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ROBUSTNESS OF THE H/V RATIO PEAK FREQUENCY TO ESTIMATE 1D RESONANCE FREQUENCY

Sylvette BONNEFOY-CLAUDET[1], Fabrice COTTON[2], Pierre-Yves BARD[2], Cécile CORNOU[2], Matthias OHRNBERGER[3], Marc WATHELET[2]
1 FMFI, Comenius University, Bratislava, Slovak Republic
2 LGIT, University Joseph Fourier, Grenoble, France
3 Institute of Geosciences, University of Potsdam, Germany

ABSTRACT - The H/V method has the potential to significantly contribute to site effects evaluation, in particular in urban areas. Within the SESAME European project (Site EffectS assessment using AMbient Excitations) we investigate the nature of ambient seismic noise in order to assess the reliability of this method. Through 1D seismic noise modeling, we simulate the ambient noise for a set of various horizontally stratified structures. We perform array analysis (*f-k*) for both vertical and horizontal synthetics and estimate the contribution of different seismic waves (body/surface waves, Rayleigh/Love waves) at the H/V peak frequency. We show that the very common assumption according which almost all the noise energy would be carried by fundamental mode Rayleigh waves is not justified. The proportion of different waves is dependent on site conditions, especially the impedance contrast. However, for the 1D horizontally layered media presented here, the H/V peak frequency always provides a good estimate of the fundamental resonance frequency whatever the H/V peak origin (Rayleigh waves ellipticity, Airy phase of Love waves, S-wave resonance). We also show that the relative proportion of Love waves in ambient noise controls the amplitude of the H/V peak.

1. Introduction

The H/V spectral ratio (i.e. the ratio between the Fourier amplitude spectra of the horizontal and the vertical component of microtremors) was first introduced by Nogoshi and Igarashi (1971), and widespread by Nakamura (1989, 1996, 2000). These authors have pointed out the correlation between the H/V peak frequency and the fundamental resonance frequency of the site, and they proposed to use the H/V technique as an indicator of the underground structure features. A large number of experiments (Lermo and Chavez-Garcia, 1993; Gitterman et al., 1996; Seekins et al, 1996; Fäh, 1997), supported by several theoretical 1D investigations (Field and Jacob, 1993; Lachet and Bard, 1994; Lermo and Chavez-Garcia, 1994; Wakamatsu and Yasui, 1996; Tokeshi and Sugimura, 1998; Bonnefoy-Claudet et al., 2006a), have shown that noise synthetics computed using randomly distributed, near surface sources lead to H/V ratios sharply peaked around the fundamental S wave frequency, when the surface layer exhibits a sharp impedance contrast with the underlying stiffer formations. However, the theoretical basis of the H/V technique is still unclear as two opposite explanations have been proposed. Nakamura (1989, 2000) claims that the horizontal to vertical spectral ratio mainly reflects the S-wave resonance in soft surface layer (removing effects of surface waves), and hence that H/V curves provide a consistent estimate of the site amplification function. This “body wave” interpretation has been contradicted in several papers highlighting the relationship between the H/V and the ellipticity of fundamental Rayleigh mode (Lachet and Bard, 1994; Kudo, 1995; Bard, 1998; Bonnefoy-Claudet et al., 2006a), and thus seriously questioning the existence of any simple direct correlation between H/V peak value and the actual site amplification factor. Recently Bonnefoy-Claudet et al. (2006b) highlighted the limited knowledge within the scientific community on the contribution of body and surface waves to the ambient noise wavefield.

The goal of the present paper is to investigate the relationship between the composition of the ambient noise wavefield and the effectiveness of the H/V method to estimate site response parameters (i.e., resonance frequency and amplification factor). We simulate the ambient noise for a set of various realistic horizontally stratified structures, the perform array analysis (f-k) for both vertical and horizontal synthetics and finally estimate the contribution of different seismic waves (body/surface waves, Rayleigh/Love waves) at the H/V peak frequency.

2. Noise Data sets

Eleven horizontally stratified media consisting of various sedimentary layers over a half-space, which are characterized by their impedance contrast, have been selected (Table 1). Ambient noise wavefield is computed at the surface of each soil model (see Figure 1 for the source – receiver geometry) using the wavenumber-based code developed by Hisada (1994, 1995).

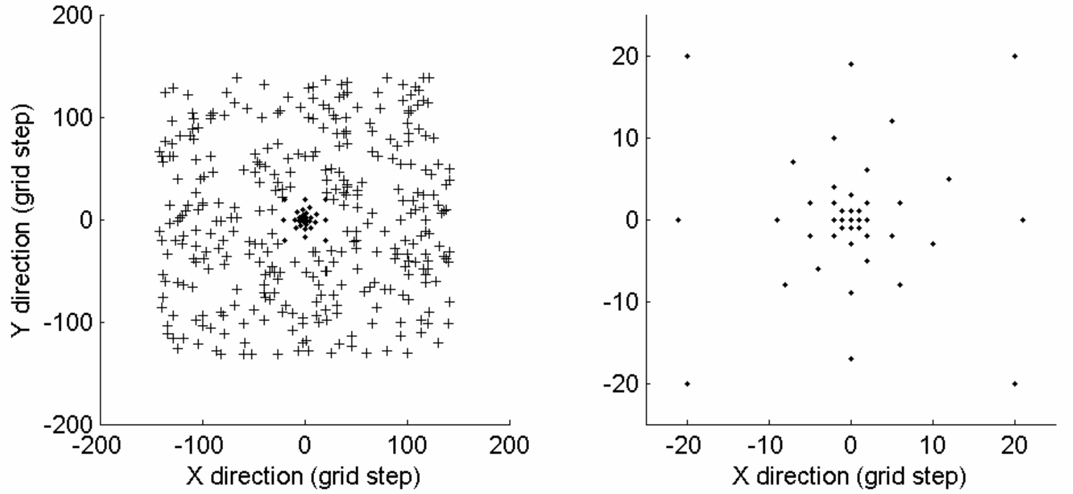

Figure 1. (left panel) Spatial distribution of the 333 sources (crosses) and 42 receivers (dots). (right panel) Zoom on the receiver geometry. See text for the values of grid the step for each soil model.

The code, that computes Green functions due to point sources for viscoelastic horizontally stratified media, allows source and receiver at very close depths. The response of the structure is then convolved with a large number of sources approximated by surface or subsurface forces, distributed randomly in space and time, with random direction and amplitude (Moczo and Kristek, 2002). The time function is a delta-like signal. The time series obtained at each receiver position is the sum of time series due to all sources contributions. In this study, Green functions were computed up to 14.28 Hz using a number of frequencies equal to 1024. The sources time function were band-pass filtered between 0.5 and 14.28 Hz, except for the deepest model (M3.3) for which sources were filtered between 0.1 and 14.28 Hz. The final duration of seismograms is 405 seconds.

Bonnefoy-Claudet *et al.* (2006a) have shown that at a given observation site local and near-surface sources dominate the ambient noise wavefield. Therefore we have set up sources location to fulfill this condition. Spatial locations of sources and receivers are defined according to the sedimentary layer thickness, and expressed in grid step (one grid step equals to 1 m). The minimum distance between two receivers and the receivers aperture are, respectively, 1 and 40 grid step. The sources aperture and depth are, respectively, 361 and 0.5 grid step. The grid step is set to 2 m for the shallow model (M2.4), to 4 m for intermediate thickness models (M2.1, M2.2, M3.1, M3.2, M4.1, M4.2, M4.3 and M4.4), to 8 m and 16 m for deep models (respectively, M2.3 and M3.3). All sources are modeled by delta-like source time function.

Table I. Soil material parameters of the 1D horizontally layered models considered in the present study: number of layers (N), thickness (H), P-wave velocity (α), S-wave velocity (β), quality factors for P and S waves (Qp and Qs, respectively) and the S-wave impedance contrast (Z). The impedance contrast is defined by considering the average S-wave velocity within the sediments and the S-waves velocity in the bedrock.

Model	N	H (m)	α (m/s)	β (m/s)	ρ (g/cm^3)	Qp	Qs	Z
M2.1	2	25	500	200	1.9	50	25	6.6
		-	2000	1000	2.5	10	50	
M2.2	2	25	1350	200	1.9	50	25	6.6
		-	2000	1000	2.5	10	50	
M2.3	2	83	1350	667	1.9	50	25	2.0
		-	2000	1000	2.5	10	50	
M2.4	2	10	1350	200	1.9	20	10	6.6
		-	2000	1000	2.5	10	50	
M3.1	3	18	1350	250	1.9	50	25	4.6
		18	1350	330	1.9	50	25	
		-	2000	1000	2.5	10	50	
M3.2	3	18	1350	250	1.9	50	25	5.5
		18	1350	625	1.9	50	25	
		-	2000	1500	2.5	10	50	
M3.3	3	31.25	500	250	1.9	50	25	4.0
		375	1800	750	2.1	10	50	
		-	3500	2000	2.5	20	100	
M4.1	2	36	1350	250+2z	1.9	50	25	4.7
		-	2000	1000	2.5	10	50	
M4.2	2	36	1350	250+5z	1.9	50	25	4.1
		-	2000	1000	2.5	10	50	
M4.3	2	36	1350	250+9z	1.9	50	25	3.5
		-	2000	1000	2.5	10	50	
M4.4	2	36	1350	250+15z	1.9	50	25	3.0
		-	2000	1000	2.5	10	50	

3. Methods

The idea of this study is to provide the relative composition of the seismic noise wavefield at the H/V ratio peak frequency. In this part we present the basis of the H/V method (so called Nakamura's technique) and the array processing method (CVFK) used here.

3.1. H/V

The H/V technique originally proposed by Nogoshi and Igarashi (1971), and wide-spread by Nakamura (1989, 1996) consists in estimating the ratio between the Fourier amplitude spectra of the horizontal and the vertical components of the microtremors recorded at the surface. In this study, the H/V ratio is calculated using 30 seconds length time windows. Fourier amplitude spectra are smoothed following Konno and Ohmachi (1998), with parameter b set equals to 40. The quadratic mean of the horizontal amplitude spectra is used here. The final H/V ratio is obtained by averaging the H/V ratios from all windows.

3.2. Array processing

The frequency-wavenumber (*f-k*) based methods are often used for deriving the phase velocity dispersion curves from ambient vibration array measurements. In this study, we have used the conventional semblance-based frequency-wavenumber method CVFK (Kvaerna and Ringdahl, 1986) implemented in the CAP software developed within the framework of the SESAME project (Ohrnberger, 2004; Ohrnberger et al., 2004a; Ohrnberger et al., 2004b). Operating with sliding time windows and narrow frequency bands, this method provides the wave propagation parameters (azimuth and slowness as a function of frequency) of the most coherent plane wave arrivals. In this study, we use a wavenumber grid layout sampled equidistantly in slowness and azimuth. The central frequency of each band was selected to be equally spaced in logarithm scale. A fraction of the central frequency f_c defined the frequency-bandwidth (0.9 f_c – 1.1 f_c). We selected the time-window length as 50 times the central period corresponding to the analyzed frequency band f_c. The CVFK method is applied, independently, on both vertical and horizontal components. We do not rotate horizontal components into radial and transverse components. We do this simplification because sources are randomly distributed in space (X, Y plane) (Bonnefoy-Claudet, 2004). For clarity purpose we show here only results for the North-South component.

4. Origin of the H/V peak

The H/V curves and apparent phase velocities computed from noise synthetics for each soil model are shown in Figure 2 to 4. Models have been classified into three groups according to the value of the impedance contrast between sediment and bedrock (see Table I):

1) high impedance contrast models, namely strictly above 4: models M2.1, M2.2, M2.4, M3.1, M3.2, M4.1 and M4.2 (Figure 2);
2) moderate impedance contrast models, namely between 3 and 4: models M3.3 and M4.3 (Figure 3)
3) low impedance contrast models, namely below 3: models M2.3 and M4.4 (Figure 4).

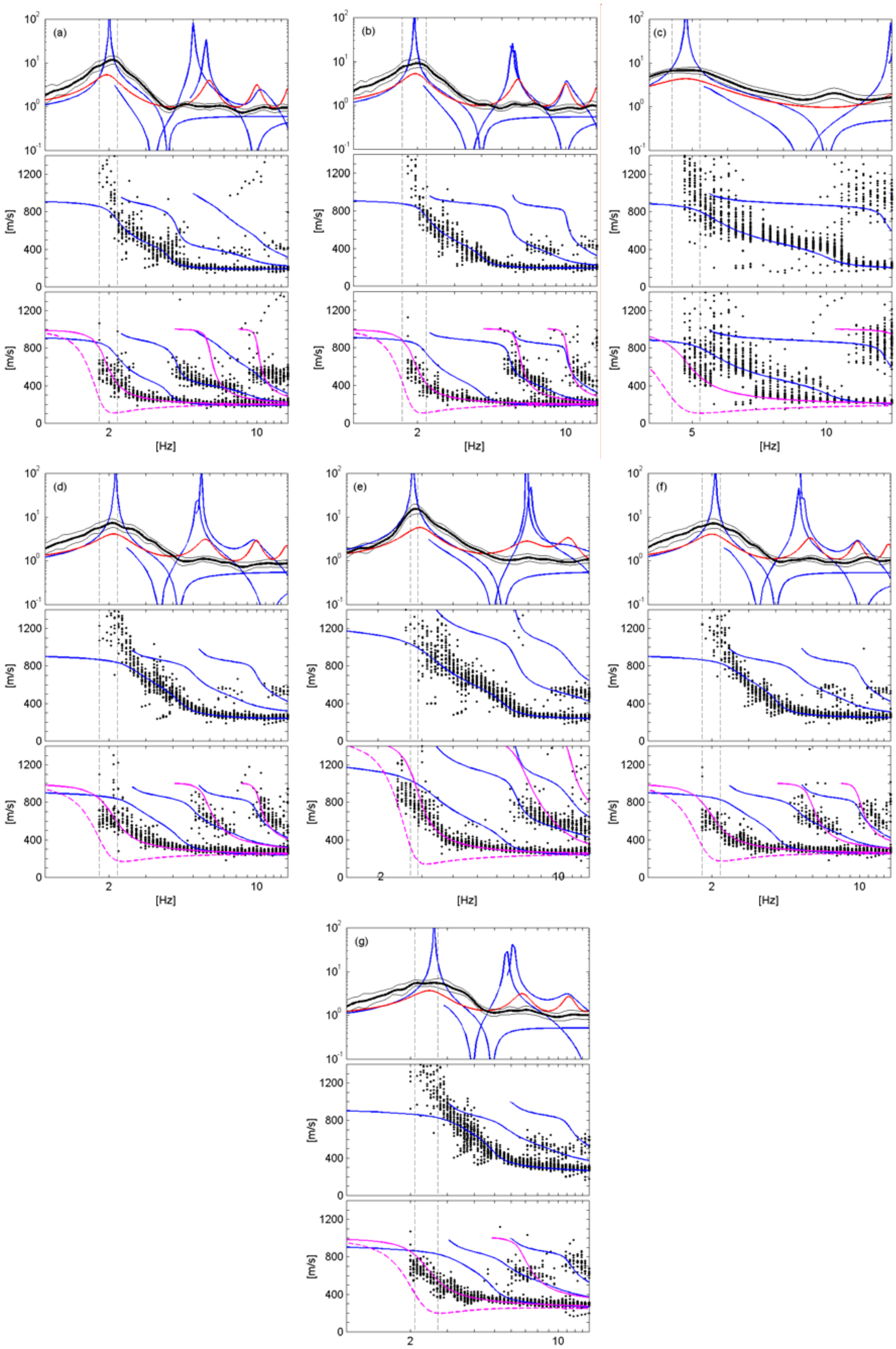

Figure 2. H/V ratio and array analysis results for the high impedance contrast models (a) M2.1, (b) M2.2, (c) M2.4, (d) M3.1, (e) (M3.2), (f) M4.1, (g) M4.2. (Top) H/V ratio curve (black thick line) and standard deviation (black thin lines), ellipticity curves of the fundamental, first and second Rayleigh modes (blue lines), 1D transfer function for vertically incident SH waves (red lines). (Middle) Phase

velocities estimates for the vertical noise wavefield (black dots), theoretical dispersion curves for the fundamental, first and second Rayleigh modes (blue lines). (Bottom) Phase velocities estimates for the North-South noise wavefield (black dots), theoretical dispersion curves for the fundamental, first and second Rayleigh modes (blue lines), theoretical dispersion curves for the fundamental, first and second Love modes (magenta lines), theoretical group velocity for the fundamental Love mode (magenta dashed lines) . Dashed grey lines indicate the location of the H/V ratio peak frequency (including standard deviation).

Whatever the soil model and the impedance contrast, the H/V curves always exhibits a peak in the vicinity of the fundamental resonance. The relative proportion of the different seismic waves strongly depends on the impedance contrast.

In case of high impedance contrast (> 4) (Figure 2), there is a good agreement between the H/V ratio peak frequency (called F_{hv} thereafter), the fundamental resonance frequency (called F_o thereafter) and the ellipticity peak frequency of the fundamental Rayleigh mode (called F_{ell} thereafter). Although the CVFK method suffers huge limitation close to F_{hv} (due to the vanishing of the energy on the vertical component), we can systematically identify the presence of the fundamental Rayleigh mode in the vertical noise wavefield from F_{hv} up to the maximum computational frequency. At higher frequency we can also note the presence of higher modes; however they have no influence on the H/V ratio peak. Note also that phase velocity estimates by using the horizontal component fit rather well the fundamental Love mode which is a strong indication that noise synthetics are dominated by Love waves in the horizontal plane.

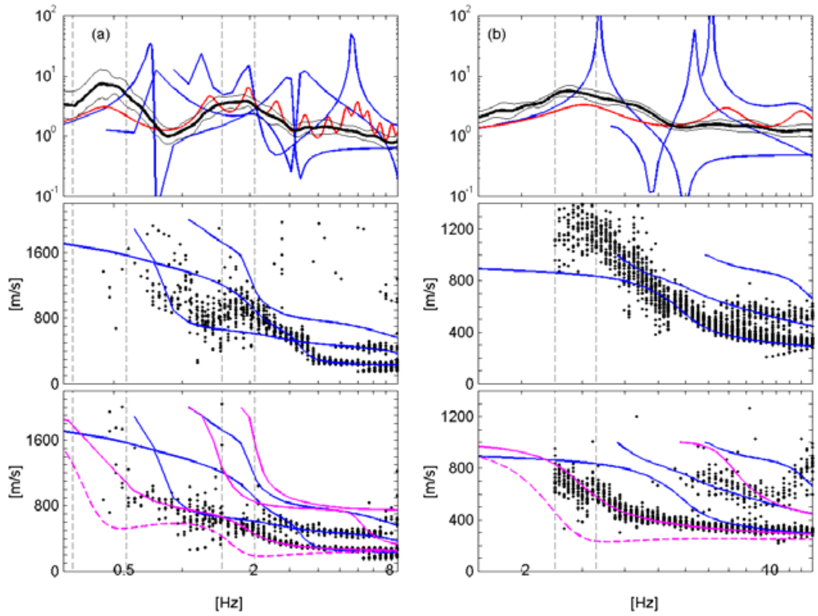

Figure 3. H/V ratio and array analysis results for the moderate impedance contrast models (a) M3.3, (b) M4.3. See Figure 2 for legend.

In case of moderate impedance contrast (3< Z >= 4) (Figure 3), there is a discrepancy between F_{hv} and F_{ell}, suggesting that the H/V ratio peak is not due to the fundamental Rayleigh mode. This hypothesis is enhanced by array analysis results. The phase velocity estimates clearly show that the fundamental Rayleigh mode is not present in the noise wavefield at F_{hv}. However, there is a good agreement between F_{hv} and F_o (deviation less than 20%). Note, for the M3.3 model, the presence of a second small amplitude H/V ratio peak (Figure 3a). The origin of this peak can not be deduced from our array analysis; it could be due either to higher Rayleigh mode, either to an S-waves resonance. Note once again the presence of the fundamental Love mode.

In case of low impedance contrast (<= 3) (Figure 4), we can distinguish two different situations. In the first case (Model M2.3), there is no ellipticity peak but the H/V curve exhibits one peak. Moreover there is a good agreement between F_{hv} and F_o (both in frequency and amplitude) (Figure 4a). It is quite difficult to identify clearly which waves are responsible for the H/V peak in such a situation. However since the H/V peak amplitude matches the theoretical amplification factor, it strongly suggests that the H/V ratio is due to an S-waves resonance. In the second case, the fundamental Rayleigh mode exhibits a peak but there is a large discrepancy between F_{hv} and F_{ell}. Once again, we observe a good agreement between F_{hv} and F_o (deviation less than 20%). Similarly to the case of moderate impedance contrast, the fundamental Rayleigh mode is not present in the noise wavefield at F_{hv}, and we note the presence of fundamental Love mode.

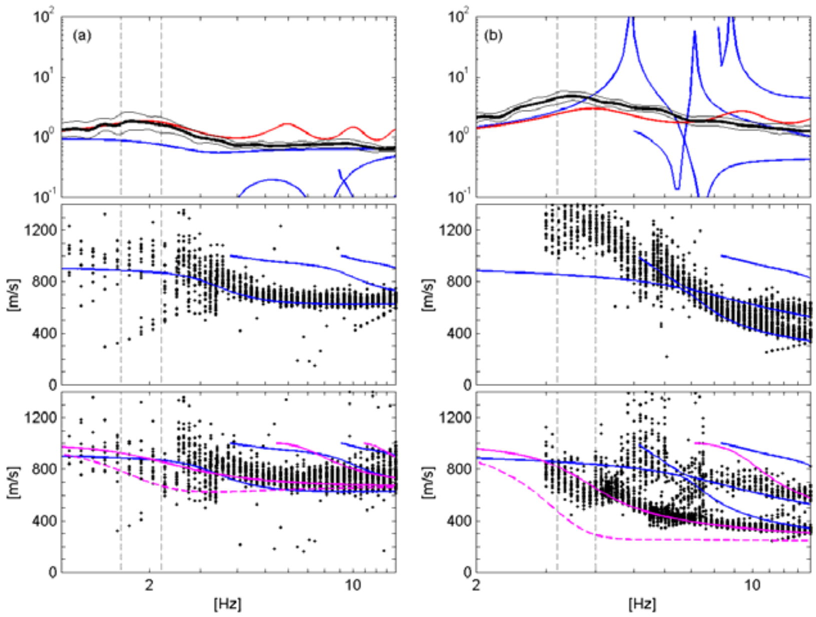

Figure 4. H/V ratio and array analysis results for the low impedance contrast models (a) M2.3, (b) M4.4. See Figure 2 for legend.

6 Discussion

The two initials hypothesis on the origin of the H/V ratio peak discussed in the beginning of the present paper were 1) the S-waves resonance within the sedimentary fill (Nakamura, 1989, 2000), 2) the horizontal polarization of the Rayleigh waves (ellipticity peak) (Lachet and Bard, 1994; Kudo, 1995; Bard, 1998; Bonnefoy-Claudet et al., 2006a). The in-depth investigation of noise wavefield structure at F_{hv} shows that the first hypothesis (S-waves resonance) is fully fulfilled only in case of low impedance contrast. The second hypothesis (Rayleigh waves ellipticity) is fulfilled in case of high impedance contrast, but it is not always satisfied in case of low or moderate contrast.

The CVFK analysis performed on horizontal component reveals the systematic presence of fundamental Love mode in the ambient noise wavefield. The strong energy on horizontal component at the Airy phase of Love waves may enhance the H/V ratio which is the ratio between the Fourier amplitude spectra of the horizontal and vertical components (see group velocity of Love waves on Figure 2, 3 and 4).

To test this working hypothesis and state about the origin of the H/V ratio peak we have plotted the value of F_{hv} in regards to F_o, F_{ell} and F_{airy} (the Airy phase frequency of fundamental Love mode) Figure 5a and 5b show the same results as already observed: whatever the impedance contrast value, there is a good agreement between F_{hv} and F_o (Figure 5a). Figure 5b indicates that the Rayleigh waves ellipticity explains the H/V ratio peak only in case of high impedance contrast and only in some cases of moderate impedance contrast. In case of low contrast, the ellipticity of Rayleigh waves can not explain the H/V peak ratio. Does the Airy phase of Love waves influence the H/V ratio? Figure 5c indicates that this hypothesis is fulfilled in case of high or some moderate contrast. It is never satisfied in case of low impedance contrast.

We then conclude that the origin of the H/V ratio peak is not unique and involve Rayleigh waves ellipticity, Love waves Airy phase, or the S-wave resonance. Nevertheless in all cases presented here, the H/V ratio peak frequency provides a good estimation of the resonance frequency.

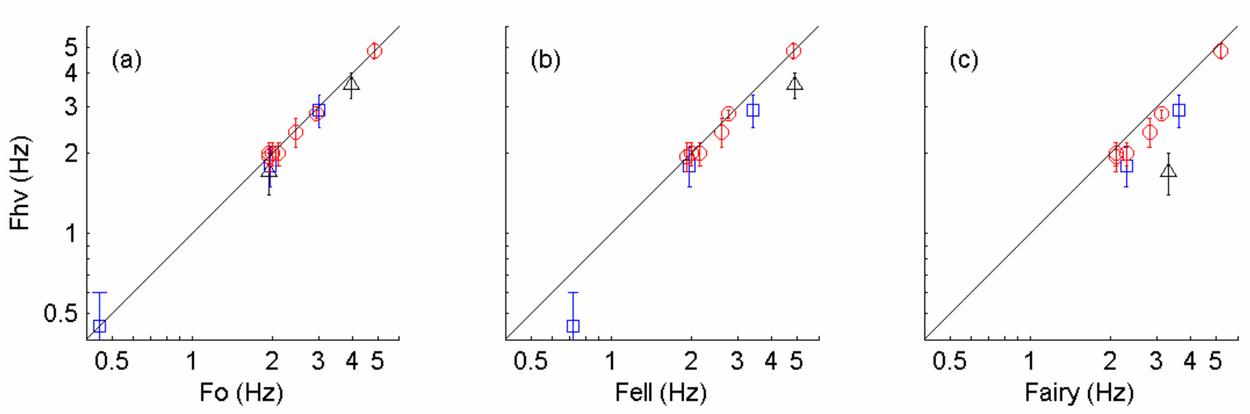

Figure 5. H/V ratio peak frequency plotted against (a) the 1D theoretical resonance frequency, (b) the ellipticity peak frequency of the fundamental Rayleigh mode, (c) the Airy phase frequency of fundamental Love mode. Results are shown for each model according to the values of the impedance contrast: high (red dots), moderate (blue dots) and low (black dots).

Figure 6a shows the relationship between the H/V ratio peak amplitude and the theoretical site amplification factor. The H/V ratio peak amplitude observed on noise synthetics overestimates the site amplification factor. This observation contradicts previous field results showing that actual H/V ratio peaks amplitude underestimates the amplification factor given by the site-to-reference earthquake method (e.g. Haghshenas (2005)). In our simulation, direction of forces is randomly distributed: such randomness could be different from actual field noise sources. Therefore we simulated noise synthetics for the same set of models and source-receiver configuration, but with different sources characteristics: 1) vertical point forces (generation of P, Sv waves), 2) radial point forces (generation of Sv waves). We observed lower H/V ratio peak amplitude in case of vertical (Figure 6b) and radial (Figure 6c) sources than for random sources (Figure 6a). Or the sources configuration of Figure 6a increases the amount of Love waves compared to sources configurations of Figure 6b and 6c. Our results then suggest a large influence of Love waves on the H/V peak amplitude. The relative proportion of Love waves in ambient noise should also control the amplitude of the H/V peak, as already discussed in Arai and Tokimatsu (2000) who show the influence of Love waves on the shape of the H/V ratio curves.

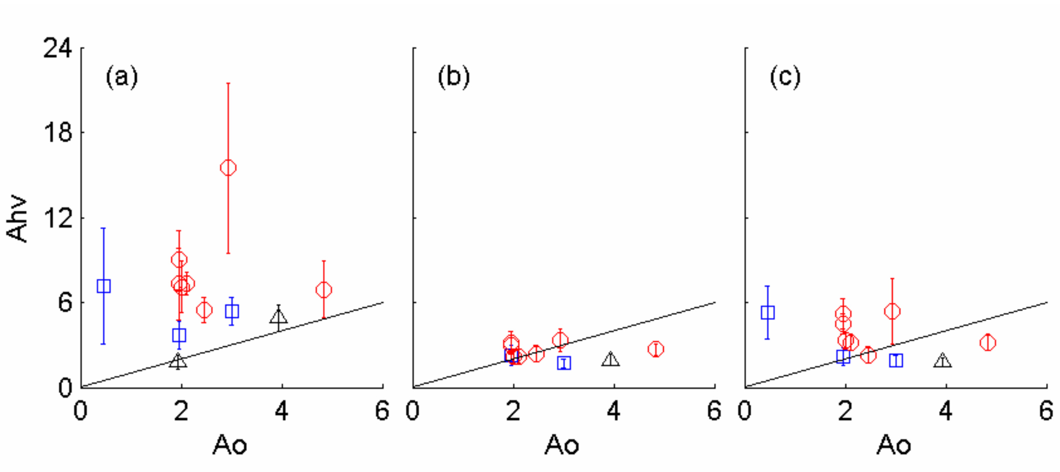

Figure 6. H/V ratio peak amplitude plotted against the site amplification given by the 1D theoretical transfer function. H/V curves are calculated from different sets of noise synthetics computed with various sources force amplitudes: (a) randomly generated in 3D space, (b) vertical and (c) radial. Results are shown for each model according to the values of the impedance contrast: high (red dots), moderate (blue dots) and low (black dots).

5 Conclusions

The relative contribution of different type of seismic waves to the ambient noise wavefield strongly depends on the impedance contrast between sediment and bedrock and sources configurations. The origin of the H/V ratio peak is not unique; three factors can explain this peak: 1) the Rayleigh waves ellipticity, 2) the Airy phase of Love waves, 3) the S-wave resonance. Whatever its origin, we show the robustness of the H/V peak to provide a good estimate of the 1D theoretical resonance frequency, at least for the horizontally layered models presented here.

This study also indicates that Love waves are always present in the ambient noise wavefield and have a significant role. This observation agrees with Bonnefoy-Claudet et al. (2006) who show that, at least, 50% of energy in actual noise wavefield is propagated by Love waves. The relative proportion of Love waves in ambient noise controls the amplitude of the H/V peak. Therefore the H/V is not reliable to providing a correct estimation of the site amplification factor. To investigate more in-depth the relative proportion of Rayleigh and Love waves in ambient noise, we propose to use the 3-components SPAC (SPatial AutoCorrelation method) array methods (see for example Köhler et al. (2006)).

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