Non linear inversion of noise array measurements for determining S-wave velocity vertical profiles

M. Wathelet[1], **Ohrnberger M.**[2] , **D. Jongmans**[1], **Camelbeeck T.**[3], **Scherbaum F.**[2]
[1] LIRIGM, Grenoble University, France, denis.jongmans@ujf-grenoble.fr
[2] Institut f. Geowissenschaften, Potsdam University, Germany, mao@geo.uni-potsdam.de
[3] Royal Observatory of Belgium, t.camelbeeck@oma.be

INTRODUCTION

The knowledge of the shear wave velocity (Vs) profile at a given site is of major importance in earthquake engineering. The geophysical techniques generally used in soil dynamics to obtain shear wave velocity as a function of depth are the borehole tests (Jongmans, 1992), which are expensive and limited to shallow depths. An alternative method, based on the inversion of surface waves generated by an artificial source, has been increasingly used for the last ten years (Stokoe, 1989; Malagnini, 1995; Jongmans, 1992). However, the penetration depth of this method is generally limited by the difficulty to generate low frequency waves with common active sources. More recently, the measurement of ambient vibrations by an array of sensors has been applied for determining the Vs profiles (e.g. Tokimatsu, 1997; Satoh et al., 2001; Scherbaum et al., 2002). In this method, ambient vibrations are considered to be mainly composed of surface waves whose dispersion curve is derived from the processing of the simultaneous ground motion recordings at various stations. Comparing to the other approaches, this exploration method can be easily applied in urban areas as the noise is used, it does not require any artificial seismic source and it allows to reach greater depths (from tens of meters to hundreds of meters according to the inter-distance between stations and the noise frequency content). Like all the other mentioned methods, the obtained geometry is purely 1D and averaged within the array, implying that the technique is not suitable when strong lateral variations are present.

The procedure of analysing ambient vibrations is illustrated in figure 1. Noise windows (fig. 1b) are simultaneously measured with an array of stations (fig. 1a) during a few tens of seconds. Two main methods can be applied for the estimation of phase velocities from array records: the frequency wave number (FK) technique (Lacoss et al., 1969) and the spatial autocorrelation method (Aki, 1957). In our study we applied the first one on the vertical components of the measured ground motions, restricting ourselves to the study of Rayleigh waves. Under the assumption of stationary noise in space and time, the peak of the FK spectrum gives for each frequency band the phase velocity and the azimuth of the source. It is then possible to construct frequency by frequency the Rayleigh wave dispersion curve (Fig. 1c). Also, noise is recorded with different array geometries in order to get the largest possible period range for the dispersion curve. However, as shown by Scherbaum et al. (2002), the ground itself acts as high-pass filter limiting the available frequency band to the resonance frequency of the site. The inversion of the dispersion curve, which gives Vs (and eventually Vp) versus depth, is usually performed by iterative linear algorithms initiated by a starting model (Herrmann, 1987). This kind of inversion leads to one optimal solution, strongly influenced by the starting model and which could be a local minimum of the misfit function. In order to better investigate the parameter space we implement a direct search algorithm (Neighbourhood algorithm) proposed by Sambridge (1999) to inverse the dispersion curve with a limited number of layers. Considering the misfit ranked set of inversion results, it is additionally possible to judge model uncertainties by this inversion approach. This method has been successfully tested on various synthetics in order to estimate its ability to reproduce the original models. In the framework of a project aimed at assessing local seismic hazard in Belgium, the method was applied on several sites, selected for the availability of geological and geotechnical data in order to test the reliability of the proposed approach.

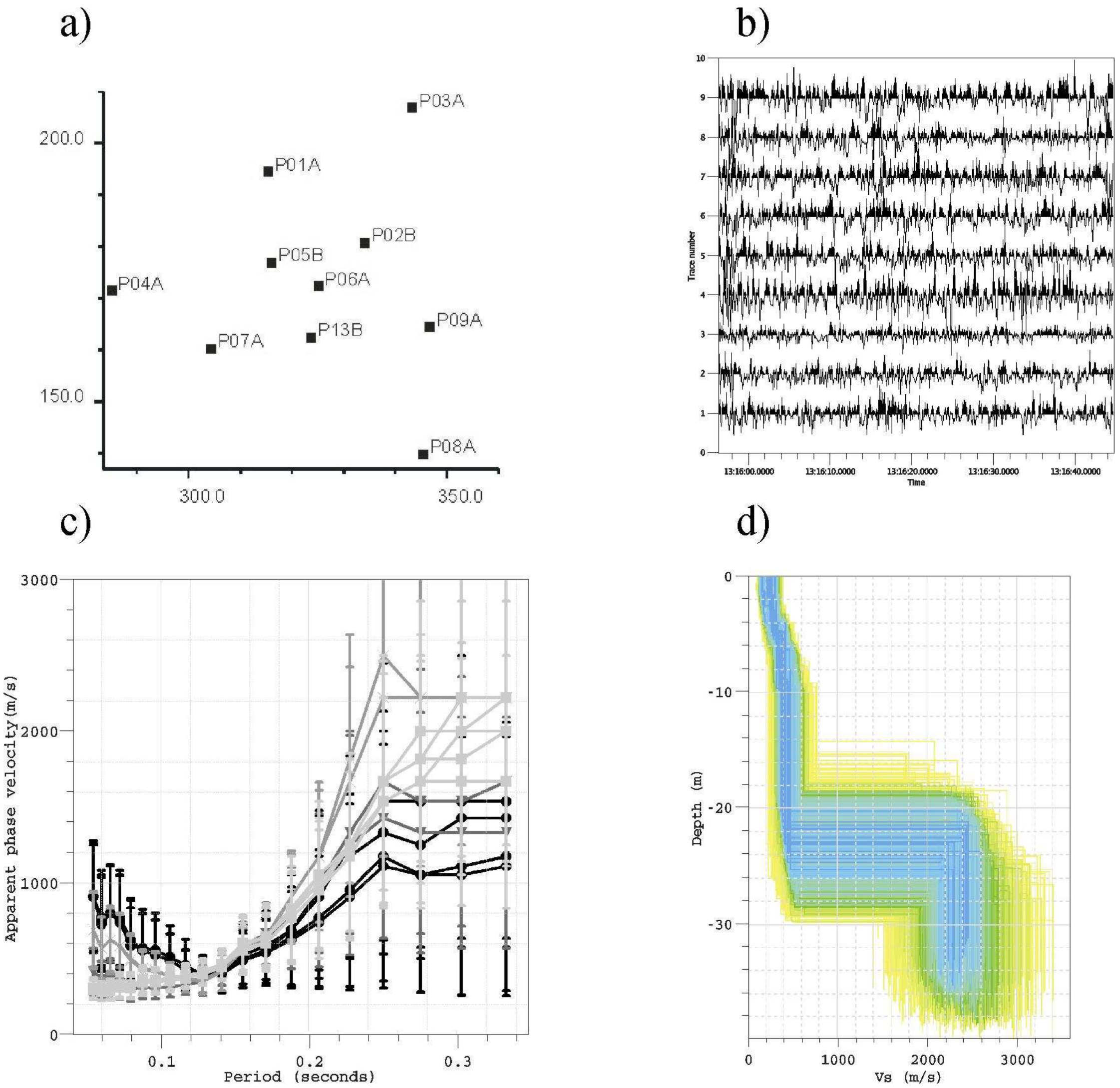

Figure 1: (a) Geometry of the station array. (b) Records of ambient vibrations at the stations. (c) Dispersion curves with error bars for different time windows and array geometries. (d) S-wave velocity profiles explaining the dispersion curves. The darkest models present the lowest misfit values.

FIELD RESULTS

Noise measurements were performed in four sites located within urban areas (Liège, Brussels, Gent and Mons) in Belgium. Here are presented the results obtained in Brussels, in the park of the Royal Observatory of Belgium (ROB). The geological structure consists of 115 m of sandy layers overlying a Palaeozoic bedrock. A natural frequency of about 1 Hz has been determined by H/V measurements (Nguyen et al., in press) for the site. Two different experiments were performed in November 2000 and March 2002. During the first one, three concentric arrays of four 1 Hz stations were deployed, with radii of 25 m, 50 m and 100 m. In March 2002, ten 5 second stations were deployed on the same location with a radius of 130 m and with a complex layout having radii of 25, 75 and 130 m (ring_25-75-130). A last array of 22 geophones (4.5 Hz of resonance frequency) distributed on a perfect circle (radius=18 m) was also installed.

The FK method was applied to the six arrays. For the first three, 3 to 4 distinct time windows of 5 to 10 minutes were analysed. For the last three, at least two distinct time windows of 15 minutes (ring_130 and ring_25-75-130) and of 4 minutes (ring_geoph) were processed. The resulting dispersion curves are all displayed on figure 2a and 2b.

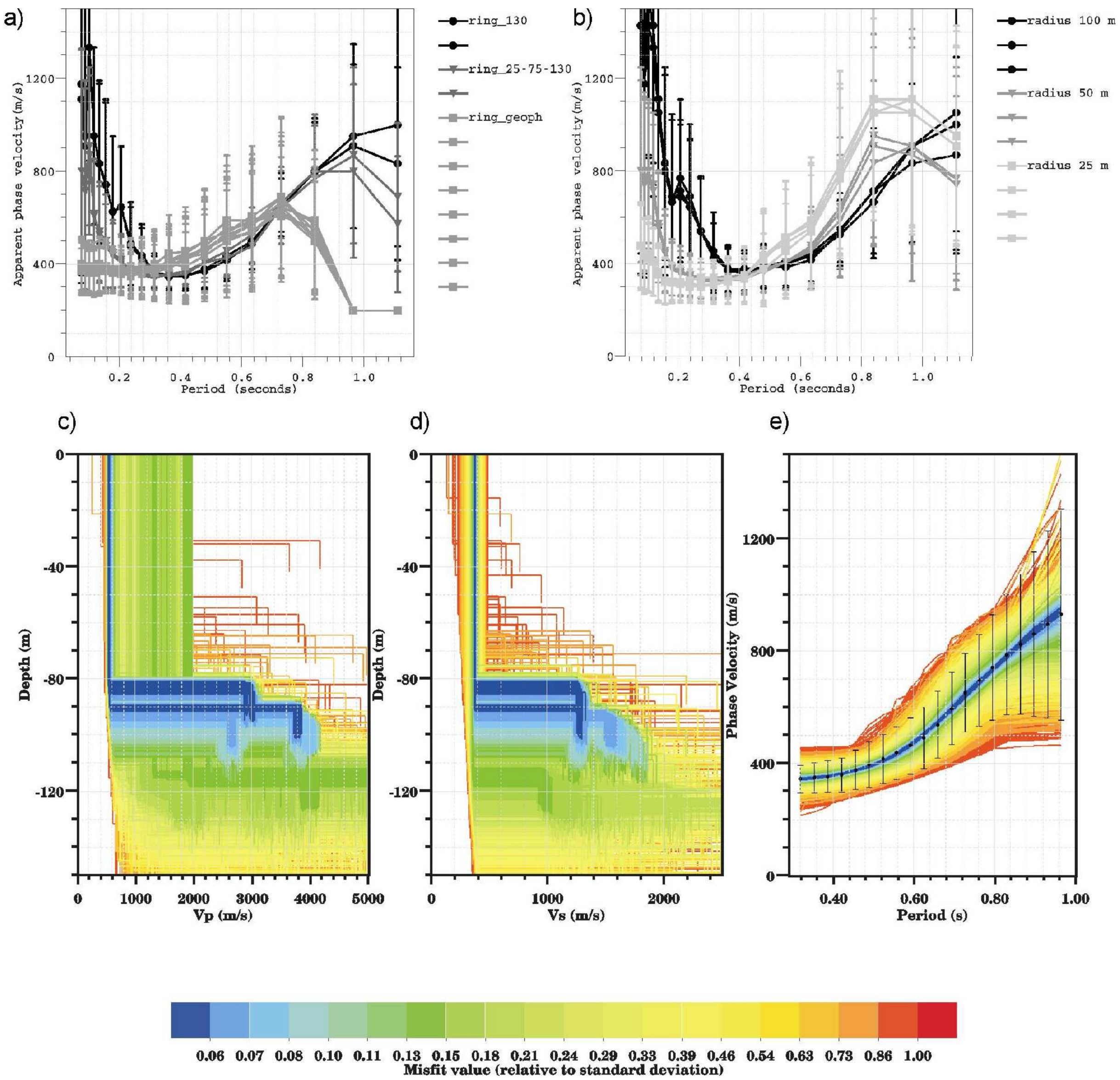

Figure 2: (a) and (b) Dispersion curves obtained at two different times with two different networks. (c) Vp and (d) Vs models resulting from the non linear inversion of the dispersion curve (e).

In general the stationarity with time inside each array is very good. The results of ring_130 and ring_25-75-130 (Fig. 2a) show a threshold period (0.9 s corresponding to the resonance frequency of 1.1 Hz) over which the curves separate. For the geophones, a decrease of the velocities was observed above 0.75 s, probably due to the great difference between the wavelength and the array aperture (about 10 times smaller). On the contrary, at high frequency, the velocity values increase, resulting to an aliasing effect affecting more the large size array than the geophone array. This phenomenon is also observed on fig. 2b (experiment with 3 radii). These observations showed that an array of given geometry gives the dispersion curve on a certain period range, which is controlled by its aperture and the resonance frequency of the site. A dispersion curve was derived between 0.32 s and 0.96 s from all the results and is presented on fig. 2e with its uncertainty. The dispersion curve was inverted using a simple two homogenous layer model. Figure 2c shows all generated models having a misfit lower than 1. The best model (dark colour) has a misfit of 0.06. The corresponding dispersion curves are drawn with the same colour scale on fig. 2d. The results show that the shear velocity over the first 80 meters is close to 370 m/s with an uncertainty of 50 m/s and increases to reach 1000 m/s to 2000 m/s between 80 and 140 m depth, an interval which includes the borehole data (115 m). P-wave velocity values are less constrained than Vs. Tests were performed with a 3-layer geometry and gave the same Vs profile.

CONCLUSIONS

Seismic noise arrays are clearly able to bring valuable information on Vs values, particularly at depth where the classical active sources methods generally fail. As all other geophysical methods it must be calibrated and confronted with other data, especially for superficial layers. The use of the Neighbourhood Algorithm proved to be efficient to investigate the parameter space, providing all the models explaining the dispersion data in a reasonable time (3 minutes with a two layer model). The inversion process has been improved and now allows to include layers with a velocity gradient and a priori information on Vs or Vp values. In the future, it is planned to implement a join inversion of the dispersion curve and the H/V curve, which could lead to a better constrain on the depth of the bedrock (Scherbaum et al., in press).

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