Site Effect Study in Urban Area: Experimental Results in Grenoble (France)

Benoît LeBrun,1 D. Hatzfeld,2 and P. Y. Bard3

Abstract—Three methods are used to determine the site effect in the town of Grenoble, located in the Western Alps. First we use the classical spectral ratio method in 14 sites to calculate the transfer function of the basin. We find an amplification of 10 in the frequency range of 0.25 to 10 Hz. Second, we compare these results with the $H$ over $V$ spectral ratio method, and propose a map of resonance frequency of the basin. We find a lower resonance frequency in the center of the basin than on the edge, that is consistent with the structure deduced from a gravity Bouguer anomaly map. Finally we use the empirical Green’s function method to simulate a $M_w$ 5.5 earthquake at a distance of 20 km from the town. The simulated acceleration reaches the level of 2 m/s$^2$ in the center of the basin compared to 0.2 m/s$^2$ on the edges. The simulated ground motion we compute is smaller than the French seismic codes on the edge of the valley but significantly larger in the center.

Key words: Microtremor, spectral ratios, empirical Green’s function, site effects.

1. Introduction

The ground motion due to large earthquakes is dependent on soil conditions as was observed in Kobe (Japan, 1995), Mexico City (Mexico, 1985) and Annecy (France, 1996). In regions where the seismicity is moderate but the seismic risk is large, due to the density of the population or to industrial plants, it is important to predict what would be the ground motion in case of a strong or moderate earthquake. This prediction is difficult in urban areas. First, most of the time, the towns are not constructed on hard rock but close to the sea (Kobe, San Francisco), or to a large river (Cairo) or within mountains (Mexico, Grenoble), where the soil is soft and then favorable to ground motion amplification, and we do not yet have accurate methods to predict the effects of a soft layer on seismic ground motion in the frequency band of interest in civil engineering (0.5 to 10 Hz). Second, the high level of industrial noise makes classical seismic analysis (e.g., by using the spectral ratios method with reference station) of small earthquakes records difficult. Third, the data that constrain

1 Now at: BRGM, 117 av. de Luminy, 13276 Marseille Cedex 9, France.
2 LGIT/IRIGM, BP 53 X, 38051 Grenoble Cedex, France.
3 LCPC, 58, bd Lefebvre, 75732 Paris Cedex 15, France.
the geotechnical models are sparse, consequently the use of numerical simulation modeling is uncertain and the results unreliable. It is therefore necessary to develop methods that do not need detailed geotechnical data or strong earthquake records to evaluate the seismic hazard in urban areas.

In this paper we attempt to use methods that are both low-cost and easy-to-use, to define the characteristics of the ground response around Grenoble, a town located in the southeast of France. First, we compute the transfer function by the classical spectral ratio method (CSR) on weak earthquakes, second we compare the results with $H$ over $V$ spectral ratios computed on ground noise (HVNR), third we use this later method to derive a map of resonance frequency of the basin. Finally, we use weak earthquake records to simulate, by the Empirical Green’s Function method, a $M_w$ 5.5 earthquake close to the city.

2. Description of the Experiments

Grenoble is a town located in the Alps (southeast of France), which includes 300,000 inhabitants and a large number of industrial plants and research facilities. The town (Fig. 1) is built on quaternary sediments located between mountains that are of hard Jurassic limestone in the west and north (Vercors and Chartreuse mountains) and crystalline rock in the south (Belledonne mountains).

The structure of the sediment basin (S-wave velocity and geometry) is not precisely known. Regarding the depth, shallow geophysics and seismic profiles were performed in the surroundings of the town (Dietrich, personal communication, 1997). In the northwest they indicate a bedrock depth exceeding 600 m. In the northeast, the analysis is quite difficult and two seismic reflectors are found at a depth of respectively 400 m and 800 m. Moreover, a drill, conducted in 1944 in the center of the valley, did not reach the bedrock at a depth of 400 m. These data suggest that the basement is about 500 m deep under the town. This is confirmed by a drill, conducted in 1999 by the IPSN (F. Cotton, personal communication, 1999), which reached the bedrock at a depth of 534 m in the northeast of the valley. However, there is no data about S-wave velocity beneath and outside the town, it is uncertain to infer from the geotechnical data as a reliable synthetic transfer function of the basin.

We first conducted a seismic survey within the town in 1995, using 10 portable seismological stations to record at 15 different sites the seismic ground motion due to earthquakes. The acquisition system consisted of Reftek stations, recording continuously, connected in 11 sites to Guralp CMG40 velocity sensor (with a flat response between 20 s and 50 Hz), and Mark Product L22 velocity sensors (with a flat response between 2 Hz–50 Hz) in the last four sites (Fig. 1).

Some sites have been instrumented during the complete experiment (10 months) and the others for a shorter period (1 month to 8 months). In total we recorded 24 earthquakes, with magnitudes ranging between 2.8 and 4.7 for those with an
Map of the Grenoble agglomeration. Light gray is the quaternary sediment; dark gray is the bedrock. The big squares represent the temporary stations installed in 1995, and used for CSR calculation and the EGF method. The dots represent the $H/V$ measurements made in 1996. The drill performed in 1944, which did not reach the bedrock at a depth of 400 m, is represented with the star. Medium straight lines represent the seismic profiles.

epicentral distance less than 200 km, and magnitudes ranging between 6 and 8 for those with an epicentral distance larger than 200 km (Table 1).

This seismicity experiment was first used to calculate the ground motion amplification in case of a weak earthquake, using the Classical Spectral Ratios method, followed by small records used as empirical Green’s Functions and simulate the ground motion due to larger earthquakes as those that occurred in the past in this region.

We also recorded noise ground motion for the HVNR method, first to compare the results at the site instrumented during the seismicity experiment and second to derive a map of the resonance frequency within the basin. We sampled 100 sites
around the town (small circles in Fig. 1). In each site we recorded seismic noise for 10 minutes. We used a Reftek acquisition system connected to different sensors. First, we used a Guralp CMG40 (0.05–50 Hz), however as this sensor needs several minutes to stabilize, we changed it for a Lennartz LE55 velocity sensor (0.2–50 Hz). For the noise measurements, we tried to find quieter possible place such as public gardens, small streets and parking lots, to avoid the noise generated by cars and buses (see MUCCIARELLI, 1998 for a discussion of the experimental approach of the technique).

3. Description of the Methods

3.1 The Classical Spectral Ratios Method (CSR)

This method (first described in BORCHERDT and GIBBS, 1970) consists in calculating the transfer function of a site by dividing the spectrum of a recorded earthquake at the studied station by the spectrum of the same earthquake recorded at a reference station. The results are relevant when the average of spectral ratio is calculated over many events (FIELD and JACOB, 1995). We present here the averaged spectral ratios of all the events recorded by each station.

To process the signal, the time series is tapered with a Hanning window of length 10% of the window, the spectrum is calculated by FFT and is smoothed with a frequency dependent smoothing window, the length of which is equal to 10% of the frequency of interest, in order to keep a sufficient resolution at low frequencies.

The spectral ratio is calculated only at frequencies for which the signal-to-noise ratio is larger than 3 for both the reference and the observed stations. We will show the mean of the spectral ratios calculated on all the recorded earthquakes, together with standard deviation of the average. The record length used for calculation varies from 15 s for the local events to 2 min for the teleseismic events, which guarantees a good resolution at low frequency.

The reference station (MUSD) is located north of the town on Jurassic limestone (Fig. 1).

3.2 H over V Spectral Ratios on Noise Records

The HVNR method was first used in Japan (NOGOSHI and IGARASHI, 1971) but popularized in the international community by NAKAMURA (1989). It consists in calculating the transfer function of a site by dividing, for a single station, the spectrum of the horizontal component of the noise ground motion by the spectrum of the vertical component. Discussions about the assumptions of the method are made by LERMO and CHÁVEZ-GARCÍA (1993), LACHET and BARD (1994), BARD et al. (1998). The main conclusion is that the HVNR method is reliable to find the resonant frequency of a site (the frequency below which there is no amplification of the seismic
ground motion), but it is not reliable to give the level of the amplification of the seismic ground motion.

The data processing is the same as for the CSR method (tapering and smoothing). We divide the 10 mn records into twenty 30 s-time windows for which we calculate the \( H \) over \( V \) spectral ratio, and take the average over the 20 windows. The horizontal component is calculated by complex Fourier transform of the NS and EW components. The comparison at the same location between two different sensors (CMG40 and LE55) yields consistent results in terms of frequency, but slightly different (10\%) in terms of peak level. We also tested the stability of the method with time and for the length of the window by making measurements at the same point during different periods of the year with the same sensor, and we obtained a good stability in frequency but slightly less in peak level (again a difference of 10\%).

3.3 The Empirical Green’s Functions Method

The method was first proposed by Hartzell (1978). The purpose is to simulate strong motion accelerograms using small earthquake records as empirical Green’s functions. The source function of the main earthquake that we want to simulate is computed with the focal mechanism, the length of the fault and the rupture history. The convolution between the Green’s function and the source function leads then to the strong earthquake ground motion. The main assumptions are related to the source function of the strong earthquake and the linearity between small and strong earthquakes. All of these assumptions, as well as the description of the source function, are discussed in e.g., Hutchings et al. (1996) and Pavic, (1997). For the calculation of the source function, we used the multiepoch model described in Zeng et al. (1994) and Lachet et al. (1996).

As there is no strong earthquake record to compare to the simulation, we compare our results with the attenuation laws calculated by Ambraseys et al. (1996) from European data and with French paraseismic codes PS92 (AFNOR, 1995).

We use this method to estimate the level of the ground motion in Grenoble in case of a moderate, local earthquake. We choose three small earthquakes of magnitude lower than 2.5, located less than 20 km from the town, to simulate a \( M_w \) 5.5 earthquake at the location of two historical earthquakes that occurred at such distances.

4. Results

4.1 Amplification of Seismic Ground Motion

(a) Time series analysis

Figure 2 displays the EW components recorded in several stations of a magnitude 3.2 earthquake that occurred 50 km northeast of Grenoble. The amplitude of the
Plots of the EW components of seismograms recorded in different stations of a magnitude 3.2 earthquake located 50 km NE of Grenoble. The x-axis represents the time in seconds and the y-axis the ground velocity in cm/s. We note that the seismograms for the stations located in the center show larger amplification and longer duration than those located at the edges.

ground motion ranges between −0.01 and 0.01 cm/s. The ground motion recorded at the reference station obviously has a lower amplitude and a shorter duration than all of those recorded within the basin. These seismograms differ between each others:

– The stations HATZ, MEYL and GLAC exhibit a larger amplification and a longer duration (approximately 35 s) than the other stations located inside the valley (duration of 25 s).
The station EYBE shows a similar amplification although a much shorter duration (20 s).

The station NEYR, which is located in the middle of the valley, has a very low amplitude compared to HATZ, which has a similar position.

The seismograms recorded at stations SASS and SYNC, very close together, have similar waveform and length, but a larger amplitude for stations SASS.

This analysis of the time series seismograms suggests that there is an amplification of the seismic ground motion recorded within the valley relative to the edges. The amplification level is similar at all the stations, except station NEYR which shows a smaller amplification. The duration of the signal is longer at the stations located in the middle of the valley than at those located on the edges.

(b) Amplification in the frequency domain

We then use the CSR method to compute the transfer function of the basin. The spectral ratio is calculated for each component, but the results are only shown for EW component, because these are similar to the other horizontal component. Figure 3 displays the CSR results, with the average (thick lines) and the average plus and minus one standard deviation (dark gray).

For the stations equipped with the L22 sensor (MEYL, SMDH and EYBE), the results are not relevant below 2 Hz, and they are not shown, because the comparison with the HVNR method is not logical. There is however an amplification of 10 between 2 and 8 Hz, and at higher frequency the CSR decreases.

For the other stations there is an amplification of the ground motion between 0.25 Hz and 10 Hz. For the stations HATZ, ESTI, SASS, GLAC the amplification is around 10 in the whole frequency band. For stations STRO, SYNC and NEYR, the amplification at 0.3 Hz is around 10 and decreases at higher frequency.

Consequently, the ground motion is amplified at frequencies between 0.25 and 10 Hz throughout the sediment deposit. Assuming a 1-D model, there is a simple relation between the resonance frequency and the thickness of the sediment, which is $f = \frac{V_s}{4 \times H}$, ($f$, resonance frequency, $H$, thickness of the sediment layer and $V_s$, S-wave velocity). If we surmise an average S-wave velocity of approximately 600 m/s for the quaternary deposit, a resonance frequency of 0.25 Hz, observed in the center of the valley, leads to a thickness of the sediment layer of 600 m which is consistent with the other data (Bouguer anomaly and seismic reflection profiles). This amplification occurs in the same frequency band as that of the resonance frequency of common buildings with more than five stories.

(c) Comparison with HVNR

Figure 3 also displays a comparison between CSR and HVNR at 7 stations. The HVNR at the reference station on the bedrock is flat and close to 1, which is consistent with previous studies (LACHET et al., 1996; LERMO and CHÁVEZ-GARCÍA, 1993; FOUISSAC, 1997). For the other stations the HVNR exhibits peaks which are
Comparison at 7 stations between CSR (thick line is the mean and the dark gray area corresponds to the mean plus and minus one standard deviation) and HVNR (thin line is the mean and standard deviation in light gray). The first curve is for the reference station where the CSR is 1. In any case, there is a good fit for the resonance frequency between the two methods. In station HATZ, we remark a second peak at a frequency of 3 Hz.

considerably smaller than those of the CSR ones. The lowest HVNR peak frequency corresponds to the lowest frequency of amplification of the CSR curves, and can be considered as the fundamental frequency of the sediments layer. The HVNR is therefore able to give the fundamental frequency of a site, that in some cases may not be the frequency of maximum amplification (e.g., HATZ, GLAC or ESTI). In most cases the HVNR decreases to 1, or even lower, at higher frequencies and greatly differs from CSR value. Only in station HATZ, do both curves show a second peak at 3 Hz, with a lower value for HVNR than for CSR. That may be caused by a superficial layer.
present beneath this station and also detected by the HVNR method, but we cannot confirm this interpretation because we do not have precise geotechnical data.

4.2 Map of the Resonance Frequency of the Basin

As seen before, HVNR is reliable to compute the resonance frequency of a sediment layer. We then recorded ground noise at 100 locations (Fig. 1), in and outside the basin, to derive a map of resonance frequencies of the urban area. This frequency is deduced from the frequency of the first peak of the HVNR ratio. Figure 4 shows examples of HVNR. Outside the valley, on hard rock, the ratio is close to 1 and we cannot infer a resonance frequency in the bandwidth that we sampled. At the edges of the valley, the peak of the HVNR curve occurs at frequencies higher than 1 Hz. At the center of the valley, the peak occurs at frequencies lower than 1 Hz (down to 0.25 Hz), which is the lowest frequency we obtained. Figure 5a presents the

![Figure 4](image_url)

Figure 4
Examples of HVNR results. The mean of the HVNR ratio is represented in thick lines; the standard deviation in thin lines. Top curves, measurements outside the valley. Center curves, measurements on the edges. Bottom curves, measurements in the center. The fundamental frequency increases at the edges of the valley.
interpolated map of these resonance frequencies. We observe that this resonance frequency is larger at the edges of the valley than in the center.

This map is similar to the Bouguer anomalies map (Vallon et al. 1996, Fig. 5b), which is also related to the thickness of the quaternary deposit. Even some details are

Figure 5
Comparison between the HVNR observation and the Bouguer anomaly suggests that the fundamental resonance frequency is due to the sediment filling: (a) Map of the logarithm of the resonance frequency of the basin computed using the HVNR method. (b) Map of the depth of the bedrock inferred from Bouguer Anomaly measurements (after Vallon, 1996).
comparable, such as the increase in the south, suggesting a shallowing of the basement.

4.3 Conclusion on Spectral Methods

The results of this study, using different spectral methods demonstrate that there is a significant amplification of the ground motion at frequencies similar to the resonance frequency of many buildings. The second conclusion is that this resonance frequency of soil varies rapidly over small distances. These results can be of importance for the construction of large buildings or bridges, in that it means that a differential response of ground motion to seismic excitation could occur between different points of the building.

The HVNR method exhibits differences with the CSR method and cannot provide the same quantitative information regarding the amplification within the whole bandwidth, nonetheless it seems to be a reliable method to determine the resonance frequency of the sediment layer. This frequency may vary rapidly over small distances, and is far more easily determined than with CSR.

4.4 Simulation of a $M_w$ 5.5 Earthquake

The previous results were found with weak motion record. But historical seismicity (Cotton et al., 1998) shows that $M_w$ 5.5 earthquake could happen very close to the city (either just underneath or within 15 km of the city center). We used EGF method to simulate the ground motion in case of such an earthquake. We considered three different earthquakes, recorded at the same stations, at similar epicentral distance but different azimuths (Table 2). The magnitude of the EGF is lower than 2.5 and we simulated a $M_w$ 5.5 earthquake. The focal mechanism of these three earthquakes is the same and is reported in Table 2. We assumed a stress drop of 22 bar for the large event, with the same focal mechanism as small events.

The three simulations using the three earthquakes exhibit a good agreement as to the amplitude and duration of the signal, either for stations HATZ and for station MUSD. But the differences between the two stations are very important: the peak ground motion is 0.2 m/s$^2$ at MUSD and 2 m/s$^2$ at HATZ, and the duration of the signal is also very different. This suggests that a $M_w = 5.5$ earthquake could rise to

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dramatic differences in the ground motion within the city, depending on the soil conditions.

Figure 6a displays the accelerogram of one of the small earthquakes, used as EGF, recorded at the station HATZ and the inferred simulated accelerograms. We see that the duration of the accelerogram is longer in the simulated one and that this simulated accelerograms registers a lower frequency content than the EGF.

We then computed the response spectra of the simulated accelerograms and, as we have no record of a $M_w$ 5.5 earthquake in Grenoble, we compare them to the spectra assumed (i) by AMBRAEYS et al. (1996), using attenuation law deduced from European data and (ii) by the French paraseismic codes PS92 (AFNOR). This

![Empirical Green's Function](image1)

![Simulation](image2)

(a)

![HATZ, GLAC, MUSD](image3)

(b)

Figure 6

(a) Seismograms of the magnitude 2.2 Pont de Claix earthquake recorded in station HATZ (top of the figure) used as Empirical Green’s function to simulate a magnitude 5.5 earthquake (bottom of the figure). The amplitude scale is different between the two seismograms. We observe that the duration is longer for the simulation and that the frequency content is different. (b) Response spectra of the EGF simulation of the ground motion produced by a $M_w$ 5.5 earthquake located at a distance of 20 km. Three weak earthquakes are used as EGF. We compare the simulated ground motion response spectra (thin lines) with the results obtained with the PS92 French norms (medium line) and the results of attenuation law calculated with European data (AMBRAEYS et al., 1996) (thick line).
comparison is shown in Figure 6b. For station MUSD the response spectra of the simulated accelerogram is considerably lower than response spectra corresponding to French code and to average attenuation law, whereas for stations HATZ and GLAC, the EGF method produces a larger response spectra than PS92 or average attenuation law. One explanation could be that the EGF method does not take the nonlinearity of ground motion into account. Another one is that neither the PS92 codes nor the attenuation law properly consider the actual site effect.

5. Conclusions

We used experimental methods to predict the ground motion in the urban area where possible moderate size earthquakes, located a few kilometers away, could take place. We show that there is an amplification of the ground motion inside the valley of Grenoble in the frequency range 0.25–8 Hz, which encompasses the resonance frequency of most common buildings. This amplification can reach the level of 10 between the center of the valley and the edges, and the resonance frequency, which varies strongly within small distances, is lower in the center of the valley than on the edge.

The second conclusion is that the HVNR method allows the determination of the fundamental resonance frequency of a site far more easily than the CSR method, but it does not allow the determination of the amplification in all the frequency bands, nor the level of the amplification. This method is an easy way to obtain a map of the fundamental resonance frequency of a city, which can be used in microzonation studies, combined with geotechnical data, to determine homogeneous areas as regards of soil response.

Taking as Empirical Green’s function small local events, we predict a peak ground acceleration of 2 m/s² in the center of the town for a $M_w 5.5$ earthquake located at 20 km. This largely exceeds the pga on rock (0.2 m/s²). The French paraseismic code, as the empirical attenuation laws, predicts response spectra which are larger than our simulation on rock but decidedly lower on quaternary deposits. We suggest that the amplification of ground motion in thick steep-sided alpine valleys is not properly provided for in the building codes.

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