GEOTECHNICAL, GEOPHYSICAL AND SEISMOLOGICAL DATA USED FOR THE ESTIMATE OF THE HIGHEST AMPLIFIED FREQUENCY IN THE BASIN OF GRENOBLE

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\textbf{ABSTRACT} – Being able to model the seismic soil response is a crucial step in characterizing local site response and in determining seismic risk scenarios. In the case of Grenoble basin, previous data collected by permanent and/or temporary networks showed two scales of amplification effects: (1) at low frequencies due to the global effect of the sedimentary deep basin and (2) at high frequency due to the topmost surface layers, consequences of the lacustrian and fluviatile deposit processes. The scope of this paper is to estimate experimentally the ability of the HVSRN method used as an exploration tool in order to map the lateral variability of the topmost (less than 20m) sedimentary layer. The study was carried out in the Grenoble basin. Geotechnical, geophysical and seismological data have been collected in the Grenoble basin for the estimate of the seismic response due to the surficial sedimentary layers. The data extracted from the seismic noise recordings are compared to the geotechnical and geophysical data at two sites in the basin.

1. Introduction

For the past twenty years, numerous studies have focused on the effects of sedimentary layers on seismic ground motion. These studies were carried out either to constrain the observed lateral variations of seismic ground motion, or to predict and account for the amplification effect for potential earthquake scenarios. Accounting for such effects in seismic regulation, land use planning or design of critical facilities has gained increasing importance in earthquake hazard reduction programs. Being able to model the seismic soil response is therefore a crucial step in characterizing local site response and in determining seismic risk scenarios. In the case of Grenoble basin, previous data collected by permanent and/or temporary networks showed two scales of amplification effects: (1) at low frequencies (less than 1Hz) due to the global effect of the sedimentary deep basin and (2) at high frequency (>1Hz) due to the topmost surface layers, consequences of the lacustrian and fluviatile deposit processes. The strong lateral variations of the topmost layer is a critical point in term of seismic regulation and microzoning, all the more in some part of the basin the high frequency amplification can be as important as the lowest. Techniques used to estimate site response are usually grouped in geotechnical and geophysical methods. Geotechnical surveys such as drilling...
boreholes and SPT or CPT provide detailed information on surface layers. Nevertheless, in cases of strong lateral variations and deep sediment layers, as observed in the Alpine valley in Europe, these methods are not suitable owing to their high cost and their discontinuous nature. Classical geophysical surveys such as S-wave velocity profiles, deduced from surface wave analyses, S wave refraction, seismic P-wave and electrical tomographic analyses are an alternative that cover wide areas in a shorter time. However, major experimental difficulties arise when they are planned in urban environments where the reduction in earthquake hazard is a critical factor.

The scope of this paper is to compare experimentally the effect of the topmost sedimentary layer on the interpretation of the HVSRN frequency used as an exploration tool. The study was carried out in the Grenoble sedimentary basin where, for the last twenty years, extensive data are available. The information extracted from seismic noise recordings at two sites in the basin is compared to geotechnical and geophysical data.

2. First level: Deepest geological and sedimentary context of the Grenoble basin

Located in the northern part of the Alps, the Y-shaped Grenoble basin is one of the most important Alpine valleys in Europe (Fig. 1). Extremely urbanised, it is located at the intersection of the Drac and Isère river valleys, inserted between the hard Jurassic limestone of the Chartreuse and Vercors massifs on the western and northern sides respectively, and the metamorphic mountains of the Belledonne chain in the south-east. The Grenoble basin is mainly filled with Quaternary deposits resulting from the Würm II period, the last major glacial period (Nicoud et al., 2002). This resulted in a deep wide valley, which was imaged using a dense gravimetric survey carried out by Vallon (1999). Considerable variations in basin depth are observed (Fig. 2), with the deeper part (more than 900 m depth) located in the centre of the Y-shaped valley. Bedrock shape variations are found in the south of the city, with a local rise in the bedrock, and a general rise in the southern and the north-eastern branches.

The basement of the Grenoble basin is made of marly limestone (Early Bajocian) overlain by Jurassic marls. A thick monotonous, sandy-silty lacustrine clay formation overlies the Jurassic formation, and stretches over the entire basin as a result of infilling of the umbilical post-glacial lakes. The thickness and monotonous sequence of the lacustrine deposits give an indication of the large size of the lakes and explain the minor variations of the nature of this sedimentary sequence from one point in the valley to another, up to the last 40m of sediments. This has been calibrated by several old and recent deep boreholes drilled in the valley.

2. Second level: the topmost sedimentary context at the Montbonnot site

The deep borehole, known as the Montbonnot borehole, was drilled in the north-east branch of the valley (Fig. 1), down to the bedrock reached at -535m depth. The abundant sedimentary information available on this site motivated the extended geophysical and seismological surveys subsequently carried out to attribute the S- and P-wave velocity profiles to the sediment column (Fig. 3). To complete the description of the topmost soil column, geotechnical (CPT) boreholes were drilled and active refraction seismic studies conducted on the site (Fig. 4). To summarise, except for the presence of a very thin topmost layer (less than 5m) characterised by S-wave velocity of around 170m/s and overlying a thin (8m thick) inserted gravel layer (fluvialite sequence) with S-
wave velocity of around 290m/s, the properties of the sediments at the Montbonnot borehole site follow an increasing gradient. Assuming reasonably that the main process of

sedimentary infilling is the same regardless of the valley branch, the soil properties inferred from the Montbonnot borehole may be extended to the entire Grenoble basin. This assumption has been recently confirmed by Dietrich et al. (Dietrich et al., 2005) in the NW branch by wide-ranging seismic refraction and reflection studies. The only differences concern the last few metres of the ground near the surface of the column which result from the lateral variations in the fluviatile sediments due to changes in the two major river beds. Indeed, after the lacustrine period, late fluviatile dynamics started due to the presence of the two major rivers in Grenoble. Both these rivers have incised the lacustrine deposits. This has resulted in the presence of a stiff surface sediment layer, mainly composed of gravel and sand and presenting spatial and vertical heterogeneities. This heterogeneities concerns the central axis of each valley branch and depends on the presence or not of the gravel layer, its depth and its S-wave velocity.

3. Effect of the topmost surface layer on the seismic ground motion

In view of the moderate seismicity of the northern part of the Alps, the high economic activity of Grenoble, the presence of a very close active fault along the Belledone massif and the presence of deep sediments, numerous recent research activities were focused on the seismic response of the basin. Seismic site effects were first observed by Lebrun et al. (2001) during a temporary seismic
experiment. They showed a considerable variability in the amplitude and frequency range of seismic amplification within the basin. These first observations have since been confirmed by data collected by the accelerometers permanently installed in the city, part of the French Accelerometric Network (RAP, http://www-rap.obs.ujf-grenoble.fr). Systematic amplified frequencies $f_0$ of around 0.3-0.4 Hz are observed, with a large amplified frequency band up to 4 Hz in the central part of the basin.

The Montbonnot deep borehole is also permanently instrumented by a pair of accelerometers installed at the bottom and at the top. In this paper, the data recorded by the two stations were analysed for 28 local and regional earthquakes (1.0<$M_l<$5.5) that have occurred since the start of monitoring of the borehole. Figure 5 shows the spectral ratio calculated between the top and the basement, for all the data available in the RAP database. The ratio was account for only frequencies for which the signal/noise ratio is greater than 3. For each data set, a time window was selected with the S-wave arrival time taken as origin. The length of the selected window is given by a compromise between the decrease in amplitude after the S-wave time arrival for the local earthquakes and the time length of the windows controlled by the triggering mode of the RAP stations for regional earthquakes. Each data set is cosine tapered (5%) and its Fast Fourier Transform is computed. The spectral amplitude is smoothed according to the Konno and Ohmachi (1998) window ($b=30$). The average spectral ratio clearly indicates the 0.4 Hz resonance frequency. As mentioned and validated previously by Lebrun et al. (2001), the lower frequency is linked to the S-wave resonance frequency of the entire column of sediments. The 8 Hz frequency corresponds to the S-wave resonant frequency of the seismic response of the topmost sedimentary layer, with a thickness equal to 5 m. This layer has an impedance contrast large enough to be detected (Fig. 4). The 8 Hz frequency value fits the simple 1D frequency resonance obtained for a bi-layer model using the simple formula linking the resonant frequency $f_0$ to the S-wave velocity $\beta$ (170 m/s) and the thickness $H$ (5 m) of the topmost layer ($f_0 = \beta/4H$).

### 4. The H/V spectral ratio used for the topmost layer detection.

The past twenty years have seen a proliferation of scientific papers dealing with the use of ambient vibration recordings for site effect estimation. Nogoshi and Igarashi in 1972 (Nogoshi and Igarashi, 1972) first proposed the use of the H/V spectral ratio of seismic noise (HVSRN) as a tool for estimating the seismic response of the sub-surface structure. This method has since been widely diffused around the world by Nakamura (1989). Since 1989, because of its low-cost, its fast deployment and the relation between the nature of the topmost sedimentary layers and the fundamental resonance frequency detected by the seismic ambient noise, the use of the HVSRN method has become widespread, mainly with the objective of detecting the sedimentary zones that could amplify seismic ground motion. Scientific papers dealing with this subject are extremely abundant and presenting an exhaustive list of references is not the goal of this paper. Reference could be made to the study by Bard (1998) who presents an overview of the H/V method, and more recently Bonnefoy-Claudet (2004) and D13.08 (2004) which indicate the references of most published studies on seismic ambient noise.
This abundant literature shows:

1. The amplified frequency deduced from the HVSRN method has been compared to the seismic ground response extracted from seismic recordings (Borcherdt, 1970; Castro et al., 1990; Langston, 1977) and applied in many seismic regions (e.g., Lermo and Chavez-Garcia, 1993; Field and Jacob, 1995; Lachet et al., 1996; Guéguen et al., 2000; Lebrun et al., 2001; Guéguen et al., 2006). All have provided a reliable estimate of the fundamental resonance frequency of the site using seismic ambient noise, despite the fact that the amplification factor is still not fully understood.

2. The amplified frequency may give information on the variability of the fundamental frequency over an extended zone. The HVSRN method is used here as a mapping tool, either in a pre earthquake situation (land use planning) (e.g., Faeh et al., 1997; Alfaro et al., 2001; Lombardo et al., 2001; Guéguen et al., 2000; Lebrun et al., 2004), or in a post earthquake situation to contribute to explaining the distribution of building damage by identification of local site effects (e.g., Guéguen et al., 1998; Guillier et al., 2004).

3. The HVSRN is used as exploration tools. Because of the close relation between fundamental frequency, shear wave velocity and thickness of the soil layer, recent studies have used the HVSRN method as a geophysical exploration tool (e.g., Delgado et al., 2000a; 2000b; Ibs-von Seht and Wohlenberg, 1999; Parolai et al., 2002). Even if some precautions have to be accounted for, e.g., the 2D or 3D effects on the HVSRN results, as shown by Guéguen et al. (2006), the average shear-wave velocity of the soil column can be estimated based on knowledge of the soil layer depth, obtained from boreholes or geophysical methods, and the HVSRN frequency value...
In this sense, we performed ambient vibration at the Montbonnot site. The experiment consists in recording seismic noise with a 3D velocimeter placed on the ground and connected to a CityShark™ station, a user-friendly digital acquisition system designed for noise measurement (Chatelain et al., 2000). The station was connected to a 3C Lennartz 5-second sensor with a flat velocity response between 0.2 and 50 Hz. This sensor is ideally suited to estimate the response of the Grenoble basin site in the lower frequency range. The seismic noise data were acquired and processed according to the recommendations outlined in the deliverables of the SESAME European project (D23.12, 2005).

The HVSRN gives information on the 0.3Hz amplified frequency (due to the deepest part of sediments) and also on the 8Hz frequency, in conformity with the amplification observed using the seismic recordings (Fig. 6). In order to valid this assumption we applied this method to other sites where wide geotechnical and geophysical data are available.

![Figure 6: HVSRN computed at the Montbonnot borehole, following the SESAME recommendation using the NS and EW component (continuous lines: average HVSRN; dashed lines: +/- standard deviation)](image)

6. Join analysis of the geotechnical and geophysical data in the center part of the Grenoble basin.

On of the most amplified site in Grenoble is located in the center part of the basin, where the 3D geometry is the most relevant. In this site, or in the close vicinity, we collected cross-hole information, SASW data and geotechnical information. Before starting our analysis, we knew that all the building resting in this area are founded through piles foundation reaching a layers of sand at around 15 m depth, stiff enough to be use as bedrock for foundation. Moreover, Lebrun et al. (2001) have shown in this area that the seismic ground motion is amplified in a wide range of frequency, from 0.3 to 4Hz, due to the 2D or 3D effects and/or to the presence of a topmost sediment layer. This one is due to the fluviatile deposits and the lateral variability can be extremely strong from one point to another one. That is one of the interests of the HVSRN which can give us almost continuous information on the presence or not of this topmost layer.
The HVSRN applied at this site gives the same amplified frequency as those extracted from the SASW and cross-hole data (Fig. 7) using the simple formula linking the resonant frequency $f_0$ to the S-wave velocity of the topmost layer ($f_0 = \beta/4H$). Both geotechnical and geophysical surveys show shear waves velocity of around 150m/s and 200m/s and the first impedance contrast is pointed out at 12-15m depth, that corresponds to resonant frequency between 2.5 and 3.5Hz. The value of this frequency is close to the frequency extracted form HVSRN. With this observation, we cannot conclude on the quality of the information extracted from HVSRN for the topmost layer. Nevertheless, because of its very low cost and the 1D geometry assumption of the topmost layer, it seems to be very useful to extend the HVSRN methods to the total urban area of Grenoble in order to have a continuous view of the high frequency amplification.

Figure 7: SASW analysis (A), cross-hole result (B) and (C) HVSRN computed at the site located in centre of the Grenoble basin.

7. Conclusion.

For several years, the HVSRN method has been widely used to assess possible seismic site effects which can have dramatic consequences on earthquake damage distribution. There is no doubt that this method is effective by the ease with which it
reveals the frequency of vibration of sedimentary layers, even if uncertainties still exist on the amplitude. Because of its ease of use, many authors chose to use it as an exploration tool since, in a 1D case, the resonance frequency is linked to the shear wave velocity $\beta$ and the sediment thickness $H$.

It is thus difficult to estimate the ground profile starting from HVSRN measurements. In particular, such measurements performed at the locations of accelerometer stations are often considered, given that the site conditions are very significant for evaluating empirical relations for predicting seismic movements and for understanding earthquake source effects. On the other hand, for large basins, there would seem to be a case for attempting to understand the amplified high frequencies which, when they exist, are representative of the upper sediment layers, given that these layers are thin and are thus comparable to 1D layers with a highly variable lateral extent. Future studies should be channelled in this direction, by combining reliable information deduced from geophysical and geotechnical methods and more systematic data obtained by the HVSRN method in order to obtain a comprehensive description of the ground surface.

8. Acknowledgment

This work was completed with the financial support of the Pole Grenoblois des Risques Naturels and the SISMOVALP Interreg IIB project.

9. References


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