR in the following, was initiated by Borcherdt and Gibbs (1970). It consists in recording seismicity at several stations and computing the smoothed spectral ratios between the various sites of interest and a "reference" site. The mean transfer function (obtained with several earthquakes for each site) reflects the ability of the site to modify the spectral contents of an earthquake (Aki, 1993). The non-linear behaviour of soft deposits under strong shaking is still a matter for debate (see, for instance, Archuleta et al., 2000). But transfer functions established from weak motions are nevertheless considered very useful (Bard, 1998). Several conditions should be respected to obtain reliable transfer functions. The reference site should be located on bedrock (preferably with no relief) and very close to the other stations. Moreover, the earthquakes should be processed only when their distance from the network is at least five times greater than the distance between the station itself and the reference site (Field and Jacob, 1995; Duval, 1996). On the other hand, a good signal to noise ratio – above 3 - is of course very important for all stations. Furthermore, such surveys are often undertaken in urban areas with a high noise level. These three conditions may mean having to wait sometimes several months before sufficient data is obtained (at least 10 earthquakes per site) especially in areas with a low seismicity rate (Field and Jacob, 1995, Field et al., 1995).

2.2. H/V on earthquake or receiver function technique (RF)

The basic idea comes from a seismological method called "receiver-function" technique used by Langston (1979) to determine the velocity structure of the crust from the horizontal to vertical (H/V) spectral ratio of teleseismic P-waves. The method (denoted as RF in the following) was used subsequently on shear waves to estimate site effect when no reference site can be found on non-weathered bedrock (Lermo and Chavez-Garcia, 1993; Field et Jacob, 1995; Theodulidis et al., 1996). The application consists in recording several earthquakes (statistical spreading can be important) to compute the spectral ratio of the horizontal and vertical components on S-waves. The signal to noise ratio must be above 3, as in the classical method, for all the frequencies studied. The implicit hypothesis is that the vertical component is unaffected by any local amplification effect. Thus, this component acts as the "reference" site mentioned in the previous paragraph. Yet, this methods ability to provide a reliable transfer function is often debated (Yamanaka et al., 1994; Lebrun, 1997). In a simple geological context, the vertical component is in fact barely affected by local site effects. But when the geology is more complex, site effects may influence vertical motion in the same proportion as for horizontal motion but at higher frequencies. Thus, although amplification determination with this method is claimed to be correct for low frequencies, it is also said to be much less reliable for high ones (Lermo and Chavez-Garcia, 1993; Field and Jacob 1995; Bonilla et al., 1997; Lebrun, 1997; Sabourault, 1999).

2.3. H/V on microtremor - or Nogoshi-Nakamura method (NN)

The principle, initiated by Nogoshi and Igarashi (1970), involves recording a few minutes of seismic background noise to provide a reliable estimate of the soil resonance frequency. The authors computed the spectral ratio of the horizontal and the vertical components of a microtremor measurement for a single station. The resulting curves pinpoint a frequency that is supposed to fit remarkably with the S-wave resonance frequency of the studied site. The explanation provided by Nogoshi and Igarashi was based on the essentially Rayleigh-wave nature of the microtremors used. This technique was later revised by Nakamura (1989) who claimed more largely that this H/V ratio is a reliable assessment of the site transfer function for S-waves with respect to bedrock, because of the mainly body wave nature of the noise. Numerous experiments carried out over the last decade, showed that this H/V ratio on microtremors is much more stable than the raw noise spectra, and that in case of high impedance contrast between surface and deep materials, the microtremors exhibit a clear peak which is well correlated with the fundamental resonance frequency (e.g. Field and Jacob, 1993; Duval et al., 1994, 1995). The recent numerical simulations of background noise (e.g. Field and Jacob, 1993; Lachet and Bard, 1994; Konno and Ohmachi, 1998; Fäh et al., 2001) confirmed Nogoshi and Igarashi's first explanations as concerns the surface-wave nature of microtremors: synthetic calculations showed the direct link between three values in case of a single soft surface layer over bedrock: the ellipticity curves of Rayleigh waves, the frequency pinpointed by the H/V ratio on microtremor and the S-wave resonance frequency of soft soil under the studied site. But these results also predicted no correlation between the amplitude of this H/V peak and the actual amplification value under S-wave incidence (except for Konno and Ohmachi, 1998). Yet, several authors claim a satisfactory empirical agreement between the level of the two types of curve (e.g., Lermo and Chavez-Garcia, 1993; Gitterman et al., 1996). Recent investigations concerning this technique are reviewed in Bard (1994, 1998) and Kudo (1995).

3. Data set

The results collected in this study come from various individual site effect studies by French and Greek teams between 1991 and 1997. The studied areas were located in the French Alps, French Antilles (Guadeloupe) and Greece. This set represents a total of 44 sites inclu-

Table 1 - Main characteristics of the data set.

Site	Team	Maximum thickness (indicative)	Frequency range of amplification (Hz)	Amplification range	Number of alluvial sites	Number of rock sites
Annecy (France)	LGIT	100 m	1 - 10	4 - 10	3	2
Ebron (France)	CETE	100 m	1 - 10	10 - 20	3	2
Grenoble (France)	LGIT	500 m	0.3 - 5	5 - 20	7	1
Nice + Tende (France)	CETE	60 m	1 - 10	8 - 20	3	1
Pointe-à-Pitre (Guadeloupe)	LGIT+ CETE	30 m	1 - 6	5 - 15	4	2
Thessaloniki (Greece)	LGIT + AUTH	100 m	0.5 - 10	3 - 8	8	2
Volvi (Greece)	LGIT + AUTH	200 m	0.7 - 10	4 - 12	5	1

ding 33 alluvial sites and 11 rock sites. Some simple indications from the relative surveys are summarised in Table 1. Detailed explanations on investigated sites, earthquakes or microtremors recorded and signal processing will be found in the listed references (Duval, 1996; Lachet et al., 1996; Lebrun, 1997; Riepl et al., 1998; Lebrun et al., 2001). These studies present the common feature of concerning recent alluvial sites, with thickness ranging from several hundred metres (Grenoble) to several metres (Guadeloupe). There are also striking contrasts in the nature of the sediments, since alluvial fill is made, for instance, of clay in the Ebron study while, in Thessaloniki, it is mainly sandstone and marl or Holocene deposits. All the reference sites are characterised by unweathered, outcropping hard rock.

4. Analysis

For each of these sites, the site effects were investigated with the three experimental techniques described above. Although processing parameters vary for each survey, the steps for the spectral analysis are common: careful window selection, instrumental and baseline correction, if needed, tapering, application of FFT, smoothing with a running window having between 3 and up to 50 points, depending on the study and the frequency (larger number of points at higher frequencies).

4.1. SR - Spectral ratio on an earthquake with respect to a reference site

The mean classical spectral ratios are taken as the basis for comparison: they are computed by averaging several (i.e., usually more than ten) individual spectral ratios from local, regional or teleseismic events. Averaging is applied only to the data corresponding to a signal to noise ratio greater than 3 at both the reference and studied sites. The spectra were computed for windows of varying length depending on the event and the study.

4.2. RF - receiver function

For the same earthquake recordings, the receiver functions (i.e., the ratio between the spectra of the horizontal and vertical components) were computed and averaged with the same signal to noise threshold, and the same spectral smoothing. For teleseisms, the S-waves are better processed. Then, a mean curve was computed for each site.

4.3. NN - Nogoshi-Nakamura method

For each site a series of noise recordings was also used to process the “Nogoshi - Nakamura” ratio. The stationary part of the signal was chosen, because transient may disrupt the results (e.g.: Sabourault, 1999). Several windows were thus selected by visual inspection in some cases, or by means of a kind of “anti-trigger” algorithm eliminating transients, in

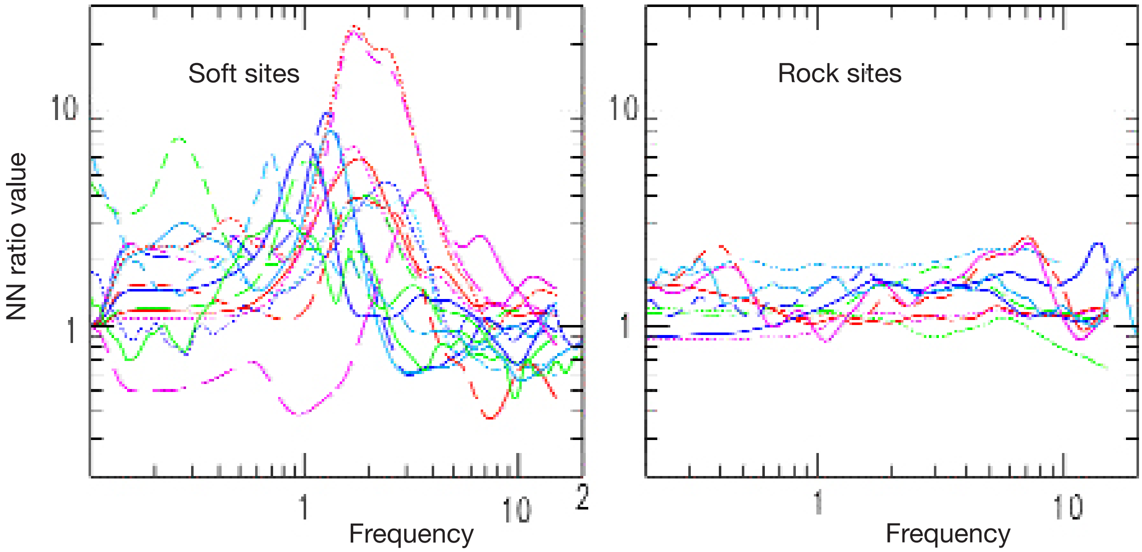


Fig. 1 - Some examples of NN mean curves (H/V on microtremors) for some of the 33 soft soil sites (left) and rock sites (right).

other cases. Their length depends on the surveys but is generally around 30 seconds. For each window, a spectral analysis for the three components was performed. H is computed as the geometrical mean of the modulus of spectra of the two horizontal components (or equivalent). It is divided by the modulus of the spectrum of the vertical component. All these H/V ratios on a site were then averaged in a mean curve (NN).

5. Results

5.1. Some representative site

In all the studies involved here, like many others in the literature (see e.g. Bard, 1998), microtremors recorded over soft soil and processed to obtain the H/V curve showed clear amplification in a single peak, whereas the curves for rock sites are almost flat (Fig. 1). Of course, the amplitude and frequency of the peak vary from site to site. The physical significance (or lack of significance) of this amplification was investigated by comparing it with other curves: the average spectral ratio (SR) with respect to the reference site indicates the fundamental frequency of the site. The meaning of the average receiver function (RF) is evaluated in the same way.

The most thorough way of comparing the three methods is to plot the three curves on the same figure for each site. This is done for 6 sites here (Fig. 2). These sites were chosen because they exhibit very different results in various geological contexts. Table 2 summarises these geological conditions. As is shown in the table, the depth of alluvium underlying a site is often quite uncertain.

Fig. 2a shows an example of a hard rock (moraine) site where the transfer function from earthquake is flat. The "H/V on microtremor" or NN curve is also flat and its value is around a unit. The receiver function is less than 1.

Fig. 2 illustrates the fact that soft soil sites show clear amplification for all three types of curves. The frequencies of the first peak for all three curves are very similar for each

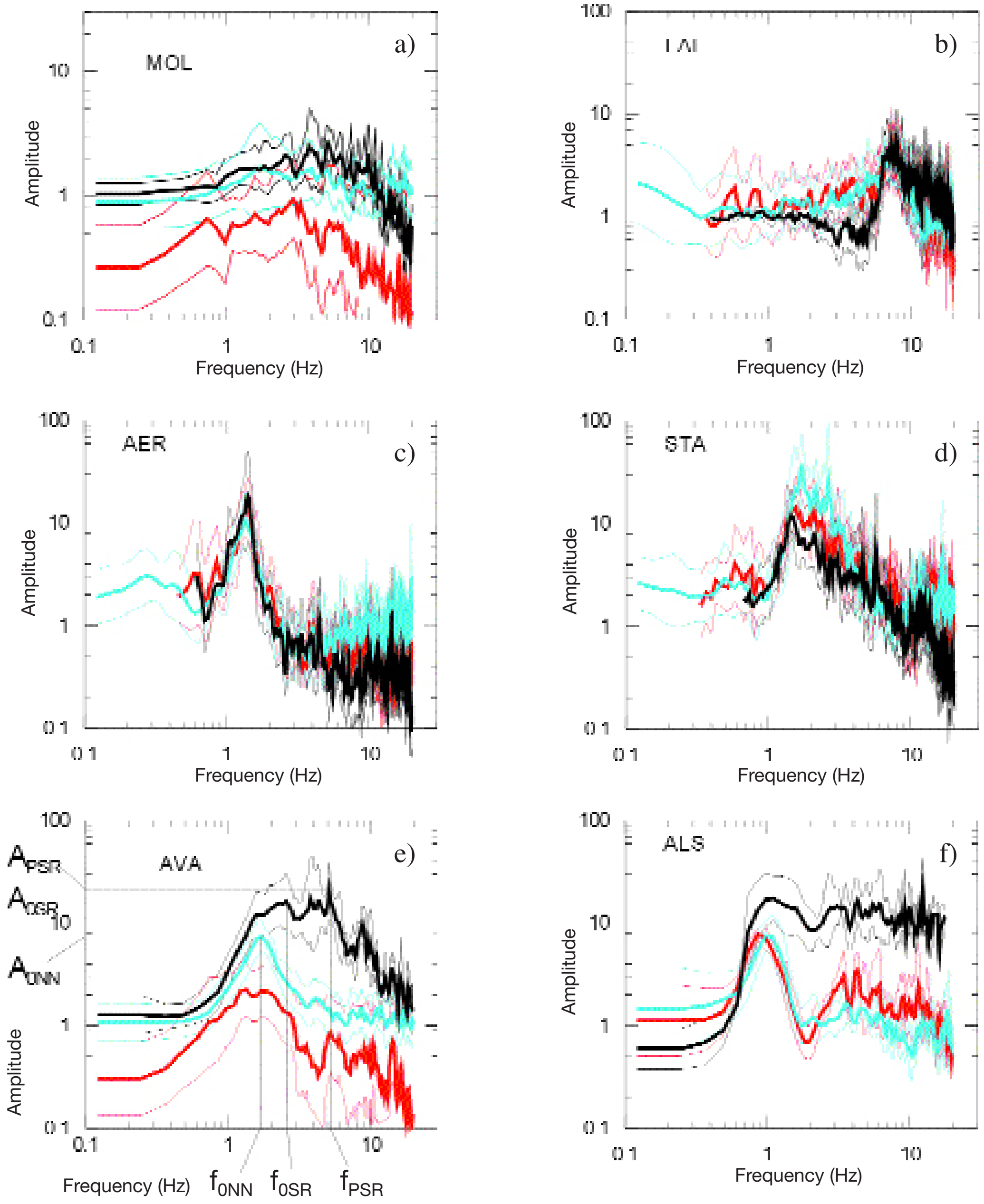


Fig. 2 - Comparison of the spectral ratios computed from the NS component using the three different methods: SR (black), RF (red) and NN (blue). The curves show the averaged spectral ratio (bold) and the standard error bands (thin lines). The panels display the spectral ratios computed at different sites: a) MOL, b) FAI, c) AER, d) STA, e) AVA, and f) ALS.

site and may differ from one site to the other. For instance, FAI (Fig. 2b) exhibits a peak of approximately 8 Hz, whereas the three curves are very similar with an amplitude between 3 and 5. Relatively shallow sediments of FAI do not respond like other superficial sedimentary fill in Guadeloupe. The nature of the surface layer in the mangrove of Pointe-à-Pitre (Guadeloupe) could explain this difference. The frequency is much lower at approximately 1.5 Hz. The level of amplification is also slightly different, between 10 and 20 for the transfer function. Nevertheless, the two sites in Guadeloupe presented here yield different results: while for AER (Fig. 2c) all three curves have the same shape with a thin peak and almost the same level, for site STA (Fig. 2d), the NN curve (H/V on microtremor) has a higher level than the SR curve (transfer function from earthquake). This behaviour is extremely rare, as will be pointed out later in the data synthesis.

Table 2 - Geological conditions at some sites investigated.

Sites	Survey	Geological condition
MOL (Fig. 2a)	Ebron, French Alps.	Moraine (hard rock)
FAI (Fig. 2b)	Nice, Tende, French Alps	10-30 of quaternary overlapping dolomite limestone
AER (Fig. 2c)	Pointe-à-Pitre (Guadeloupe)	About 20 metres of alluvium above hard rock
STA (Fig. 2d)	Pointe-à-Pitre (Guadeloupe)	10-20 metres of quaternary alluvium above hard rock
AVA (Fig. 2e)	Ebron, French Alps.	About 100 metres of clay above limestone
ALS (Fig. 2f)	Nice, France	60-100 metres of alluvium above limestone

Figs. 2e and 2f are more representative of other sites for the relative position of the different curves: the SR transfer function reaches a higher level at the maximum amplification than the NN curve (H/V on microtremor) and the receiver function RF curve.

It must also be noted that for ALS, the transfer function remains high after the first amplification, while curves obtained with the NN and RF method decrease immediately after the first amplification peak.

5.2. Variograms for all sites

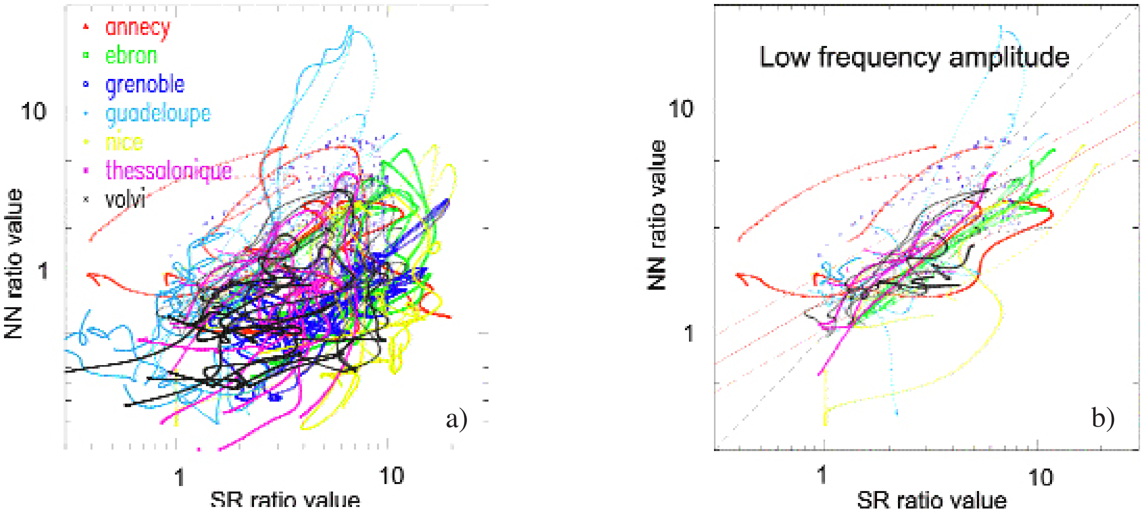
As already mentioned, one of the major issues in this kind of investigation is to check the meaning and the use of the H/V ratio amplitude. In this context we decided to perform an amplitude comparison of the different techniques by means of variograms. An important question was whether it is possible to deduce the frequency dependent amplification function (best estimated by the classical spectral ratio with respect to a reference site) from the NN curve. If the answer was yes, then plotting the NN(f) versus the corresponding values SR(f) should yield some kind of regular, reproducible curves.

For each of the 33 alluvial sites, we stored the SR and NN amplitudes for each frequency (Fig. 3). Fig. 3a shows the variogram of NN versus SR between 0.1 and 20 Hz: If NN is a good indicator of amplification, the NN values plotted as a function of the corresponding SR values (according to the frequency) should give a cluster of points elongated along the first diagonal, or, at least, exhibiting a satisfactory correlation. This is obviously not the case in Fig. 3a.

Nonetheless, there is some indication that there may be a better correlation at low frequencies. Therefore, we plotted the same values only for the frequencies under the peak frequency (i.e., for $f \leq f_0$) for each site. The resulting plot, shown in Fig. 3b, seems to show a better trend, whose characteristics are summarized below:

$$\mathrm{NN}(f) \sim 1.45\ \mathrm{SR}(f)^{0.51}, \qquad R = 0.68, \qquad \sigma_{\log} = 0.115.$$

When considering higher frequencies ($f > 2\, f_{0NN}$), no correlation can be found, since the NN values are much smaller, while SR values remain large in most cases, as shown in Fig. 3c.



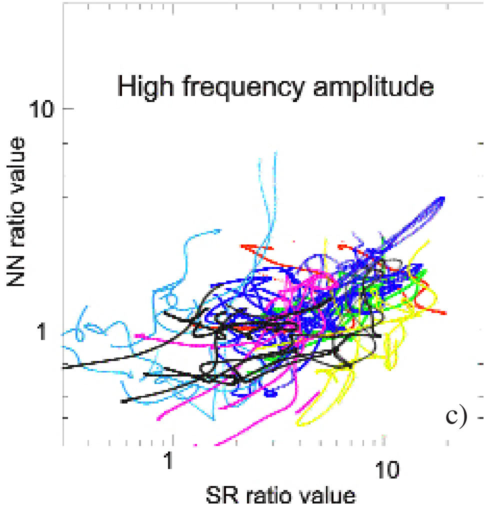


Fig. 3 - Variogram of the spectral ratios values computed using the NN and SR methods, respectively. The symbols identify the values of NN(f) versus SR(f). Each individual symbol corresponds to one frequency f. The data of all 33 alluvial sites are included. Colors and markers represent different surveys (see list in Fig. 3a).

a) Frequency range ($0.1\text{Hz} \leq f \leq 20\text{Hz}$).

b) Low frequency range ($0.1\text{Hz} < f < f_0$). Black dashed line is the diagonal $X = Y$. Red solid line is the best fit curve: $Y \sim 1.45\ X^{0.51}$; with red dotted lines for the standard deviation.

c) For high frequency range ($20\ \text{Hz} > f > 2\, f_0$).

5.3. Frequency comparison

We tried to obtain a “summary” comparison using only some reduced or compressed information from all sites, except bedrock. The first useful comparison, for engineering purposes at least, is the fundamental frequency, defined as the first major peak in either ratio (SR or NN), below which there is no amplification, for the two horizontal components.

The frequency and amplitude of this initial peak is called f_0 and A_0, regardless of the method used. This fundamental frequency does not always correspond, however, to the maximum peak amplitude, as for site AVA (Fig. 2e). The frequency and amplitude of this maximum peak is called f_P and A_P.

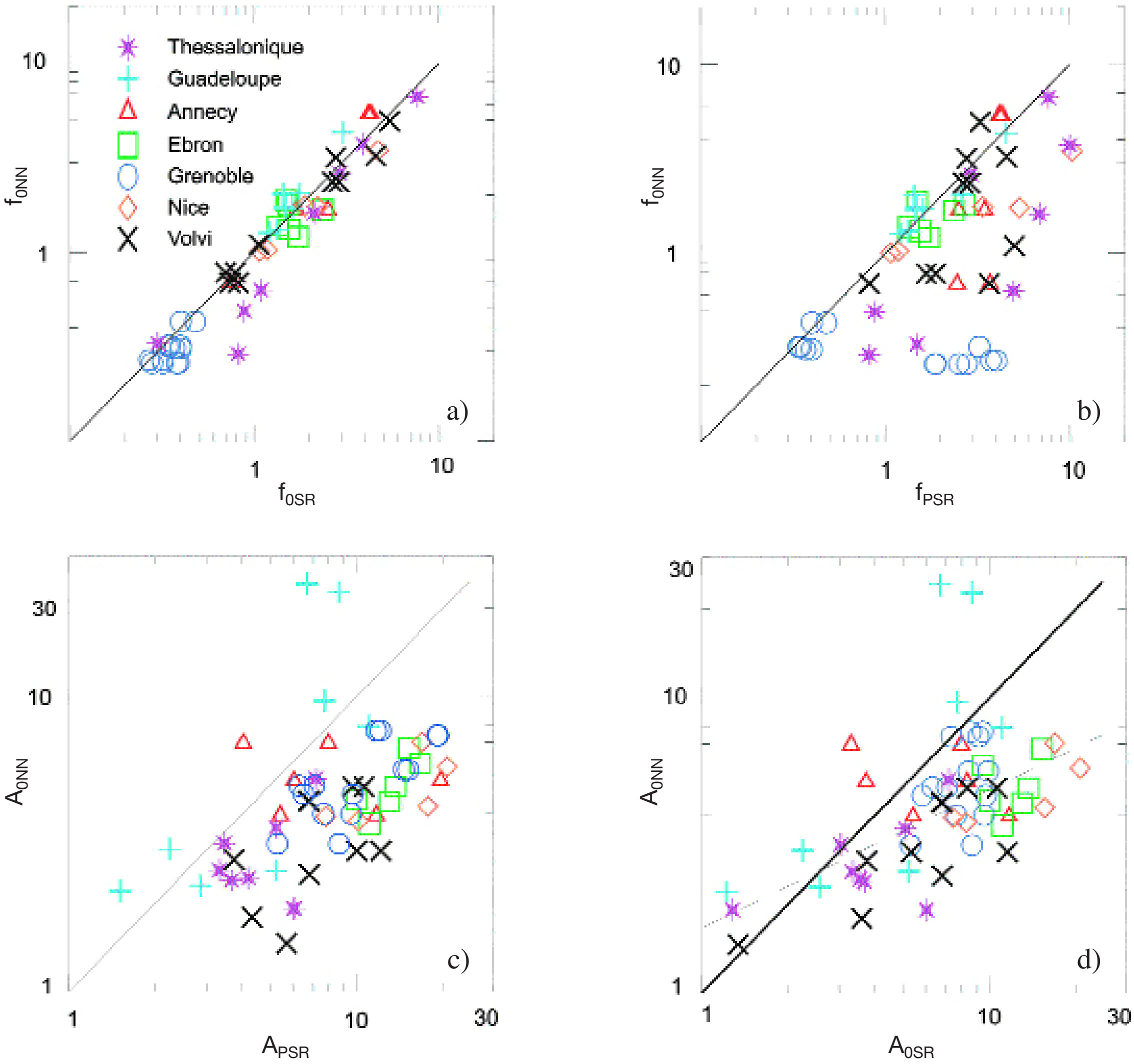


Fig. 4 - Characteristic response frequencies for the 33 soft soil sites (58 symbols). Symbols are representative of each survey. The line is diagonal $X = Y$. a) f_{0NN} ($= f_{PNN}$) versus f_{0SR}; b) f_{0NN} ($= f_{PNN}$) versus f_{PSR}; c) A_{0NN} versus A_{PSR}; d) A_{PNN} ($= A_{0NN}$) versus A_{0SR}. The dotted line is the best-fit curve: $Y \sim 1.66\ X^{0.47}$.

Thus, we picked the frequencies f_{0SR} for the SR curve (f_{0NN} for the NN curve, respectively) and the corresponding amplitude A_{0SR} (A_{0NN}, respectively) of the fundamental peak for each site. Then, considering the maximum peak for the same curves, the relative frequencies f_{PSR} (f_{PNN}, respectively) and amplitude A_{PSR} (A_{PNN}, respectively) are also located, as shown in Fig. 2e. For the 33 alluvium sites of the compilation, the two horizontal components are considered to obtain this kind of result (Fig. 4). There should be 66 points in each figure. But some experimental problems on specific components limit the number of available curves (and relative frequency and amplitude values) to 57.

As mentioned above, f_{0NN} and f_{PNN} tend to be the same, since there is usually only one peak on the NN curve for the data processed here; although in some (very few) cases there several peaks in the NN ratio may exist, the highest one systematically occuring at the lowest frequency (Bard, 1998). The same holds for the receiver function techniques: the peak amplitude is usually the only one and frequency f_{0RF} is generally very close to the fundamental frequency f_{0SR} obtained with the SR technique. Moreover, it tends to be lower than or equal to the frequency of the maximum amplification on transfer function (f_{PSR}).

Fig. 4a displays the fundamental frequency f_{0NN} as a function of f_{0SR} for the 33 alluvial sites in the compilation. All the symbols are clustered along the first diagonal ($X = Y$). This very clearly illustrates what many authors have repeatedly asserted (Lebrun, 1997; Riepl et al., 1998, among others) i.e., that the NN technique provides a very reliable estimate of the fundamental frequency f_{0SR}.

Fig. 4b displays f_{PNN} ($= f_{0NN}$) as a function of f_{PSR}. Most of the symbols are plotted on or under the first diagonal ($X = Y$). This figure shows that f_{0NN} is generally a lower bound estimate for the peak frequency f_{PSR}. Sites where f_{PSR} differs from f_{0SR} can be found in the following surveys, for instance: Grenoble (Lebrun, 1997), Thessaloniki (Lachet et al., 1996) and Volvi (Riepl et al., 1998). These multi-peak curves could be interpreted with Rayleigh-wave ellipticity for sites with high-impedance contrasts at two very different scales (Lachet et al., 1996).

5.4. Amplitude comparison

In Fig. 4c, the maximum amplitude of the NN ratio, A_{PNN} or A_{0NN}, is plotted as a function of A_{PSR}, the peak amplification measured on earthquake spectral ratios with respect to a reference site. A_{0NN} is greater than the corresponding A_{PSR} for only 6 of the 57 studied curves. Only 2 of these 6 curves display an amplitude ratio A_{0NN} / A_{PSR} higher than 2 (two components of the same station).

Although there is no clear correlation, one relationship clearly appears, which presents a great interest for engineering applications: the peak amplification A_{PSR} is generally greater than or equal to the amplitude of the fundamental NN peak A_{0NN}, which implies that the NN technique provides a lower bound estimate of amplification at a given alluvial site. This also holds for the receiver function amplitude A_{0RF}.

Fig. 4d again displays A_{0NN}, but as a function of the corresponding fundamental amplification A_{0SR}. The curve that best fits the data corresponds to the following equation:

$$A_{0NN} \approx 1.66\, A_{0SR}^{\;0.47}, \qquad R = 0.68, \qquad \sigma_{\log} = 0.100.$$

Similar relationships were also sought for the receiver function amplitude, but the correlation coefficient was found to be very poor (0.18).

6. Conclusions

It is a well-known fact that strong motion data are not available at all sites where local hazard should be quantified in terms of prevention. As a matter of fact, the surveys gathered here are representative of such surveys where the choice of earthquake data can be limited. That is why we tried to check the ability of the H/V techniques to infer local hazard information about a few isolated records of earthquake or ambient noise measurements. The overall comparison with other types of results contributes to assessing experimentally such methods in these conditions. This compilation of studies certainly presents some limitations: these studies were performed by different scientists in non-standard ways, e.g., the smoothing (which strongly influences amplitude) was not always the same, the selection of the windows for the NN analysis did not use common criteria. This study could, therefore, be repeated after careful standardized reprocessing of each data set. Nonetheless, we consider that some of the results obtained here are robust and should remain valid after such reprocessing:

- the ability of NN and RF techniques to image very clearly the fundamental frequency of alluvial sites, below which there is no amplification;
- the ability of NN and RF techniques to provide reliable, lower bound estimates for peak amplification on a given site;
- the ability of the NN technique to check whether a rock site is a good “reference” site or not;
- the inability of NN and RF techniques to provide reliable estimates of the bandwidth of the amplification phenomena at a given site (they simply indicate the fundamental frequency) and therefore to provide any indication on high frequency amplification.

On the other hand, the existence of a slight correlation between NN peak amplitude and SR fundamental amplification calls for further analysis to better understand the phenomena. Noise waves should be more clearly identified and the role of each wave type explained. The approach to surface topography effects with the NN method should also be clarified: in theory, if such sites are not extensively weathered near the surface, polarization curves of Rayleigh waves should not present any prominent peak or trough.

Finally, further theoretical and experimental investigations are needed before this “H/V technique on microtremors” can be commonly used for microzoning purposes, taking into account clear and validated limits of use. This inexpensive tool will allow dense measurements and could lead to precise seismic hazard maps even in areas with low seismic rates.

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