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SIMULATION OF SEISMIC AMBIENT VIBRATIONS – II H/V AND ARRAY TECHNIQUES FOR REAL SITES

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SUMMARY

Within the SESAME project (Site EffectS Assessment using Ambient Excitations), we have simulated seismic ambient noise originated by human activity for a shallow (Colfiorito, Italy) and a deep (Grenoble, French Alps) sedimentary basin whose structures are sufficiently well known to allow crosschecking with observations. Comparison of H/V and array techniques applied on the noise synthetics with the 1D local resonance frequencies and known structure has outlined the capability of the H/V technique in mapping the sediment thickness variation and the array technique in retrieving the shear waves velocity profiles. Such a potential is confirmed when cross-checking with actual noise measurements.

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INTRODUCTION

The analysis of ambient vibration recordings for site effect estimation has gained more and more interest in recent years and it is commonly thought that both single station methods (H/V technique after Nakamura [1]) as well as array measurements [2] may allow to obtain estimates of the fundamental resonance frequency (H/V technique) and the shallow shear velocity profiles at a given sensors array location. Considering that such field experiments are inexpensive and do not require heavy seismic sources or drilling, the passive recording of ambient vibrations may provide a low-cost mapping tool of site features even in urban areas, where geotechnical information is usually difficult to obtain. However, physical basis and actual relevancy for site effect estimates of such methods have never reached a scientific overall agreement. Numerical simulations of the noise wave field and cross checking of observations, numerical simulations and known structure for a set of canonical models [3] and a few well-known test-sites should also help in investigating the reliability of these techniques to retrieve relevant information for site effect estimation, whatever the structure (1D, 2D or 3D). Within the European SESAME project (Site EffectS Assessment using Ambient Excitations), we have simulated ambient noise for the shallow sedimentary basin of Colfiorio (Italy) and the deep sedimentary basin of Grenoble (French Alps). The structure of both sites is well known and array ambient vibrations have already been performed within the scope of the SESAME project [4]. We first shortly describe the geophysical settings of these basins, the ambient noise modeling procedure and the array and H/V techniques used here. Then, the simulated ambient noise and the known structure are compared in terms of fundamental resonance frequency and inverted velocity profiles at array sites that were actually deployed in the field. Next, synthetics and actual noise are compared at these array sites in terms of inverted seismic profiles. These comparisons should finally help in answering the following questions: is the ambient noise modeling procedure used here able to capture the actual noise wave field? Do the H/V and array techniques provide relevant information about the site features?

NOISE SIMULATION, H/V AND ARRAY ANALYSIS AND SYNTHETIC DATA SET

Simulation of ambient noise

The numerical code [5] that has been developed within the SESAME project is intended to simulate ambient 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 a either delta-like signal (impulsive sources) or a pseudo-monochromatic signal ("machine" sources) (a harmonic carrier with the 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 [6].

H/V, array analyses and inverted seismic profile

The H/V ratios were computed using 40 seconds time duration windows overlapped by 20% and smoothed following Konno and Ohmachi [7]. The frequency-wavenumber and the spatial autocorrelation (SPAC) methods are the two main array techniques used for deriving the phase velocity dispersion curves from ambient vibration array measurements. In this paper, we have used the classical (CVFK) or the High-Resolution frequency-wavenumber (HRFK) analysis ([8], [9]) and the inverted seismic profiles were obtained using an Neighbourhood algorithm developed within the SESAME project by [10] after [11].

GEOPHYSICAL SETTINGS OF THE COLFIORITO AND THE GRENOBLE BASINS AND NOISE SYNTHETICS DATA SET

A shallow sedimentary basin: the Colfiorito plain

The Colfiorito basin displayed in Figure 1A is a 3 km wide and 180 m maximum thickness small intra-mountain basin of the Apennine in Umbria (Central Italy). The sediment fill is composed of Quaternary alluvial deposits overlaying a rock basement of limestones and marls of the Umbria-Marche Meso-Cenozoic Sequence. Extensive geophysical measurements (seismic and electric profiles) have allowed to precisely estimating the low-velocity layer thickness throughout the basin [12]. For the noise simulation, we have considered 346 receivers (Figure 1B) located at the free surface, some of them fitting the actual noise array measurement locations [4]. 2046 sources (Figure 1B) composed of 50% of delta-like and 50% of pseudo-monochromatic signals have been randomly distributed at the free surface within the basin. The minimum receiver-to-source distance is 60 m. The noise synthetics are 176 s long duration and, for some time computation considerations, simulation was splitted up into two frequency bands: from 0.3 to 1.6 Hz and from 1.3 to 3.3 Hz. The model dimension $(X \times Y \times Z)$ of the part of the Finite-Difference grid that encompasses the basin is $16140 \times 16140 \times 320$ meters and $5550 \times 4770 \times 310$ with a grid spacing of 20 m and 10 m for the 0.3-1.6 Hz and the 1.3-3.3 Hz frequency ranges, respectively. This 0.3-3.3 Hz frequency range encompasses most of the frequencies that were amplified during last 1997 Umbria Marche seismic sequence [12].

A deep sedimentary basin: the Grenoble basin

The Y-shaped sedimentary fill of the Grenoble basin consists of late quaternary post-glacial deposits overlaying Jurassic marls and a marly limestone bedrock. Both geometry (Figure 2A) and mechanical properties of the basin were inferred from gravimetric, active reflection and refraction seismic and microtremor recordings studies [13]. In addition, these methods were calibrated and validated by a deep borehole drilled in the NE branch of the valley (Figure 2A). We have simulated 180 s of noise for the 0.2 to 1 Hz frequency band that corresponds to the lowest part of the actually amplified frequency band, from 0.2 to 10 Hz [14]. 1273 receivers (Figure 2B) and 19998 sources (Figure 2B) have been distributed at the free surface. Some of the receiver locations fit with the real noise array measurements locations [15]. As it is the case for Colfiorito basin, sources are composed of 50% of delta-like and 50% of pseudo-monochromatic signals and the minimum receiver-to-source distance is 200 m. The model dimension $(X \times Y \times Z)$ of the portion of the Finite-Difference grid that encompasses the basin is $33300 \times 33300 \times 1550$ meters and the grid spacing is 50 m.

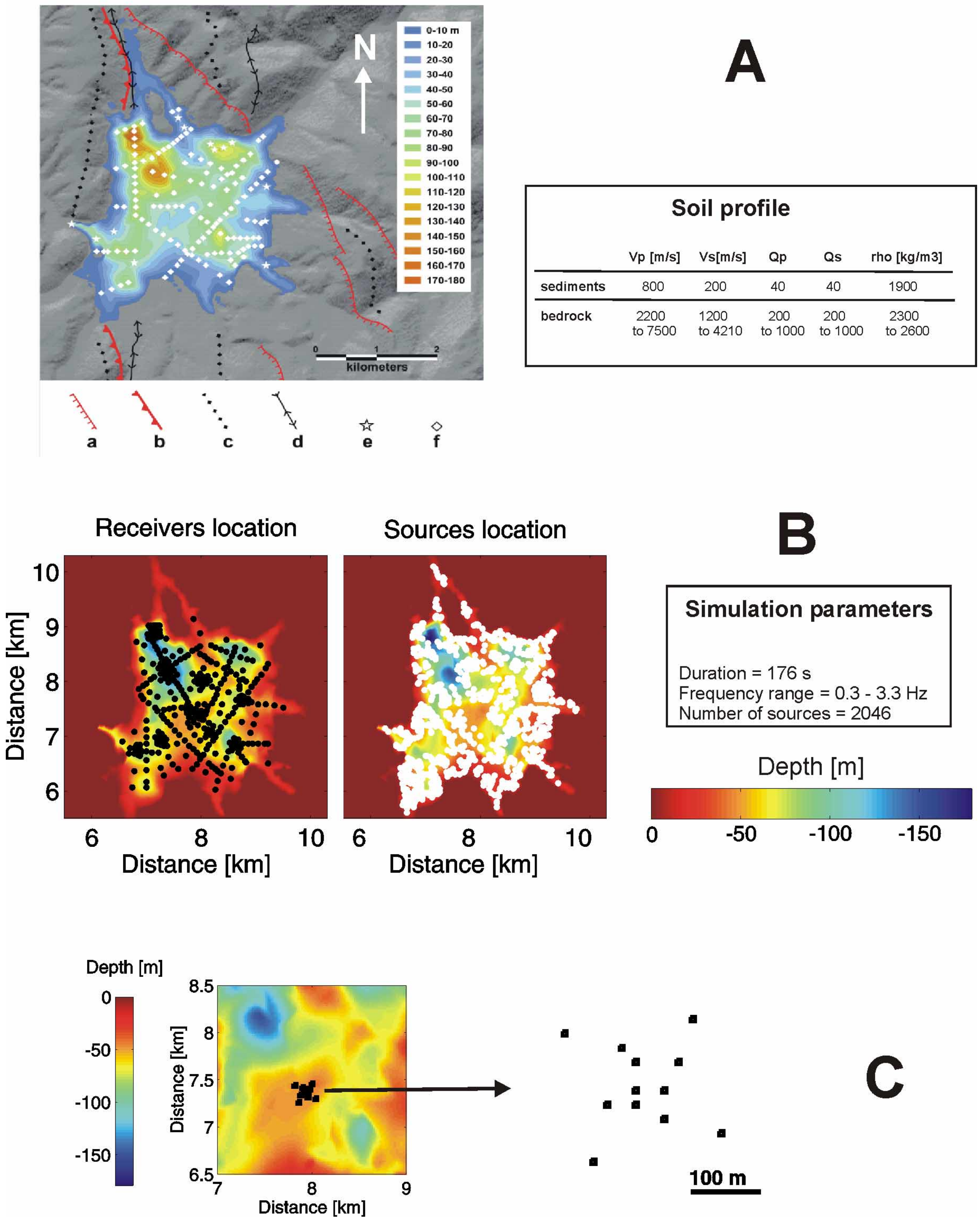

Figure 1: (A) Contouring thickness of the low-velocity layer within the basin (left) after Di Gliuo [12] and soil profile (right); (B) Topography of the low-velocity layer, receivers (black dots) and sources (white dots) location and parameters used for the noise simulation; (C) Configuration of the array considered in this study for the noise array analysis.

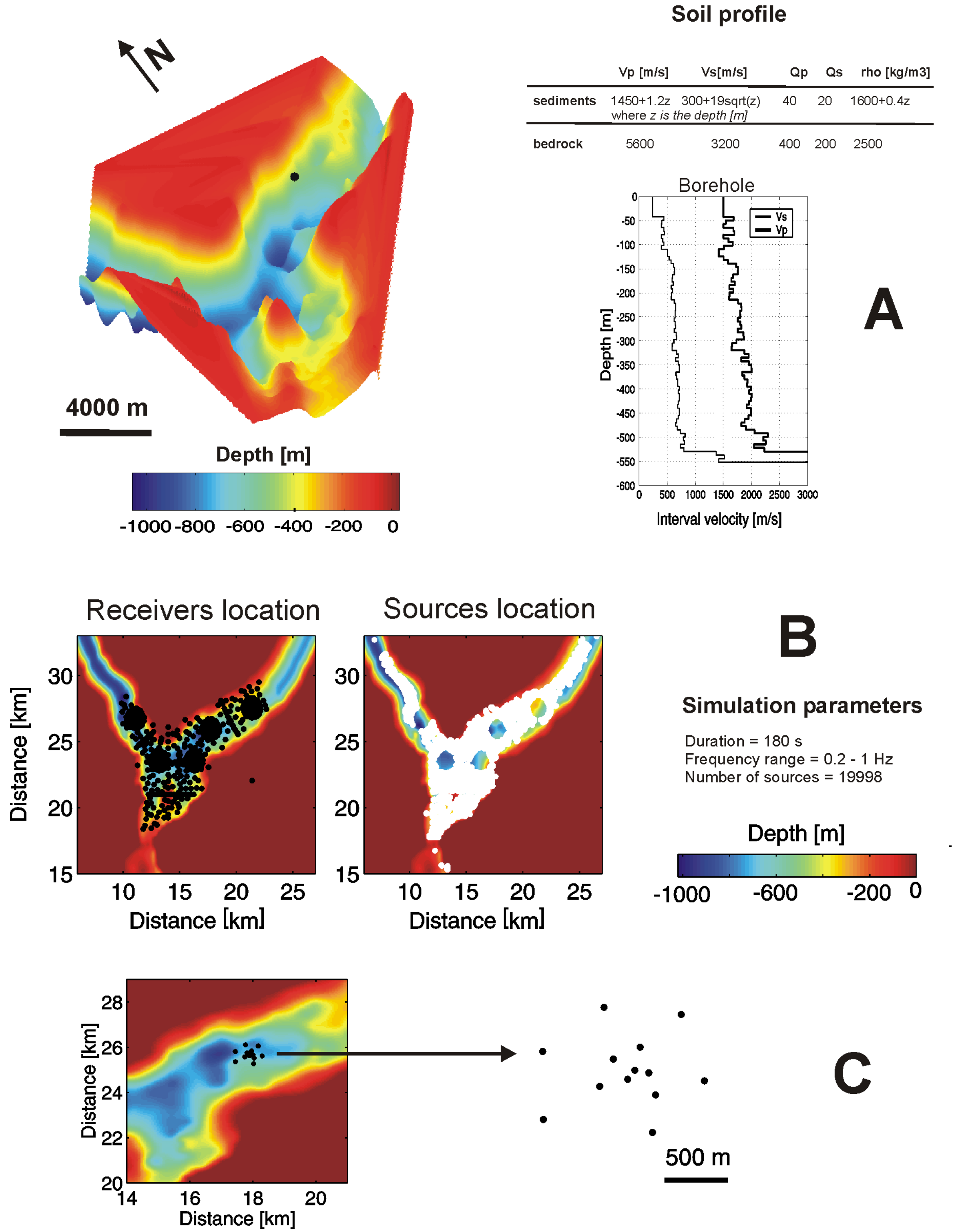

Figure 2: (A) Topography of the sediments-to-bedrock interface (left); soil profile, P- and S- wave velocity profiles at the borehole location and parameters used for the simulation of noise (right); (B) Topography of sediments-to-bedrock interface, receivers (black dots) and sources (white dots) location and parameters used for the noise simulation; (C) Configuration of the array used for the noise array analysis.

H/V AND ARRAY TECHNIQUE ON SIMULATED NOISE

H/V ratios

We have compared the H/V peak frequencies computed on the simulated noise with the theoretical 1D resonance frequencies given by the 1D transfer function computed for vertically incident S-wave. When comparing frequencies, no standard deviation for the peak frequency estimates was considered since the short duration of noise time series did not allow meaningful statistics. Figures 3 and 4 display for both sites: (a) a contouring display of the 1D resonance frequency estimated at each receiver location, (b) a contouring display of the H/V peak frequency, (c) the relative deviation (in %) of the H/V peak frequencies from the 1D resonance frequencies, (d) the H/V peak frequency as a function of the 1D resonance frequency.

For Colfiorito basin (Figure 3), the H/V peak frequencies map very well the low-velocity layer thickness variation throughout the basin. Moreover, most of the H/V peak frequencies agree within a deviation range of 10-20% with the 1D frequencies, the most extreme deviation are found for receivers that are located at the border of the model. For Grenoble basin (Figure 4), the H/V peak frequencies are correlated with the thickness variation. However, most of the H/V peak frequencies significantly overestimate the theoretical 1D local frequency, with a relative deviation up to 50%.

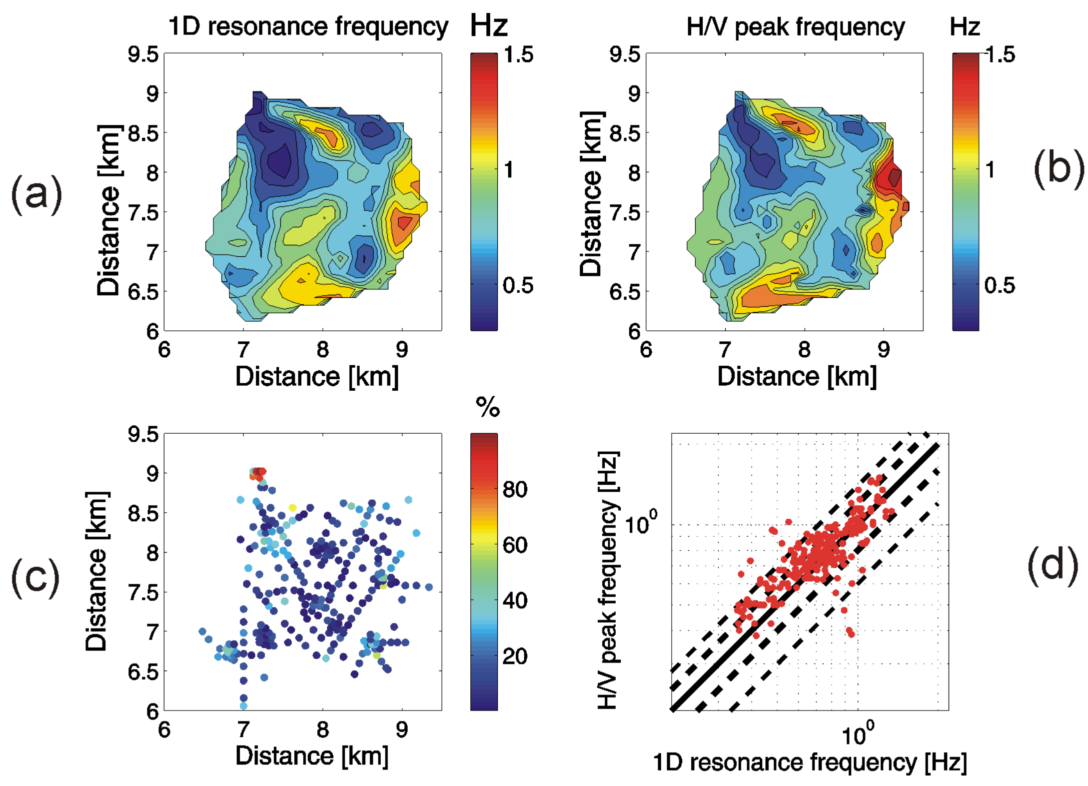

Figure 3: Noise simulation for Colfiorito basin: (a) contouring display of the 1D resonance frequencies estimated at each receiver location; (b) contouring display of the H/V peak frequency; (c) relative deviation of the H/V peak frequencies from the 1D resonance frequencies; (d) H/V peak frequency as a function of the 1D resonance frequency, the 1:1 relative deviation from the 1D resonance frequency is indicated by the thick black line, the 20% and 40% deviation are indicated by the thick and thin dashed lines, respectively.

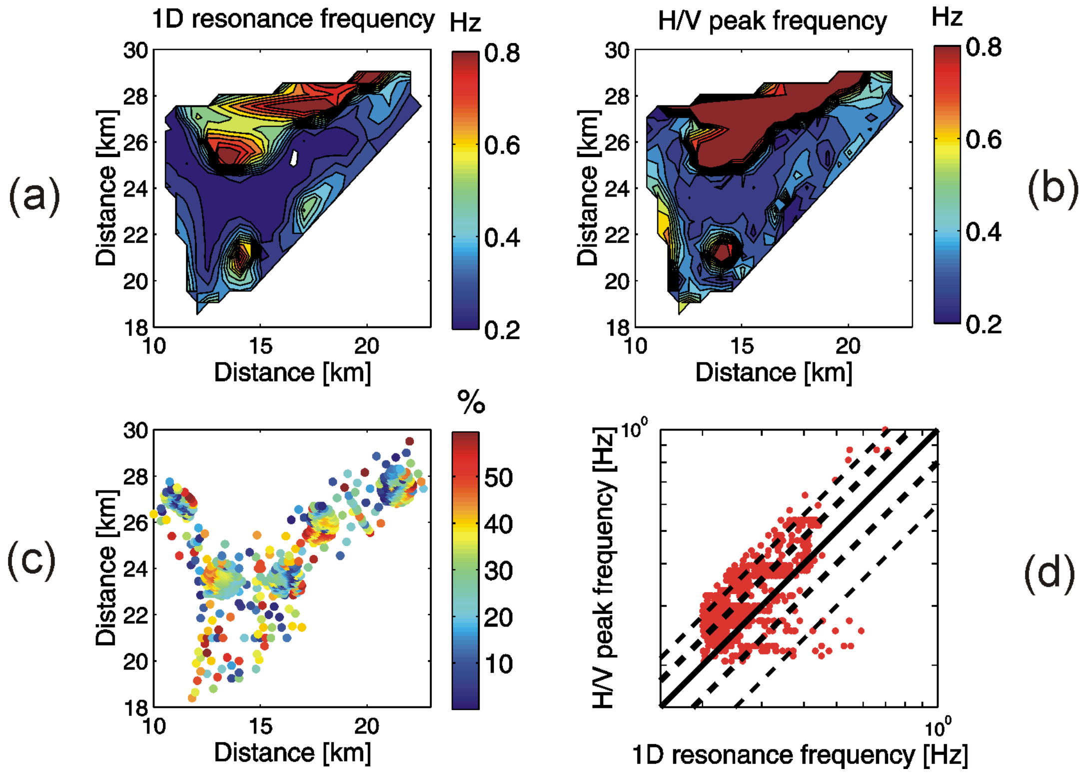

Figure 4: Noise simulation for Grenoble basin: (a) contouring display of the 1D resonance frequencies estimated at each receiver location; (b) contouring display of the H/V peak frequency; (c) relative deviation of the H/V peak frequencies from the 1D resonance frequencies; (d) H/V peak frequency as a function of the 1D resonance frequency, the 1:1 relative deviation from the 1D resonance frequency is indicated by the thick black line, the 20% and 40% deviation are indicated by the thick and thin dashed lines, respectively.

Array techniques

For the array analysis, we have used the two arrays displayed in Figure 1C and 2C. The location and geometry of these arrays are similar to some arrays that have been deployed in the field ([4], [15]). Figure 5 (top) and Figure 6 (top) for Colfiorito and Grenoble sites, respectively, displays the inverter P- and S-wave velocity profiles as well as the measured phase velocities.

For Colfiorito site, the array is located above an almost flat sediment-to-bedrock topography. The average sediment thickness below the array is 48 m (Figure 1C). The inversion has been performed using a band-limited portion of the estimated dispersion curve, from the H/V peak frequency of the site at 0.85 Hz up to 2.7 Hz. The array analysis did not indeed provide reliable estimates of the phase velocities at frequencies below the resonance frequency because of the lack of coherent energy (that comes from the limited aperture of the array or/and the fact that we do not include in the simulation the effects of impinging coastal surface waves that propagate at low frequency throughout the crustal structure). The inverted P- and S- wave velocity profiles are in very close agreement with the 1D local soil profile.

For Grenoble basin, the thickness of the sediments varies from 576 to 792 m below the array with an average thickness of 650 m. The dispersion curve was inverted from 0.4 to 0.95 Hz. The inverted seismic profiles provide a sediment-to-bedrock interface at around 550 m. The estimated gradient velocity is larger by a factor of about 20-30% than the gradient introduced in the modeling. The velocities in the bedrock are poorly constrained and could be explained by the lack of coherent energy at frequencies below the resonance frequency of the site, as previously mentioned. It has to be also pointed out that the scattering of the measured phase velocities, which is mainly due to the short time duration of the noise time series considered in this study.

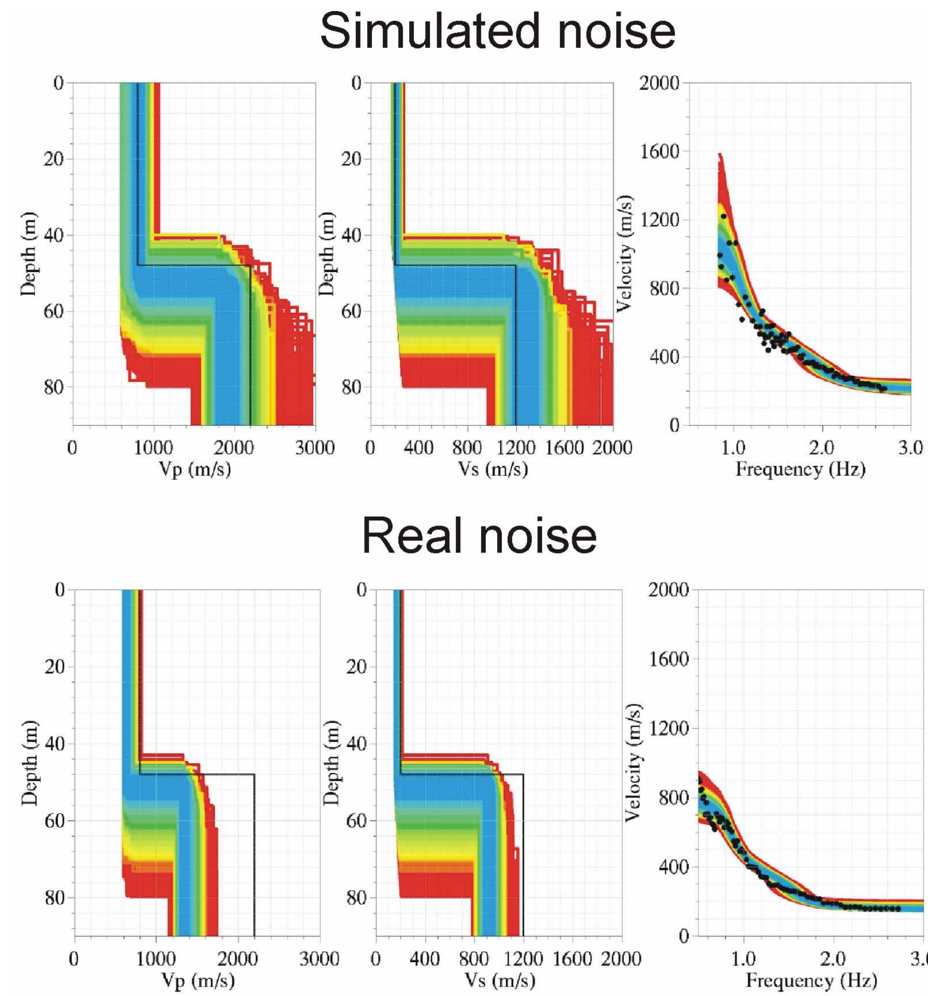

Figure 5 : Colfiorito basin : P- and S- wave seismic profiles estimated using simulated ambient noise (top) and real ambient noise (bottom). The best inverted seismic profiles are displayed by the blue color. The black line on the inverted velocity profile indicates the theoretical local soil profile and the black dots on the dispersion curves show the phase velocities obtained from the CVFK analysis.

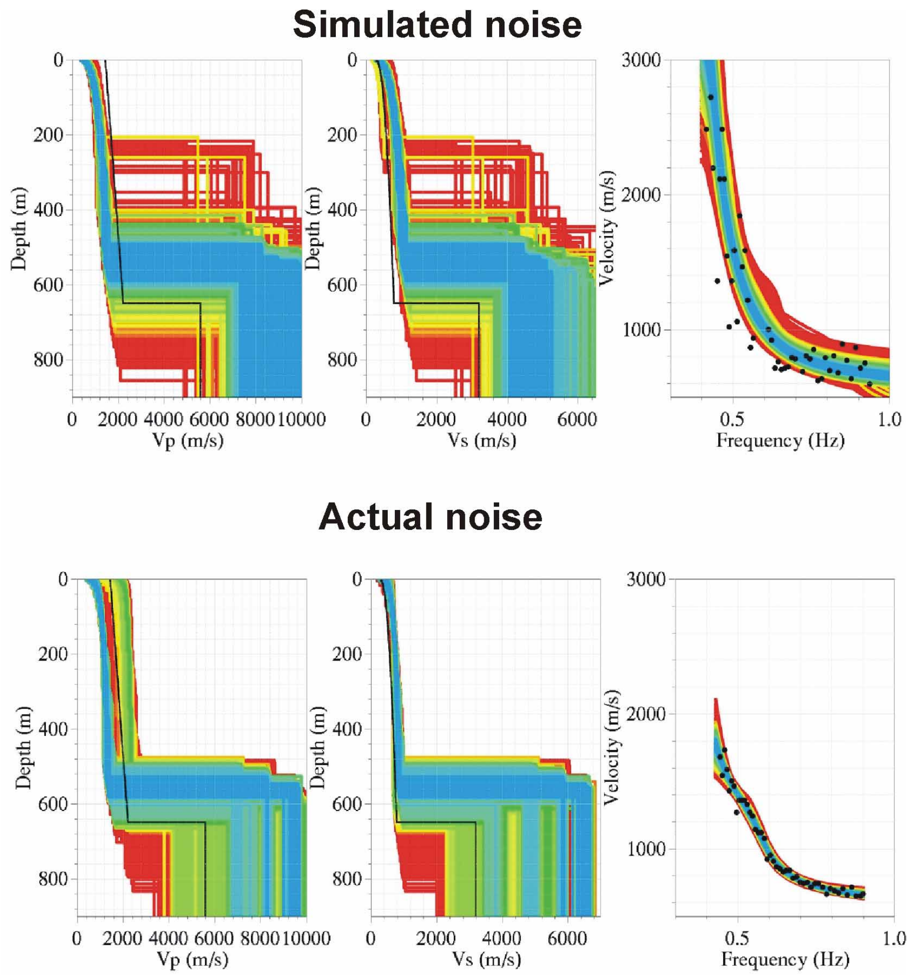

Figure 6: Grenoble basin : P- and S- wave inverted seismic profiles estimated using simulated ambient noise (top) and real ambient noise (bottom). The black line on the inverted velocity profile indicates the theoretical local soil profile and the black dots on the dispersion curves show the phase velocities obtained from the HRFK analysis.

COMPARISON WITH ACTUAL AMBIENT NOISE

Colfiorito basin

We did not compare here the simulated H/V peak frequencies with the actual H/V observations. However, it has been observed during a noise measurement campaign in the basin [16], that the H/V peak frequencies were very close to the 1D local resonance frequencies, which is in agreement with previous observations on simulated noise. For the array analysis, we have used twenty minutes of ambient noise recorded by the same array as for the noise synthetics analysis (Figure 1C). The inversion was performed within the 0.5 to 2.75 Hz frequency band. The P- and S- seismic inverted profiles (Figure 5, bottom) are in very close agreement with both the 1D local soil profile and the velocity profiles derived from simulated noise. The main difference between actual and simulated noise analysis is the estimated S-wave velocity within the surficial layer: the S-wave velocity is 165 m/s and 200 m/s for the actual and the simulated noise, respectively. The related dispersion curves exhibit therefore a similar shape but are "shifted" one another in the phase velocity domain (Figure 5). Especially interesting for this array site is also the observation of a similar back-azimuth distribution as a function of frequency for both the actual and the simulated noise wave field (Figure 7), which strongly suggests the importance of the structure geometry in shaping the wave propagation.

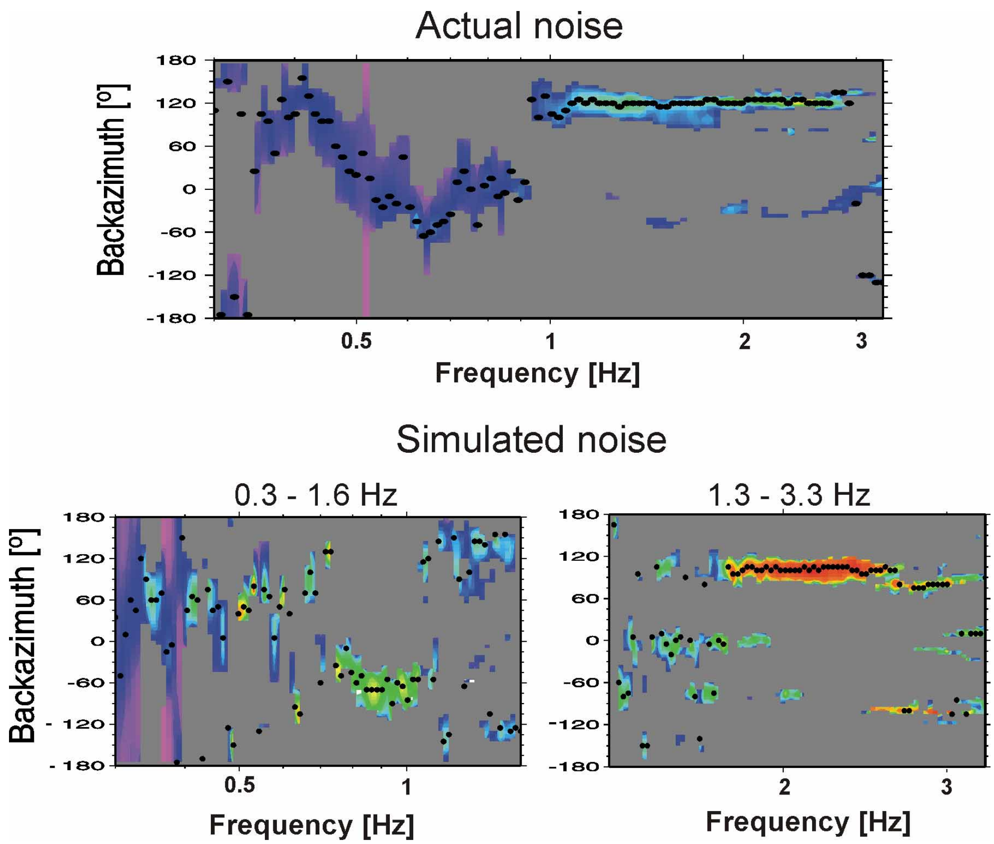

Figure 7: Histograms of the back-azimuth distribution for the actual noise (top) and the simulated noise (bottom) for the two computed frequency bands. The maximum values of the histogram observed at each frequency are indicated by black dots. The HRFK technique was used here.

Grenoble basin

For this site, we have only compared the H/V peak frequencies values estimated by [13] at 91 different sites throughout the basin and the simulated H/V peak frequencies. Even though these H/V peak frequencies are differing by a factor ranging from 10 to 40% (that might be explained by the differences in computing the H/V ratio and the not accounting for standard deviation), they show a similar trend to overestimate the 1D local resonance frequencies as indicated in Figure 8. For the array analysis, we have considered twenty minutes of noise recorded by the array displayed in Figure 2C. The inversion was performed within the 0.4 to 0.9 Hz frequency band. The dispersion curve obtained using actual noise and synthetics are similar in that frequency band (Figure 6), leading to close inverted P- and S- waves velocity profiles with a sediment-to-bedrock interface at around 550 m, that slightly underestimates the average thickness below the array (650 m).

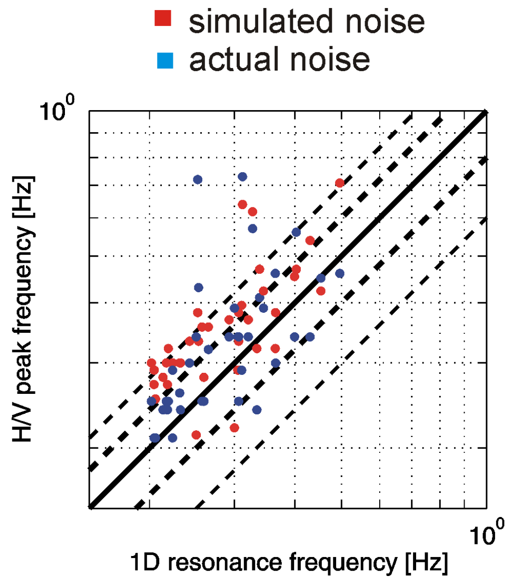

Figure 8: Grenoble basin: Observed (red dots) and simulated (blue dots) H/V peak frequencies as a function of the 1D local resonance frequency. The H/V peak frequency values used for the actual noise are the ones estimated by [14]. The 1:1 relative deviation from the 1D resonance frequency is indicated by the thick black line, the 20% and 40% deviation are indicated by the thick and thin dashed lines, respectively.

CONCLUSION

The very good correlation between synthetics and actual noise characteristics at the Colfiorito and the Grenoble sites confirm first that the modelling of ambient noise as resulting of surface or subsurface forces produced by the human activity is appropriate. Second, the H/V and array analysis applied on simulated noise and the comparison with the actual noise measurements for these two categories of structures (the Colfiorito basin is a shallow structure, while Grenoble basin is a deep sedimentary structure) have highlighted:

- The capability of H/V technique in mapping the sediment thickness variation. For Colfiorito basin, the simulated H/V frequencies are in very close agreement with the 1D resonance frequencies. For Grenoble site, the simulated H/V frequencies are correlated to the sediment thickness variation. However, simulated H/V frequencies significantly differ from the 1D frequencies. Even though the two studied sites exhibit 3D geometries, the width-to-thickness ratio of the structure is much smaller for the Grenoble basin than for the Colfiorito basin, which may lead the structure having resonance frequencies significantly differing from the 1D local resonance frequencies [17]. The comparison of the H/V peak frequency with the 3D resonance frequency given by the 3D transfer function of the site should also help in clarifying the discrepancies between H/V and 1D frequencies for the Grenoble site and the meaning of the H/V ratio as well as in drawing some practical recommendations when interpreting H/V frequencies for different type of structures.

- The capability of the array technique in retrieving relevant information about the site velocity structure. As for the H/V technique, an almost perfect agreement between the known soil profile and the inverted seismic profiles derived from synthetics and observed noise is observed for the shallow site of Colfiorito basin. For the Grenoble site, the inverted velocity profiles using actual noise or synthetics provide a gradient velocity within the sediment that is in rather well agreement with the known gradient and a sediment thickness that slightly underestimates the average thickness below the array. However, some further studies have to be conducted using 3D canonical models [3] in order to better assess the relation between the site geometry and properties and the wave velocity profiles obtained using array analysis.

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