SEISMOLOGICAL MEASUREMENTS FOR SITE EFFECT INVESTIGATION IN THE VAR VALLEY, NICE, FRANCE

E. Bertrand[1], J. Dupuis[1], A.-M. Duval[1] and S. Vidal[1]

[1] *LRPC de Nice, CETE Mediterranee, Nice, France*
Email: etienne.bertrand@developpement-durable.equipement.gouv.fr

ABSTRACT :

Quantitative assessment of site effects, is a major issue in seismic hazard and engineering seismology studies. The frequency dependent site amplifications, observed since decades during the past earthquakes over the world, are known to be mainly caused by reverberations and resonance effects of S-waves within unconsolidated sediments overlaying stiffer formations. We carried out several seismological investigations of site effects in the Var Valley near the city of Nice, southeastern France. The valley is less than 1 km width but previous geophysical and geotechnical studies show that the bedrock could be reached at a maximum of about 200 m depth. In the studied area, the sediments are mainly composed of sand and gravel layers overlaying Pliocene marl. In order to investigate the effect of this sedimentary filling, two kinds of field experiment were set up through the sedimentary basin during 2005 and 2006. Firstly, several profile of ambient vibration recordings were done through the valley in order to apply the Nakamura's technique and estimate the resonance frequency of the soil column beneath the recording points. We also used array technique in order to estimate the Rayleigh waves dispersion characteristics from ambient vibrations recordings. The inversion of the observed dispersion curves allows us to recover the shear wave velocity profiles of the subsurface. The H/V ratios exhibit amplifications down to 0.5 Hz in the centre of the valley and the shear wave velocity in the sediments is estimated close to 300 m/s. These results are in good agreement with geotechnical observations and 1D linear-equivalent modelling. Secondly, a temporary array of 10 broadband velocimeters was deployed in order to record the surrounding seismicity. These data help us defining transfer functions by the computation of spectral ratio between the recordings at a reference station located on rock site and the ones obtained with the station located in the basin. Resonance frequency in the valley is observed between 1 Hz and 4.1 Hz.

KEYWORDS: seismic hazard, site effect, H/V, site/reference, spectral ratio

1. INTRODUCTION

We carried out several seismological investigations of site effects in the Var Valley near the city of Nice, southeastern France, one of the most seismically active region of the French metropolitan territory (figure 1). The valley is 1.2 km wide and is bordered by small hillside where Pliocene conglomerates outcrop on a height close to 200m. These conglomerates were set up in a former delta of the river. They overlay Pliocene marl. The area results from the plio-quaternary evolution of the alpine landscapes at the time of sea level variations and tectonic readjustments. Indeed, at the end of Miocene, a marine regression involves the digging of a deep canyon currently immersed off the airport of Nice. The plaisancian transgression that goes up to 20 kilometres inside the land produces the deposit of marl sediments that moves, in a final phase, into thick conglomerates of several hundreds of meters. Lastly, the quaternary alternation of regressions and transgressions, in particular the large wurmian regression, models the current plain and guides the installation of the alluvial terraces that borders it (Guglielmi, 1993). The valley sediments are mainly composed of alluvial deposit with variable thickness alternating sands, clays, gravel and pebble. Previous geophysical and geotechnical studies show that in the studied area the bedrock could be reached at a maximum of about 200 m depth (Guglielmi, 1993). Esteron river flows into the Var river in the studied area. Bedrock topography is thus rather complex in this region.
The objective of the study presented in this paper is to carry out various techniques based on seismological measurements in order to better know and to quantify the site effects in the Var valley. The combined use of these methods enables to check their validity and their limits. The used methods are based on the recording of

ambient vibration (H/V and array analyzes) as well as the recording of the natural seismicity (spectral ratios site/reference). H/V spectral ratios on ambient vibration recordings were computed at 16 locations across the valley. We also deployed two arrays for a 45-minutes simultaneous recording at 15 and 16 points respectively. Finally, 10 seismic recorders were set up in the area on sedimentary sites as well as on rock sites. This experiment lasted more than one year, allowing us to record in particular about 20 local events reaching a magnitude of 3.7.

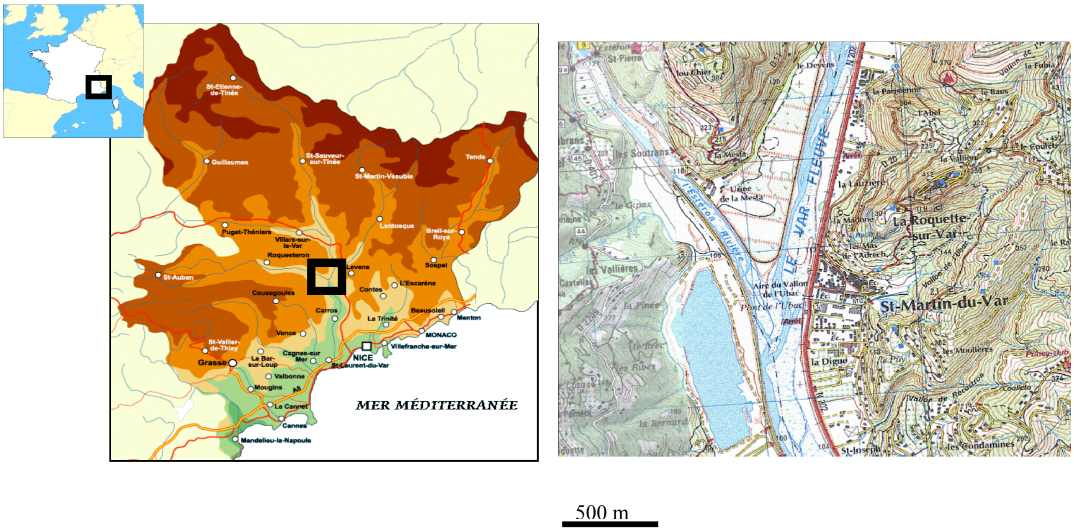


Figure 1 The studied area

2. METHODOLOGY

The soil fundamental resonance frequency can be evaluated on the field thanks to various methods. The experimental methods are commonly based on the recording of surface vibration due to earthquake or ambient noise.

2.1. H/V spectral ratio on noise recordings

A method based on microtremor has been introduced in Japan for estimating dynamic characteristics of surface layers, in early 1970 (Nogoshi and Igarashi, 1971). After an English paper by Nakamura (Nakamura, 1989), many people paid a renewed great attention for estimating dynamic characteristics of ground using this technique, since clear and reliable information was provided by very simple and inexpensive noise measurements. In recent years, the theoretical background of the method has been studied (see for instance the SESAME project) and there have been many successful experimental studies based on it.
The principle of the method consists in recording the ambient vibrations according to 3 directions (a vertical, two horizontal). Signals are processed numerically to obtain the corresponding Fourier spectra. Horizontal spectra are then divided by the spectrum of the vertical component. This ratio computation results in a curve that presents a peak corresponding to the site fundamental resonance frequency. It is the frequency below which there is no amplification of the surface ground movement during seismic action.

2.2. Array recordings

Array method consists in recording at the same time in different places the ambient vibrations. Several techniques, based on the notion that ambient vibrations are composed mainly of surface waves, exist to process the recorded data. We focus on the frequency - wave number analysis, which allows to retrieve in particular the Rayleigh wave dispersion curve. In this method, the dispersion curve is built frequency by frequency following

the CVFK (a conventional semblance based proceeding) technique after Kvaerna and Ringdahl (1986) by identifying the azimuth and velocity of the wave field for each considered frequency in each defined time window.
A flexible software (SESARRAY, http://www.geopsy.org/index.html) developed by Wathelet during his PhD thesis (Wathelet, 2005) is used to compute not only the dispersion curves but also the inversion which gives us the compressional and shear wave velocities as a function of depth. This inversion is done using the neighbourhood algorithm, using a random search scheme, first developed by Sambridge in 1999.
Because of the non-uniqueness of the solution, the applied technique needs some external information that can be at least partially provided by the H/V computation. Thus, combining these two methods can provide some strong constrain on the subsurface dynamic characteristics.

2.3. Site/reference spectral ratio

Borcherdt and Gibbs have described this technique for the first time in 1970. It consists in recording earthquake on various sites, suspected of seismic amplification and comparing the gathered data with simultaneous recordings at a reference station placed directly on a flat-outcropped rock. The acquired signals are processed numerically to obtain their Fourier spectrum and the ratio site-over-reference is then computed.
For a given place, these spectral ratios are function of the earthquake source. According to Field and Jacob (1995), reliable results are only obtained considering a mean of several spectral ratios computed from a significant number of well-distributed earthquakes over a large magnitude and distance range. When this condition is full filled, the mean spectral ratio can be considered as an estimated transfer function of the investigated site.
The main difficulty of the method lies in the choice of the reference station. The critical assumption made is that the surface-rock-site record used as a reference is equivalent to the input motion at the base of the soil layers. However, surface-rock-site can have a site response of their own, which could lead to an underestimation of the seismic hazard when these sites are used as reference sites (Steidl *et al*., 1996). The other difficulty comes from the time consuming need of a significant number of earthquakes to validate the method. Indeed seismological stations should be running during a long time period and even more in region of moderate seismicity like south-eastern France, in order to record the required number of events.

3. AMBIENT VIBRATION

3.1. H/V technique

3.1.1. Field campaign
The use of Nakamura's method is booming for several years. Its success is due to its low implementation cost and to its setting up simplicity. Few material is actually necessary: It is composed of a sensor recording the ground velocity in three orthonormal directions linked to a digitizer and recorder station. We are using a Lennartz Le3D velocimeter, with a transduction of 400 mV/mm/s and a natural frequency of 0.2 Hz. The recorder we have selected is a LEAS CitiShark II. This station allows us to record up to 18 channels simultaneously. 16 measuring points across the Var valley have been treated. Measurements have been done following the SESAME implementation guidelines (SEASME, 2004).

3.1.2. Results
The data processing has been done using the SESARRAY software developed in the frame of the SESAME European project (Wathelet, 2005). An example is given figure 2. We consider 30 second time window, allowing us to have a reliable H/V ratio down to 0.3 Hz. Their selections are done using the ratio computation of the short-term-average over the long-term-average. Most of the time, noise signal is considered to be stationary when this ratio lies between 0.3 and 2. The spectrum smoothing is done with the Konno and Ohmachi (1998) smoothing technique. This method is recommended by SESAME guidelines (SEASME, 2004)

as it accounts for the different number of points at low frequencies.

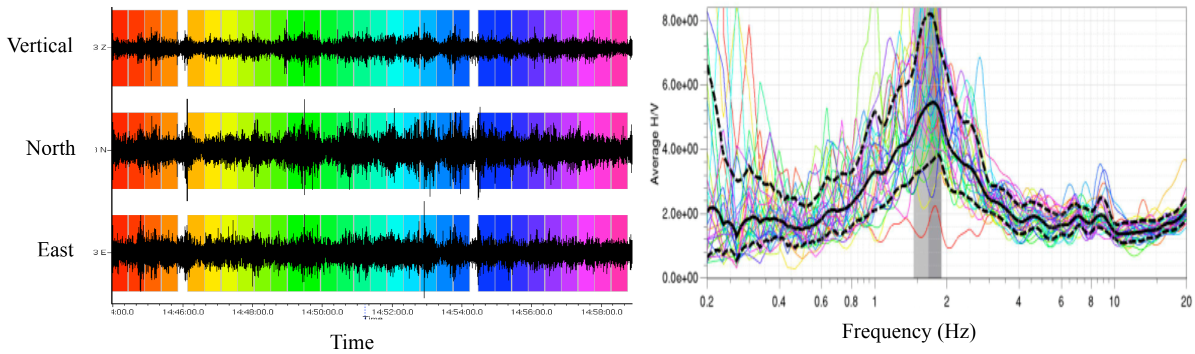


Figure 2. Example of H/V spectral ratio computation (point n°9).

H/V curve interpretation is some times difficult. If no doubt subsists in the case of a clear sharp peak, some precautions have to be considered in other cases. For instance, SESAME guidelines assert that all peaks of amplitude lower than 3 are not reliable. In such case we do not infer any resonance frequency.
At measurements points n°13 to n°16 the H/V spectral ratio curve does not highlight any resonance frequency. But sharp peak can be observed on the H/V curve at all the other measurement sites. Associated frequencies are given in the following table.

Table I. Frequency deduced from the H/V spectral ratio computation.

Points Nb	f_0
1	8 Hz
3-4-5-6	1,6 Hz
9	1,7 Hz
7	3,5 Hz
8	3,5 Hz
10-11 and 12	5,5 Hz
13-14-15-16	No

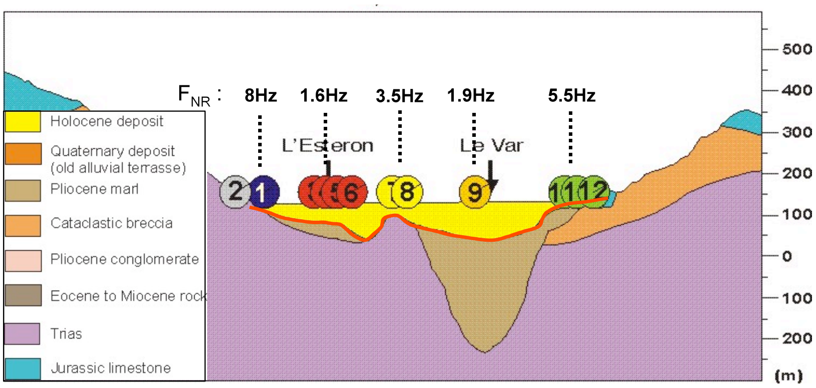


Figure 3. Comparison of the resonance frequencies of this study with an interpreted geological cross-section (after Guglielmi 1993).

The resonance frequencies inferred from our computation are ranging between 1.6 Hz and 8 Hz depending of the recording point. Going from West to East we notice that at the edge of the Esteron basin the observed frequencies are high (site n° 1) and they decrease towards its centre (from site 3 to site 6) (figure 3). Between

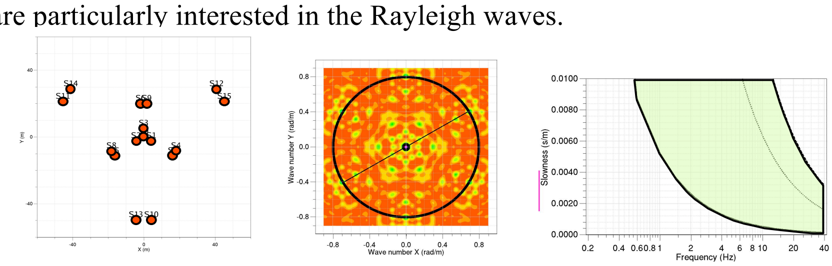
the Esteron and Var basins (sites n° 7 and 8), the frequencies increase slightly for then decreasing again towards the center of the Var basin (site n° 9). By considering constant S-waves propagation velocities over the area, we can interpret these frequencies like a deepening of the bedrock towards the centre of the two basins with a high point separating these two basins (sites n° 7 and 8). We observe in addition that the sediment maximum thickness seems, in the region of study, rather similar for the Var and Esteron basins. Finally our measurements suggest that the deepening of the substratum is very fast, at least on the western edge of Esteron basin.
Our observations are in good agreement with previous studies. Indeed, Guglielmi (1993) made some electrical survey for hydro-geological purposes in the entire Var valley. An interpreted geological cross-section inferred from this study is presented figure 3. The bedrock topography deduced from the electrical survey shows the same pattern as the one deduced from our noise measurement. Both study emphasize two distinct basins for the Var and Esteron rivers and a fast plunging rocky substratum in the center of the two basins.

3.2. Array technique

3.2.1. Field campaign

Figure 4. Studied area. Left: Stars mark places where H/V technique is applied. The dense arrays are located at red and yellow circle. Right: Setting up area of dense array experiment.

The reliability of array techniques applied to ambient vibrations for site effect investigation has been already assessed in SESAME project (Ohrnberger *et al*. 2004). Because the technique needs a large flat space, we choose an embankment area located on the right bank of the Esteron river (figure 4) and where some geotechnical data already exist. We use our Le3D sensors and CityShark II recorder in different arrays laying out with an aperture of 100 m but we show here only the one giving the best result in terms of slowness-frequency domain validity. This array is composed of 16 sensors recording the vertical ground movement since we are particularly interested in the Rayleigh waves.



Geometry Response Validity

Figure 5. Array geometry presented in this paper in this.

The sensors distribution is triangular in shape, leading in the particular array response shown in figure 5. The slowness-frequency validity domain, in which the dispersion curve reliability is ensured, is restricted by the aliasing and resolution limits depending on the array response. The reliability of the estimated dispersion curve is ensured here from 2.5 Hz to 20 Hz.

3.2.2. Results

A drilling core reaches the bedrock, composed of pliocene marl and triasic rock, at 47.5 m-depth. The quaternary alluviums are made of sand, gravel and clay distributed in three different layers. Furthermore, H/V spectral ratio on noise measurement emphasizes a resonance frequency of 3.1Hz. And thus the mean S-wave velocity in the subsurface deposits is estimated close to 590 m/s. These data allow us to constrain the starting model we use for the dispersion curve inversion. Considering homogenous bedrock and neglecting the last thin clay layer, the parameterization of the subsurface model is achieved by a two-layers over halfspace model. The free parameters of the inversion are the compressional and shear-wave velocities as well as the thickness of each sedimentary layer. The overall thickness of the alluvium is kept close to 50 m (table II).

Table II. Parameter space used for the dispersion curve inversion.

	Bottom (m)	**Vp (m/s)**	**Vs(m/s)**	**Density**
Layer 1	[1;20]	[100;200]	[0;1400]	1800
Layer 2	[45;50]	[200;3000]	[0;2100]	1800
Halfspace		[800;6000]	[0;4300]	2000

The inversion results are shown in figure 6. The best fitting dispersion curves and the respective corresponding velocity models are shown in red colors. The best solution presents rather high shear wave velocity in the sediments (up to 870 m/s) but the overall soil column is in good agreement with the borehole. The associated fundamental resonance frequency is slightly higher than the one obtained from the H/V technique.

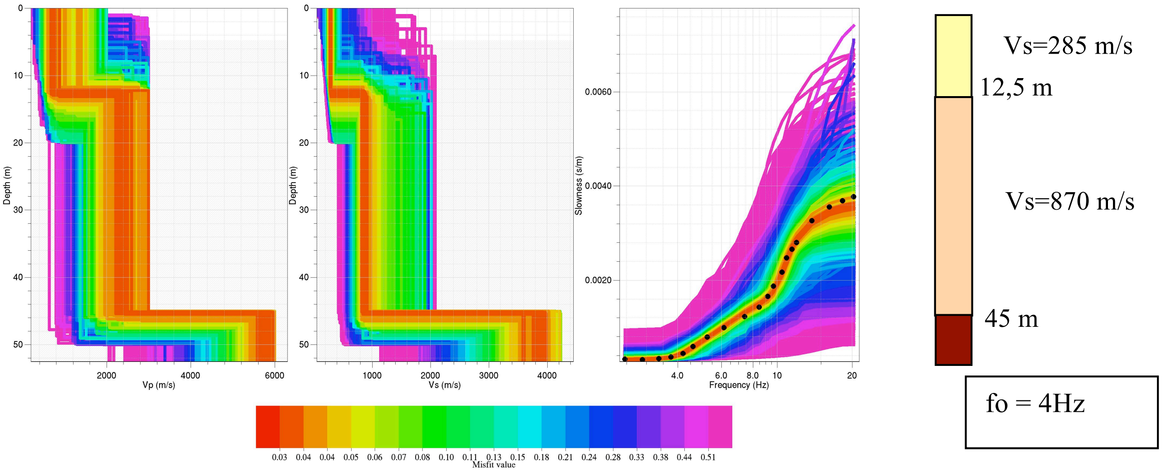


Figure 6. Result of the dispersion curve inversion. From the left to the right: Vp velocity profile, Vs velocity profile and dispersion curves overlaid by input data. Color of curves are given by the misfit value. Best fitting models are in red color tone. The righter most picture represents a schematic soil column corresponding to the best solution.

4. Earthquake recordings

4.1. Array description

The seismological array was progressively set up in the Var valley in early 2005. It is composed of 10 velocimeters (figure 7). The array works almost during one year but all stations did not record all the events that occured during this period. LANT, VAZZ, LOUC and DELA stations (highlighted in brown in figure 7) are located on rock sites whereas the others are installed on sedimentary sites in the Var valley. Some of these rock sites may present some topographical site effect and for instance we observe some amplification at DELA, VAZZ and LOUCH comparatively to LANT.

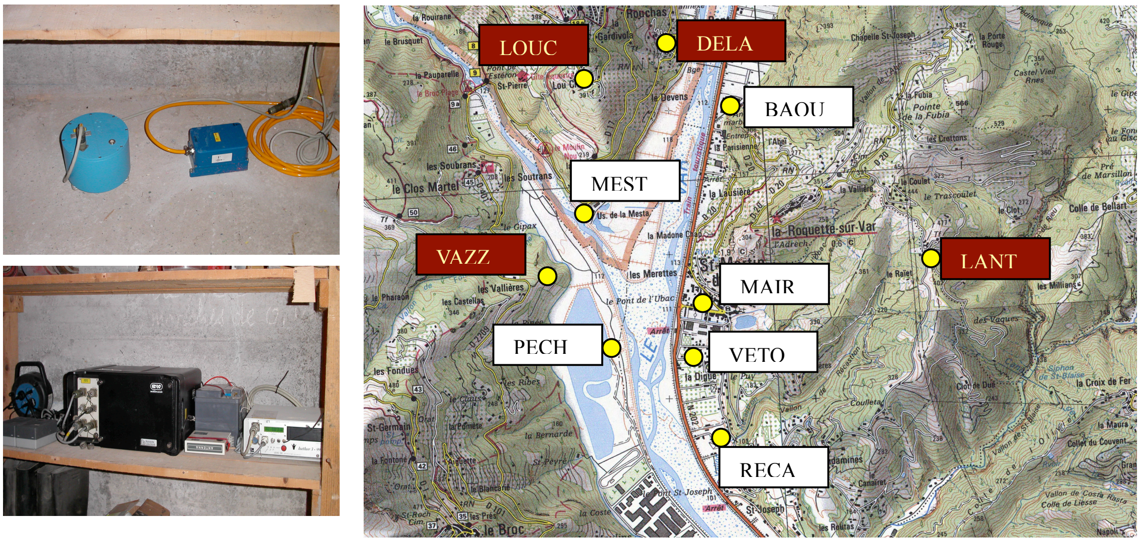


Figure 7. Seismological array deployed in the Var valley.

4.2. Results

The array records almost 20 useful regional or local events. Site/reference spectral ratios are computed using station LANT as a reference since the H/V spectral ratio on ambient vibration at this station is characteristic from a rock site contrary to VAZZ, DELA and LOUCH. According to the result we obtain, fundamental resonance frequency in the valley is observed between 1 Hz and 4.1 Hz but maximum of amplification is reached at frequencies close to 10 Hz (figure 8). The fundamental resonance frequencies are in good agreement with the noise measurements (table II). Surprisingly, we observe similar amplification for stations DELA, VAZZ and LOUCH than for the stations located on soft soils.

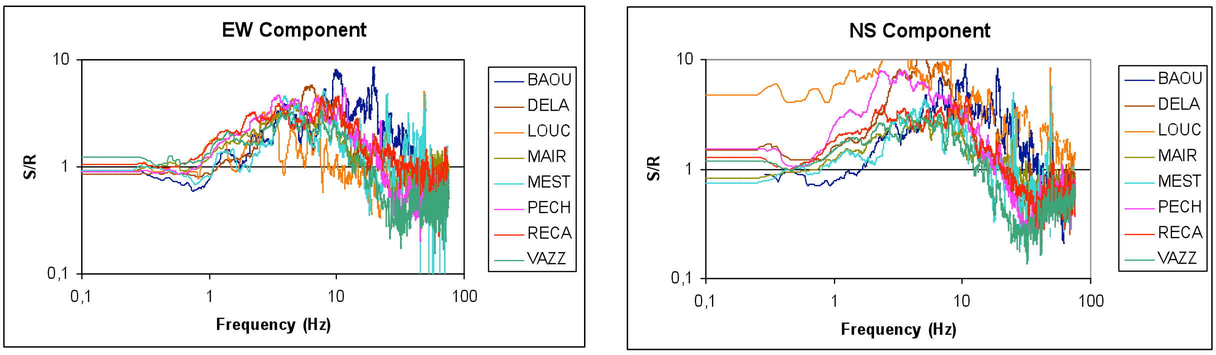


Figure 8. Mean Site/Reference spectral ratio of horizontal components considering LANT as a reference.

5. Conclusion

We have performed a complete set of seismological measurements of site effect in the Var valley. Our study is based on ambient noise as well as earthquake recordings. The simultaneous use of these different kinds of data help the site effect assessment.

By applying the Nakamura's technique, ambient noise measurements allow us to estimate the resonance frequency due to alluvial deposits at different locations in the valley. Frequencies that we have found are ranging between 1.6 and 8 Hz, mapping thus properly the sediment thickness variations across the valley.

We also have analyzed ambient vibration array recordings from inside the valley. The method has already been shown to be suitable for Rayleigh wave dispersion curve computation (Ohrnberger *et al*., 2004). The use of a large number of stations and a specific distribution geometry allow us to push the spatial aliasing limit away towards greater frequencies and thus to constrain the dispersion curve over a larger frequency domain. The inversion of the dispersion curve seems to be efficient if independent data are used to constrain the starting model. Here, the use of H/V spectral ratio computation as well as available geotechnical data leads in a reliable even if the 1D hypothesis is clearly not checked under the array we have deployed. This assumption seems to overestimate slightly the shear wave velocity in the sediment. We suggest now to use other methods such as spatial autocorrelation technique (SPAC) to better constrain the model. Site/reference analysis gives already some interesting results in good agreement with the other technique. But work must go on and the first analysis should be improved and stated more precisely since some stations considered at rock sites exhibit large amplification considering LANT as a reference. These amplifications could be due to some topographical site effect.

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