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SIMULATION OF SEISMIC AMBIENT VIBRATIONS: DOES THE H/V PROVIDE QUANTITATIVE INFORMATION IN 2D-3D STRUCTURES?

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ABSTRACT

Ambient vibration techniques such as the H/V technique are very powerful tools to study local soil behavior and thus to significantly contribute to effective seismic risk mitigation, in particular in urban areas. In addition to mapping the resonance frequencies of the soil, the H/V technique has been used in recent studies as an alternative tool to classical geophysical exploration for characterizing sediment infilling (typically sediment thickness or average shear velocity) by taking advantage of the simple relation ($f_0=V_s/4h$) between the resonance frequency (f_0), the average shear-wave velocity (V_s) and the average sediment thickness (h). Although reliable in horizontal layering, this simple interpretation that relies on 1D wave propagation may be thus misleading in case of 2D or 3D structures. Within the framework of the SESAME project (Site EffectS Assessment using AMbient Excitations) ambient seismic noise has been simulated for a set of 2D and 3D structures in order to test the relevancy of H/V in providing qualitative and quantitative information on site features. Ambient noise was modeled by using a finite-difference scheme with spatially and temporally random surface sources. Analysis of these noise synthetics led us to deduce the following features between the site geometry, the shape of the H/V curve and the H/V peak frequency: H/V curves systematically exhibit clear peaks in the flat parts of the structures, and broad peaks or plateau-like shapes of low amplitude in parts with strong lateral sediment thickness variation (valley edges for example). In the flat parts or parts of gentle underground slopes of both 2D or 3D structures the H/V peak frequencies agree within +/-20% the theoretical 1D resonance frequencies. For 2D structures H/V systematically overestimates by around 15% the resonance frequency at the valley edge, while for 3D structures, H/V peak frequencies strongly underestimate (up to 80%) the 1D resonance frequency at sites with the steepest underground slopes. From a practical use of H/V, we suggest that H/V curves exhibiting broad peaks or plateau-like shapes of low amplitude should not be used for deriving any quantitative information of average shear-wave velocity or average sediment thickness by using the simple $f_0=V_s/4h$ relation.

1. Introduction

Ambient vibration techniques such as the H/V technique (Nakamura, 1989) are very powerful tools to study local soil behavior and thus to significantly contribute to effective seismic risk mitigation. In addition to mapping the resonance frequencies of the soil, the H/V technique has been used in recent studies as an alternative tool to classical geophysical exploration for characterizing sediment infilling (typically sediment thickness or average shear velocity) by taking advantage of the simple relation ($f_0=V_s/4h$) between the resonance frequency (f_0), the average shear-wave velocity (V_s) and the average sediment thickness (h). Although reliable in horizontal layering (Bonnefoy-Claudet et al., 2004), this simple interpretation – that relies on 1D wave propagation – may be misleading in case of 2D or 3D structures. Within the framework of the European SESAME project (Site EffectS Assessment using AMbient Excitations) ambient seismic noise has been simulated for a set of typical 2D and 3D structures (dipping layer, shallow and deep valley, etc.) as described in Cornou et al. (2004). In this study, we present the results obtained by applying the H/V technique to a subset of 2D and 3D structures and draw some practical recommendations regarding the availability of H/V to detect strong lateral underground thickness variation and to derive quantitative information by using the $f_0=V_s/4h$ relation.

2. Description of models, noise synthetics and H/V processing

Models and noise synthetics. The numerical code used is intended to simulate ambient seismic noise originated by human activity, for sites with heterogeneous subsurface structures. Noise sources are approximated by surface or subsurface forces, distributed randomly in space, direction (vertical or horizontal), amplitude, as well as in time. The time function is either delta-like signal (impulsive sources) or pseudo-monochromatic signal (“machine” sources) (a harmonic carrier with Gaussian envelope). Computation of the associated wave field is performed using an explicit heterogeneous finite-difference scheme solving equations of motion in the heterogeneous visco-elastic medium with material discontinuities (Moczo et al., 2002a, 2002b). The simple 2D-3D structures considered in this study are described in Figure 1 and characteristics of noise synthetics and data processing parameters are indicated in Table 1.

Models	Freq. Band (Hz)	Time duration (s.)	Nb windows / time window (s.)	Smoothing (b) / cosine taper (%)	Nb receivers
M3A	0.7 – 7.8	104	4 / 22	40 / 10	576
M4A	0.9 – 8.0	90	6 / 15	40 / 10	801
M6A	0.18 – 1.7	252	4 / 63	40 / 10	469
M7A	0.18 – 1.7	168	3 / 56	40 / 10	485
M9A	1.0 – 7.9	89	4 / 22	40 / 10	801

Table 1: Signal characteristics and data processing parameters: reliable frequency band for noise simulation, time duration for noise synthetics, number of windows and windows length used for H/V processing, the Konno and Ohmachi smoothing parameter (b), the cosine taper used and number of receivers for each model.

H/V processing. H/V have been computed by using the *geopsy* software (www.geopsy.org) following the SESAME guideline (Köller et al., 2004). Duration of noise synthetics being limited, no anti-trigger tool was used to define time windows. The H/V peak frequencies have been manually picked by screen viewing the NS/V, EW/V and average H/V curves and by considering the following rules:

- the H/V peak should have an amplitude greater than two;
- for H/V curves exhibiting a "plateau like" shape, the H/V peak frequency is defined as the frequency cut-off of the plateau (Figure 2). Such "plateau-like" shapes have already been observed in complex subsurface structures by Uebayashi (2003).

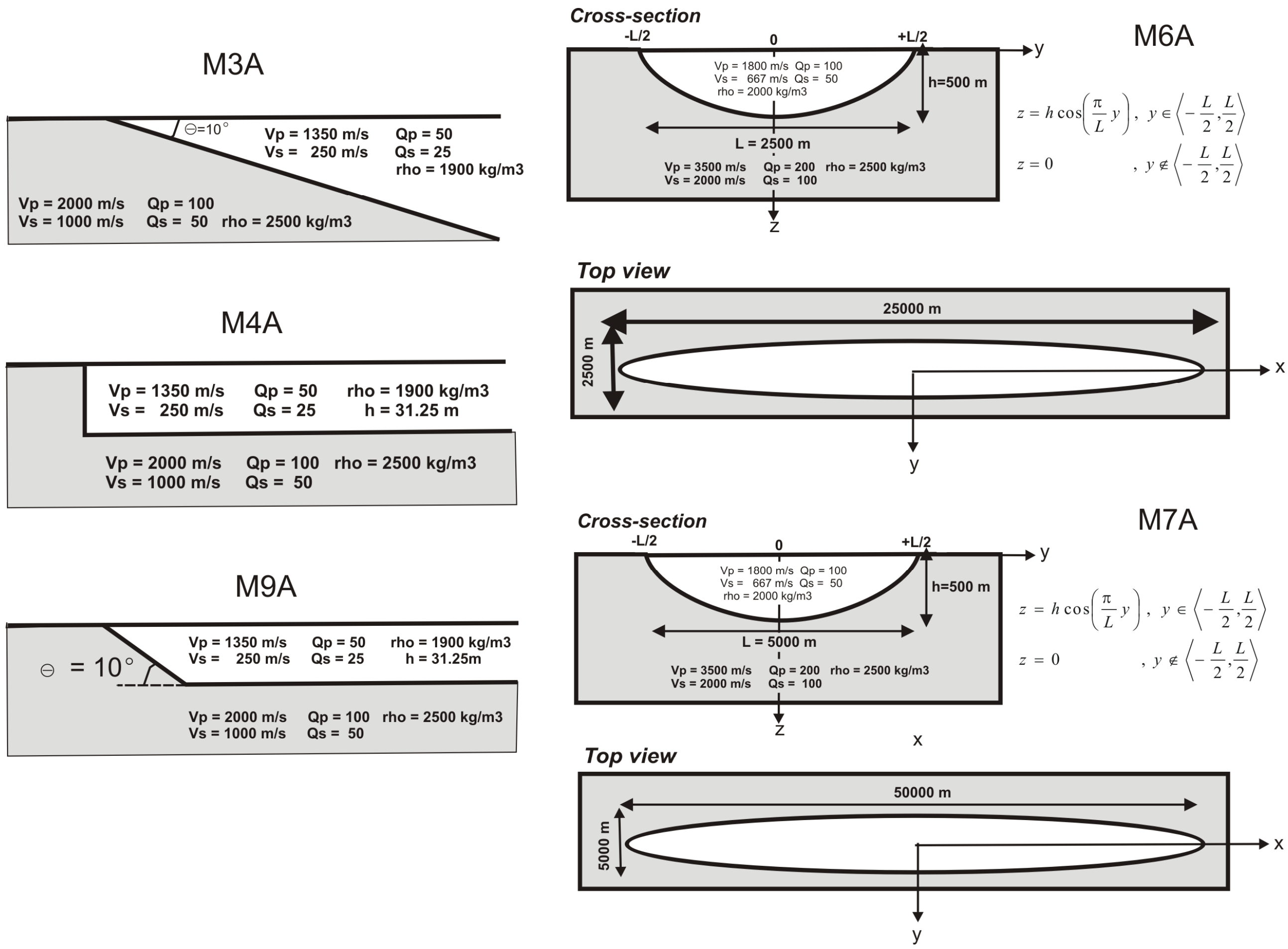

Figure 1: Geometry and material properties of the models considered in this study

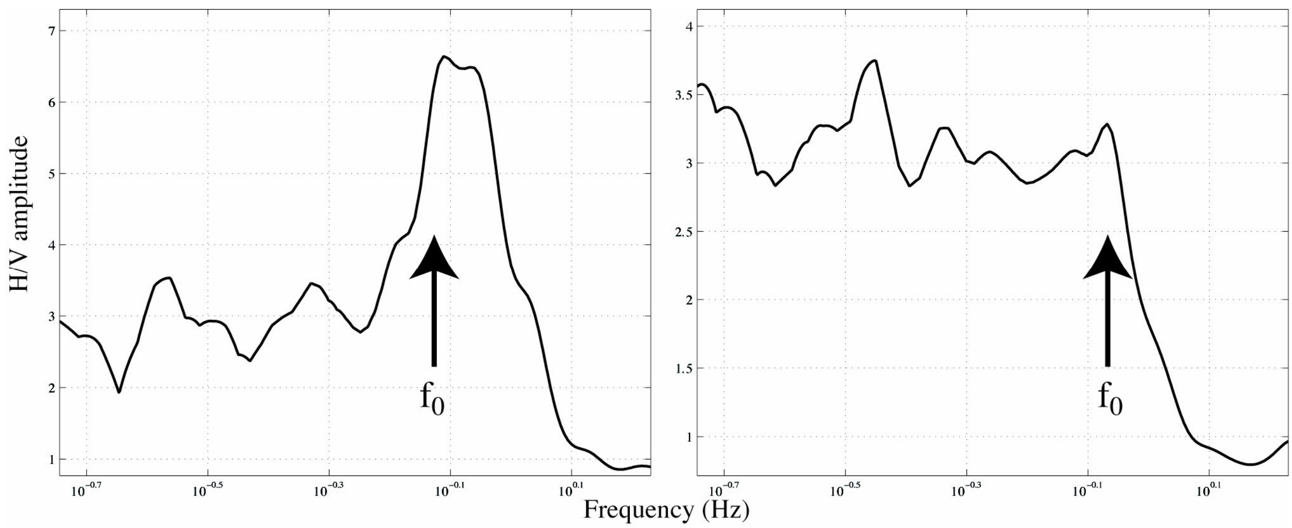

Figure 2: Picking of the H/V curves: (left) simple H/V peak; (right) in case of "plateau-like" H/V curve shape, the H/V peak frequency is defined at frequency cut-off of the plateau.

3. Results for 2D models

Results for M3A model are displayed in figure 3. The three H/V curves (H/V, NS/V, EW/V) show, as expected, a decrease of the H/V peak frequency with an increase of the sediment thickness (figure 3B). Although the frequencies related to the H/V highest amplitude are close to the 1D theoretical resonance frequency (determined by applying the formula $f_0 = V_s/4h$), the picked H/V peak frequencies overestimate in most cases the 1D theoretical resonance frequency, the mean relative deviation being 14% over the entire frequency band. Despite the homogeneous impedance contrast, the amplitudes of H/V are not homogenous, the relative amplitude variation being up to 100% (figure 3B). Furthermore, it has to be pointed out that the H/V peak is broader and much less pronounced at low frequency.

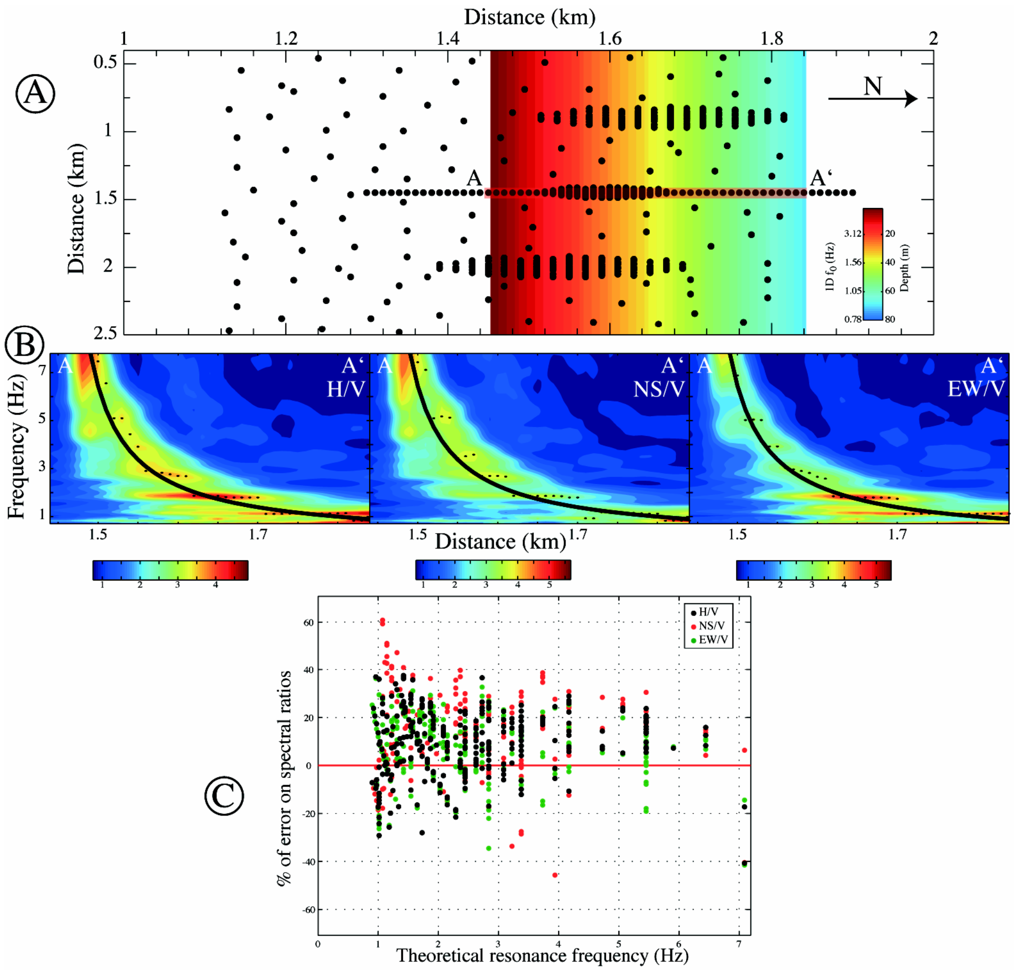

Figure 3: Results for M3A model. A: model with location of the A-A' cross-section and receiver locations (black dots). B: H/V cross-sections along the A-A' profile; black circle: f_0 picked from H/V curve, black line: theoretical 1D f_0. C: relative deviation in percent of the H/V, NS/V and EW/V peak frequencies from the 1D theoretical resonance frequency f_0.

For M4A model (figure 4B), the three H/V curves (H/V, NS/V, EW/V) displayed as a function of distance along the AA' profile show a good agreement with the theoretical 1D curve, the picked H/V frequencies agreeing within ± 20% with the resonance frequency of the structure (Figure 4C), the mean relative deviation being 8% over the entire frequency band. Once again, despite the homogeneous impedance contrast, the three H/V peak amplitudes are not consistent, the relative amplitude variation being up to 50% (figure 4B).

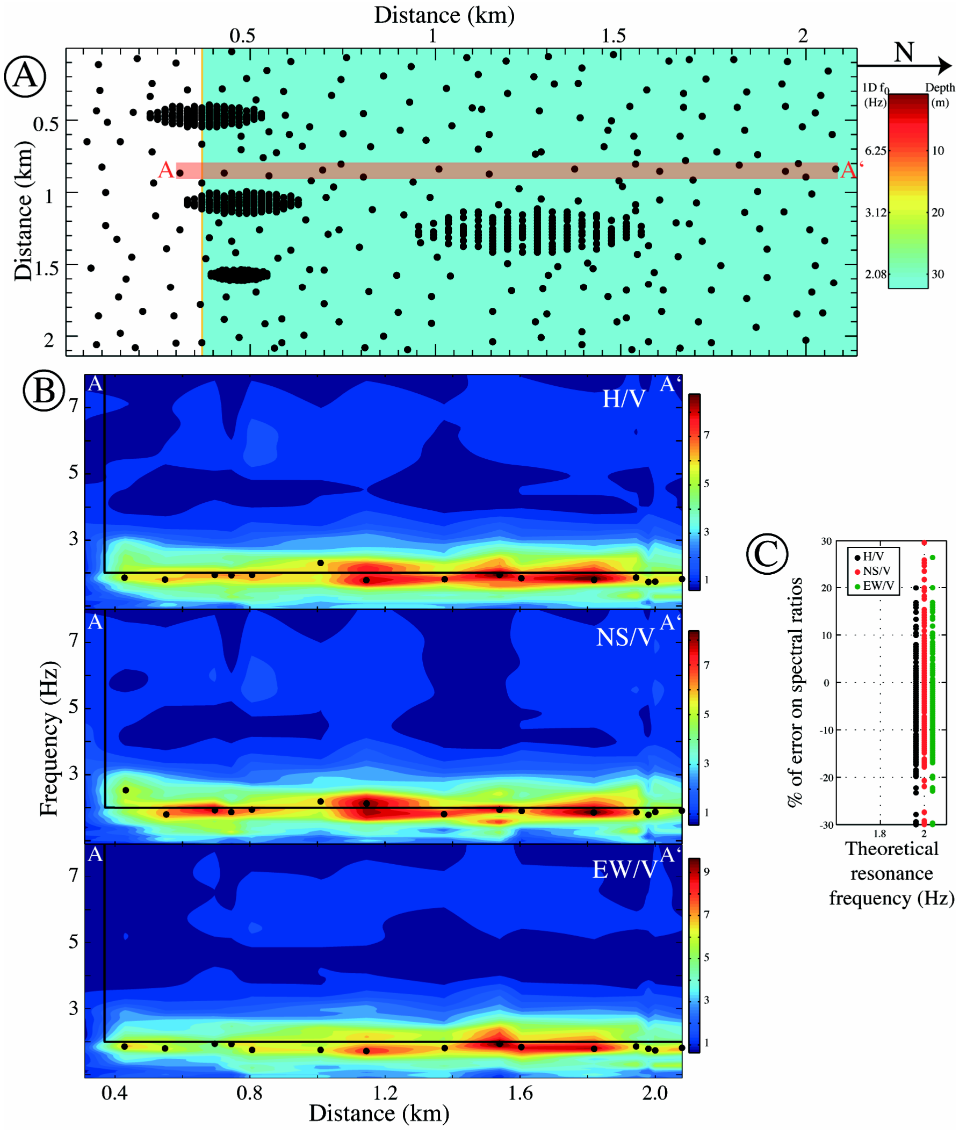

Figure 4: Results for M4A model. A: model with location of the A-A' cross-section and receiver locations (black dots). B: H/V cross-sections along the A-A' profile; Black circle: f_0 picked from H/V curve, black line: theoretical 1D resonance frequency f_0. C: relative deviation in percent of the H/V, NS/V and EW/V peak frequencies from the 1D theoretical resonance frequency f_0 (since the theoretical frequency is 2 Hz, we have shifted the frequency abscissa by -0.1Hz for H/V and by +0.1 Hz for EW/V).

While the H/V curves for M9A model (figure 5B) exhibit clear peaks in the flat part of the model, H/V peaks are much broader and especially exhibit low maxima in the part of rapidly varying thickness. The H/V peak frequencies in the flat part agree within ± 20% with the resonance frequency of the structure, and overestimate in most cases by 14% the theoretical frequency at the valley edge (figure 5C).

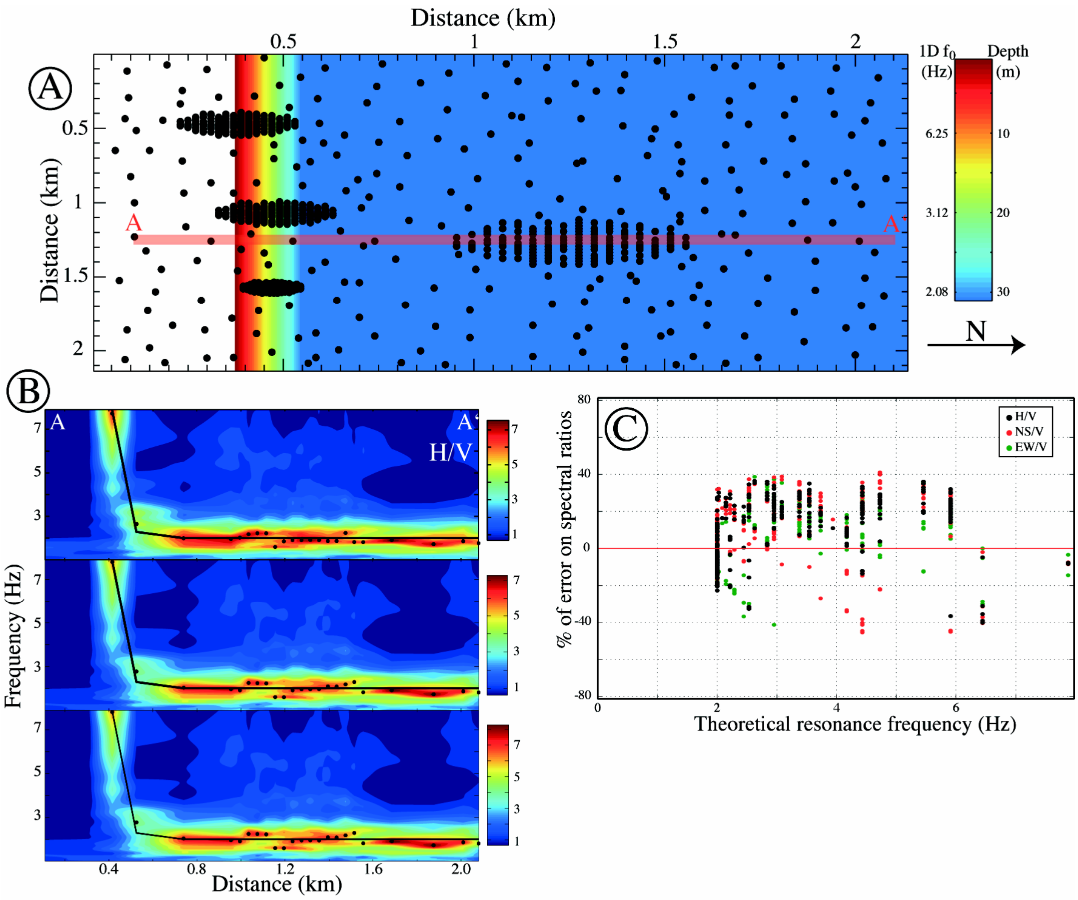

Figure 5: Results for M9A model. A: model with location of the A-A' cross-section and receiver locations (black dots). B: H/V cross-sections along the A-A' profile; black circle: f_0 picked from H/V curve, black line: theoretical 1D resonance frequency f_0. C: relative deviation in percent of the H/V, NS/V and EW/V peak frequencies from the 1D theoretical resonance frequency f_0.

4. Results for 3D models

For M7A model, the H/V curves and the H/V peak frequencies computed along the AA' profile map rather well the sediment thickness variation and the theoretical resonance frequency, respectively (figure 6B). Along the BB' and CC' profiles (figure 6C), only the display of H/V curves as a function of distance along the profile allows to following the sediment thickness variation, especially near the valley edges. Along these profiles, the H/V curves exhibit indeed very broad peak or plateau-like shape of low maxima. Whenever it was possible to pick H/V peak frequencies following the above mentioned rules, their values showed up significant deviations from the theoretical 1D resonance frequency (relative deviation from –70% to 40%, mean of 14%, figure 6D)

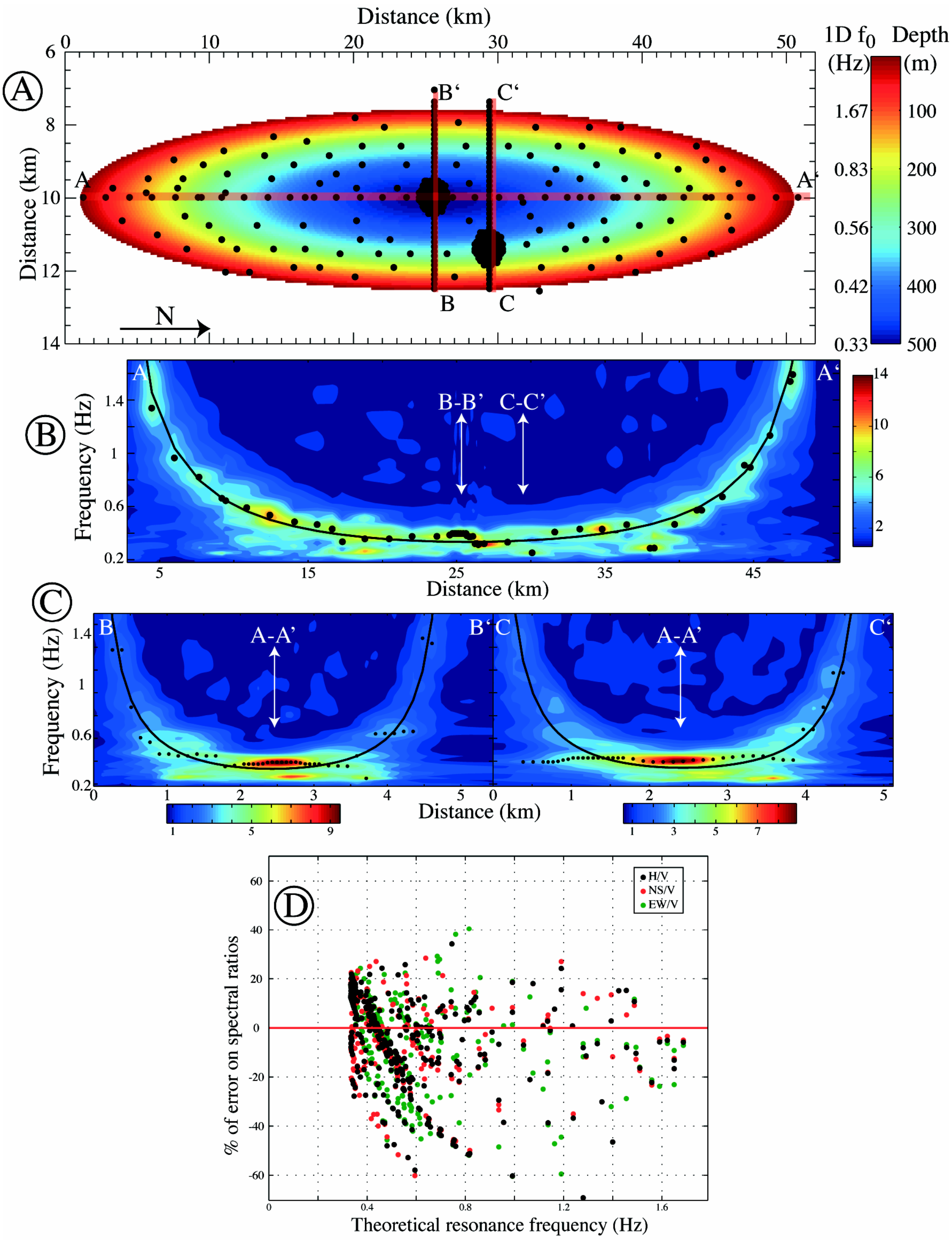

Figure 6: Results for M7A model. A: model with location of the A-A' – B-B' and C-C' cross-sections and receiver locations (black dots). B: H/V cross-sections along the A-A' profile. Black circle: f_0 picked from H/V curve, black line: theoretical 1D resonance frequency f_0 . C: H/V cross-sections along the B-B' and C-C' profiles. Black circle: f_0 picked from H/V curve, black line: theoretical 1D resonance frequency f_0. D: relative deviation in percent of the H/V, NS/V and EW/V peak frequencies from the 1D theoretical resonance frequency f_0

The only difference between the M6A and the M7A model is the apex ratio of the valley, the width-to-thickness ratio being smaller for the M6A model. Underground slopes along profiles perpendicular to the valley main axis are thus larger than for the M7A model. While H/V curves map rather well the sediment thickness variation along the AA' profile (figure 7B), it is difficult to follow any clear trend of increasing H/V peak frequencies with decreasing local thickness along BB' and CC' profiles (figure 7C). Along these profiles, the picked H/V frequencies systematically underestimate the 1D resonance frequency near the valley edges. For this model, the relative deviation of the H/V peak frequencies from the 1D resonance frequencies ranges from +40% to –80% (figure 7D).

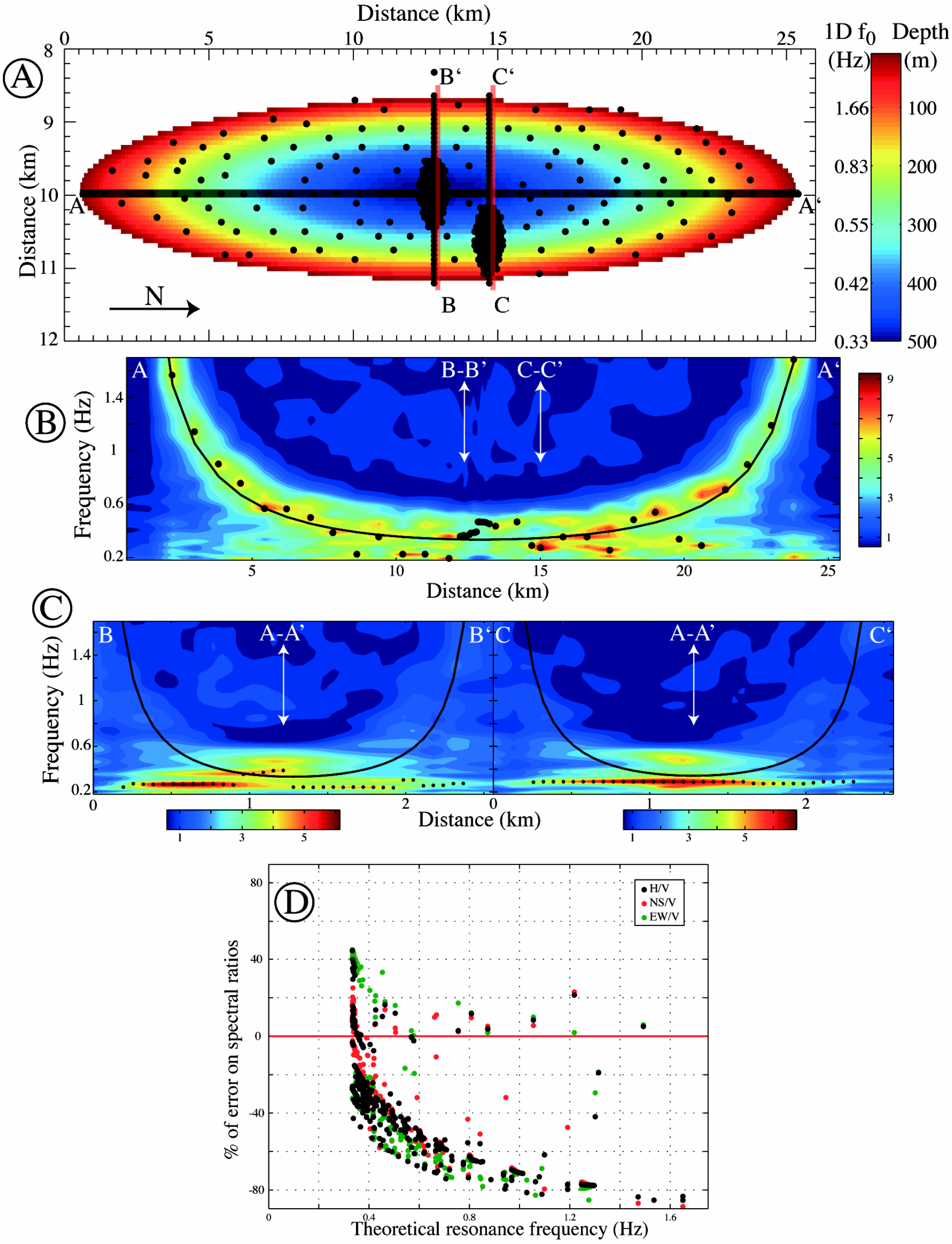

Figure 7: Results for M6A model. A: model with location of the A-A' – B-B' and C-C' cross-sections and receiver locations (black dots). B: H/V cross-sections along the A-A' profile. Black circle: f_0 picked from H/V curve, black line: theoretical 1D resonance frequency f_0 . C: H/V cross-sections along the B-B' and C-C' profiles. Black circle: f_0 picked from H/V curve, black line: theoretical 1D resonance frequency f_0. D: relative deviation in percent of the H/V, NS/V and EW/V peak from the 1D theoretical resonance frequency f_0

5. Conclusion

The analysis of ambient noise simulated for 2D and 3D structures have shown that, as expected, the H/V peak frequency decrease with increase of the sediment thickness variation. For both structure types (2D and 3D), the H/V curves exhibit clear peaks in the "flat" parts of the structures, and broad peaks or plateau-like shapes of low amplitude in parts with strong lateral sediment thickness variation (valley edges). Such broad H/V peaks are most probably related to the more complex wavefield (diffracted body and surface waves) close to lateral heterogeneities than in the flattest parts of the structure (mainly surface waves). The H/V peak frequencies have been manually determined on all individual H/V curves. For 2D models, whenever it was possible to pick the H/V peak frequencies, the H/V peak frequencies agree within +/-20% the theoretical 1D resonance frequencies in the flat parts of the structure and overestimates by around 15% the resonance frequency at the valley edge. For 3D models, H/V peak frequencies are close to the theoretical 1D resonance frequency at sites with gentle underground slopes, while H/V peak frequencies strongly underestimate (up to 80%) the 1D resonance frequency at sites with steep underground slopes.

From a practical use of H/V, peculiar shape of the H/V curves (broad peak, plateau-like shape, low maxima) is obviously an indication of the presence of strong underground lateral thickness variation. When ones want to use H/V for mapping the sediment-to-bedrock topography, the results shown here suggest that, after a dense geographic coverage of ambient vibration measurement points, H/V curves should be plotted as function of distance along profiles in order to properly follow the spatial variation of H/V curves and to qualitatively drive the picking of H/V peak frequencies. When one wants to use H/V for retrieving quantitative information of the average sediment thickness or the average velocity, the results presented here suggest that the simple formula $f_0=V_s/4h$ can be only used when 1D wave propagation occur (clear H/V peaks) and should be completely disregarded when strong lateral variation are detected (broad peaks or plateau-like shapes of low maxima).

6. References

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