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Site Amplification Effects in the Ubaye Valley (France): Measurements and Modeling

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ABSTRACT : Local soil conditions can yield to significant variations in ground motion generated by earthquakes. During the last two decades, these amplification effects have been observed by numerous authors for well-documented earthquakes. On the other hand, theoretical models and numerical techniques have been proposed to physically understand site effects.

However, few comparisons have been made between observations and theoretical results for well-known 2D structures (sediment-filled valleys).

The aim of this paper is to present a study of the response of a valley in the French Alps. The structure (Ubaye valley) was chosen for its moderate dimensions (500 metres wide and a 65 metres thick) which allow an accurate determination of the deposit characteristics, and for the relatively high seismicity of the region.

The study has included the set-up of a temporary array of five seismological stations, a geophysical survey of the valley to determine the dynamic properties and the geometry of the soft deposits, and numerical modeling (1D and 2D cases) of the response.

Comparisons between observed and computed amplifications show a good agreement for particular input motions (corresponding to the SH case). In the other cases, the spectral ratios exhibit a great variability between different groups of similar earthquakes and more developped simulations should be used (2D P-SV, 3D).

Introduction

Strong ground motions are characterized by a great spatial variability as it is usually indicated by the distribution of damage during large earthquakes. The influence of shallow structures is now widely accepted to play an important role in the amplitude and spectral characteristics of the ground motion (see Sanchez-Sesma, 1987 and Aki, 1988 for reviews). While the qualitative observations of site effects are numerous, the quantitative evaluations of the amplification of a well-defined structure remain rare. In order to model the response of a superficial structure to seismic waves, the S-wave velocity distribution is required. This report describes an experiment associating a seismic surveying with the operation of a temporary seismological array in a small area of width of about 500 m.

The location of the experiment was chosen in the Ubaye Valley for three main reasons: the level of seismicity of the region, the absence of seismic noise due to human activity and finally the topography near the site of Maljasset that suggests that the valley can be considered as two-dimensional.

Geological and seismological setting

The site of Maljasset along the Ubaye river is located in the French Alps close to the Italian border (see Figure 1). This zone belongs to the Briançonnais arc which is an internal unit of the western Alps. It consists of a siliceous basement (Permo-Carboniferous age) overlain by a calcareous cover (Mesozoïc and Eocen).

This region presents one of the highest rate of seismicity in the French Alps. Several historical earthquakes were reported. The last damaging earthquake was felt in 1959 (magnitude 5.3). During a seismicity study in this area Frechet and Pavoni (1979) recorded about 1500 earthquakes in one month. During our experiment the earthquakes were much less numerous (about 25). Presently, permanent networks are operating in the region (SISMALP and LDG networks) and have allowed to locate

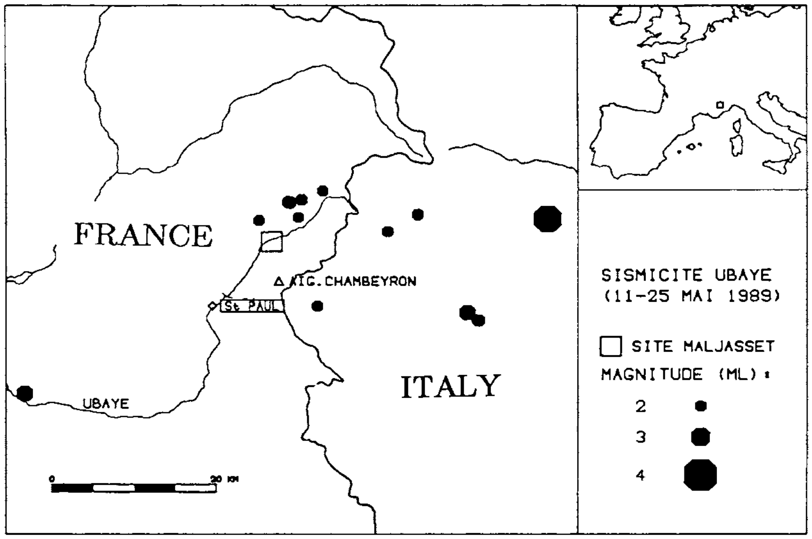

Figure 1: Sketch map of the region studied. The heavy line indicates the border. The black dots show the locations of the earthquakes computed from regional arrival times (see Table 2)

half of the events. The characteristics of these earthquakes will be discussed in the following.

Seismic exploration of the site

Our prospection has two goals: to determine the geometry of the valley at depth and to measure P and S wave velocities and quality factors in each geological unit.

The substratum corresponds to Cretaceous limestone that outcrops on the northern edge. The filling of the valley is a mixture of alluvium and moraines.

The exploration of the site began with 17 reversed refraction profiles (P wave) whose lengths range between 45 and 360 meters. The sources used were hammer for the shortest profiles and explosives for long distances. We also performed a series of 4 S-wave refraction profiles with a maximum source-receiver distance of 180 meters. The horizontal impact of a hammer on to one side of a loaded plank was used as a shear wave source. The location of the different seismic profiles are shown in Figure 2. During this experiment we have increased the duration of the records in order to get the surface waves. We used the Rayleigh wave dispersion to infer the distribution of S wave velocity at depth by an iterative inversion (Herrmann, 1985). The results obtained with this approach are in good agreement with those inferred from S wave

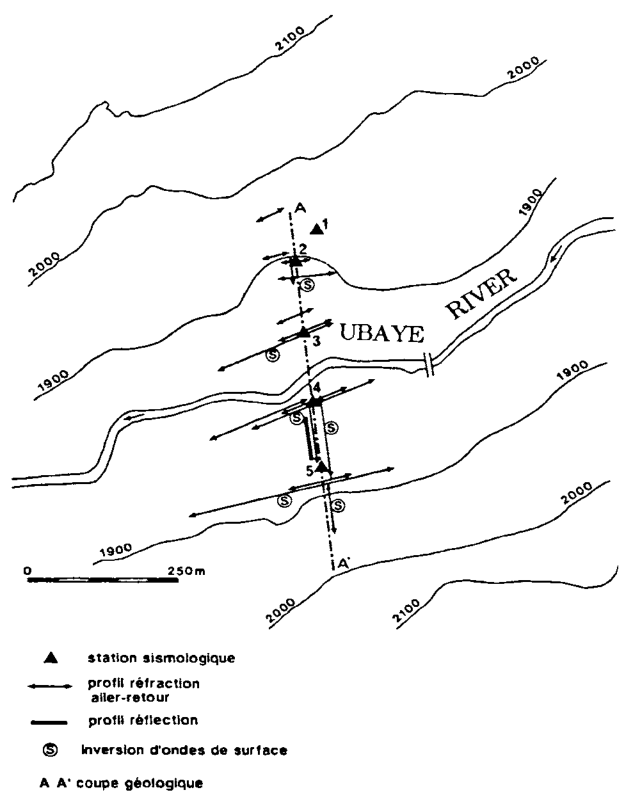

Figure 2: The locations of the different seismic experiments.

efraction profiles when they are available Jongmans et al., 1990).

A high resolution reflection profile was .lso carried out in order to map the bedrock in he central part of the valley at a depth of ıbout 65 meters.

The results obtained indicate that the ›edrock consists of sound limestone with P wave ·elocity varying from 4500 to 5500 m/sec (Vs = :100-2400 m/s). The maximum thickness of the leposits is of about 65 m. The inner structure ɔf the valley presents 3 different units, as ;hown in Figure 3 where we present its geometry ʋith the values of P and S waves respectively. The superficial layer (referred as Formation 1) is made up of recent alluvium from the Ubaye River and of colluvium from the relatively steep shoulders of the valley. The corresponding wave velocities are low and present rapid lateral variations (Vs = 150 to 350 m/s). The deeper deposits can be separated into two distinct units with different wave velocities. Formation 2 lies just beneath Formation 1 and extends throughout the structure. The S-wave velocity is ranging from 500 to 750 m/s. In the deeper part of the valley, the bottom of the deposits (Formation 3) presents higher velocities (Vs=1100 m/s) which may correspond to consolidated moraines.

Since we found a reliable model of the valley, both in terms of geometry of the interfaces and of the different wave velocities, we need another important parameter to compute the valley response : the shear wave quality factor Qs. We applied the rise time technique (Gladwin and Stacey, 1974) to the S

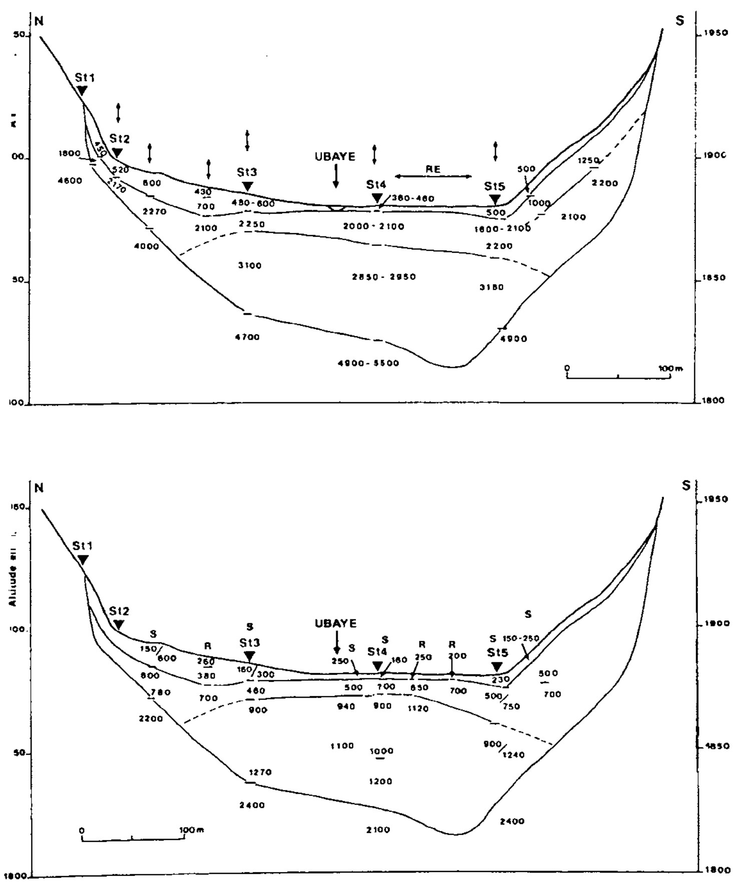

Figure 3: Cross sections of the valley (along the line **AA'** shown in Figure 2) deduced from seismic experiments. The velocities are given in m/sec.

Unit	Method	Qp	Qs	Frequency (Hz) P	S
2	Rise time	5.5-7.5	5-6	50-90	40
	Surface wave	—	10	—	9-16
3	Rise time	11	5-6	60-100	30-50
	Surface wave	—	20	—	9-16

Table 1 Qs values inferred from in-situ tests.

refraction profile data. By considering separately the different branches of refraction, we were able to measure Q for the formations 2 and 3. These results which concern high frequency waves (more than 30 Hz) are presented in Table 1 together with Qs values deduced from Rayleigh wave analysis. These last measurements corresponding to lower frequencies (9 to 16 Hz) were performed by inversion of the frequency dependant attenuation factor of the surface wave amplitude (Herrmann, 1985). We found that the values of Qs obtained at high frequency with the rise time technique are systematically lower that the values inferred from Rayleigh waves. This may indicate a frequency dependence of Q in surficial materials. This discrepancy is presently a source of uncertainty that must be taken into account for the modeling of the response of the structure to incoming waves.

Seismological experiment

During one month (may 1989), a temporary network of 5 seismological stations was installed in the site of Maljasset (see Figure 2 for their location). We used identical digital stations composed of 3 component seismometers with natural frequency of 1 Hz. Station 1 is located on hard rock and is used as a reference to evaluate the incoming wave field. The other stations were set up at equal interval across the valley. Since the site is at an altitude of 1900 m, technical problems arose due to the large variations of temperature.

In order to study the experimental site response, we selected the events recorded by at least 3 stations. The locations of the 15 earthquakes used in the following analysis are shown in Figure 1 while their main characteristics are given in Table 2. With respect to their locations we organized this set of earthquakes into 3 groups. In order to verify that this choice is sounded, the spectra of the horizontal motions (S waves) at the hard rock station are compared for the different events and the analogy of the shape of the spectra was checked for the different groups of earthquakes.

number	date	hour	M_L	t_s-t_p (sec.)	epicentral distance (km)	depth (km)
3	11-05	13h40	2.2	1.12	9.6 ± 2	4 ± 3
5	12-05	11h27	3.6	3.79	34.3 ± 2	9 ± 4
7	17-05	03h09	2.3	0.46	6.9 ± 2	0 ± 2
10	17-05	06h04	0.5	0.55	10 ± 26	0 ± 8
11	17-05	07h59	2.5	0.54	6 ± 3	3 ± 2
12	17-05	08h12	1.8	0.54	3.2 ± 1	2.8 ± 0.5
13	17-05	08h14	< 2	0.52	—	—
15	18-05	12h16	< 2	2.30	4.5 ± 3	16 ± 1
16	18-05	13h03	1.9	2.18	14.4 ± 2	9 ± 1
19	22-05	20h05	2.3	2.00	18.5 ± 2	7 ± 2
20	22-05	20h46	< 2	0.53	—	—
21	25-05	13h32	< 2	0.55	—	—
22	25-05	13h51	2.4	3.30	27.3 ± 1	2 ± 2
23	25-05	18h58	2.7	3.24	26.1 ± 1	7 ± 2
24	25-05	22h00	2.7	3.50	36.5 ± 2	3 ± 3

Table 2 List of the earthquakes with their main characteristics.

The earthquakes are subdivided as follows:

- group 1 : events 7, 10, 11, 12 and 13
- group 2 : events 15, 16 and 19
- group 3 : events 22, 23 and 24.

The event 05 is different from the other both by its magnitude (3.6) and its location Group 1 consists of local shallow earthquake that occurred in the North of the site in th direction of the alignment of our stations The epicentral distances are less than 10 km Groups 2 and 3 correspond to earthquake located at distances larger than 15 km and 2 km, respectively.

Site response

We present in Figure 4 an example o records at the different stations across the valley. The signal duration is of 25 sec. The seismograms are plotted at the same scale and illustrate the amplification of the ground motion at location over the alluvium with respect to hard rock site. The amplification appears on all the components (note that one horizontal component of station 5 is inoperative). Figure 5 presents another example for a shorter record of 5 sec. The amplification effect also exists but in this case the change of spectral content of the signal can be clearly seen.

In order to quantify this amplification effect, we computed the spectral ratios between the signals observed at sites in the valley and the signal recorded at the reference hard-rock station. The spectra ratios, computed for the two horizontal components from the records of the events of Group 1, are presented in Figure 6. The mean spectral ratio is also drawn with dashed lines. At each station the ratios exhibit some very similar features in most of the cases. The existence of spectral bands of amplification centered on the same values of frequency is characteristic of the response of the soft deposits.

We have just shown the relative stability of the spectral ratios for earthquakes of a given group but this property exists no more when comparing records for events from different groups. This is illustrated with Figure 7 which presents the mean values of the spectral ratio computed for each group of earthquake. We have plotted separately the

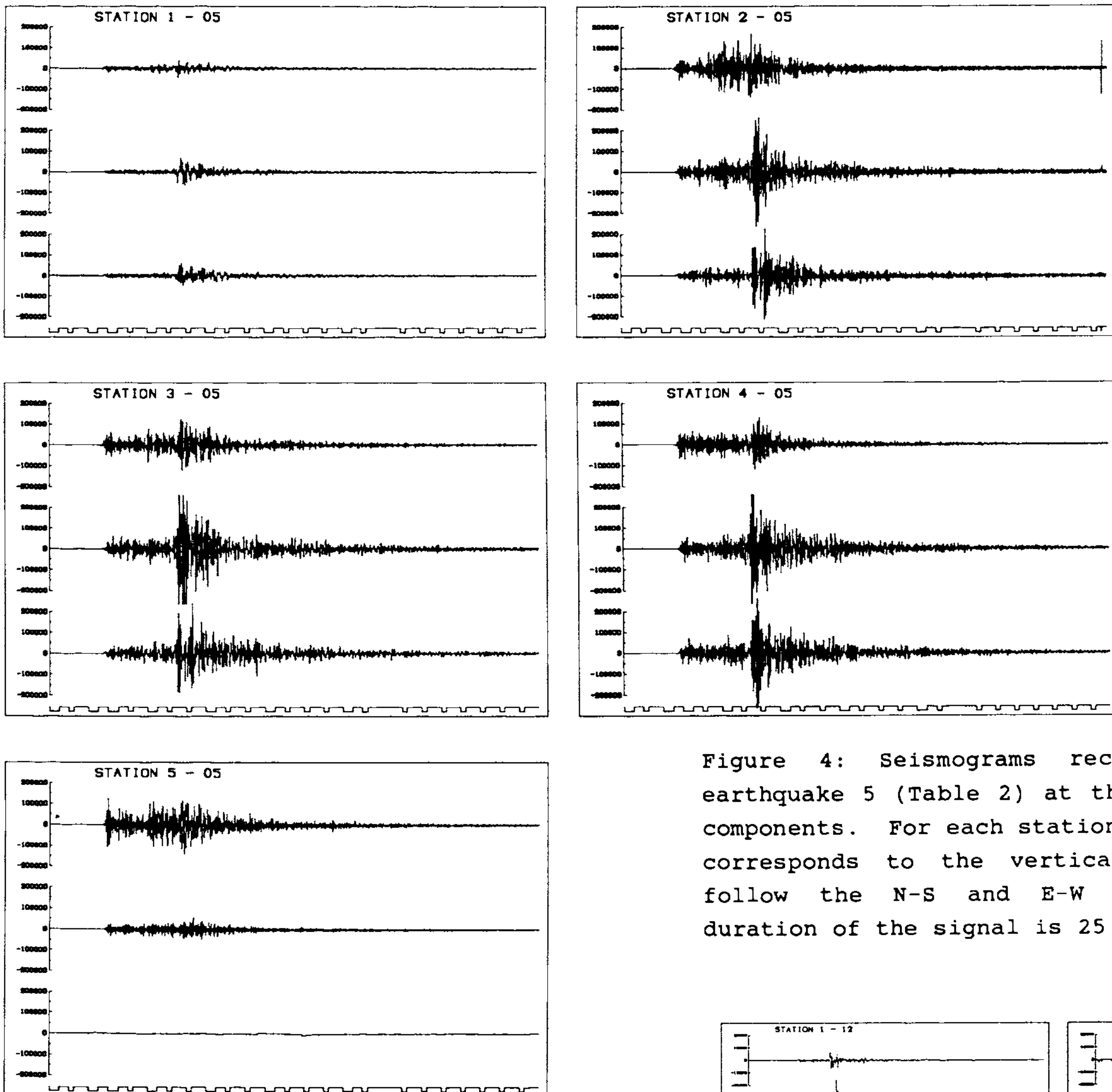

Figure 4: Seismograms recorded during the earthquake 5 (Table 2) at the 5 stations on 3 components. For each station , the upper trace corresponds to the vertical component, then follow the N-S and E-W components. The duration of the signal is 25 sec.

curves corresponding to the earthquake 05 which has a magnitude and an epicentral distance different from the other events. In some case we have also computed the spectral ratio for the seismic noise. The clear difference between the results obtained from earthquakes and from noise is probably due to the part played by the river. The spectral ratios computed for the earthquake groups show in most cases some differences that prevent to identify a common response of the sites.

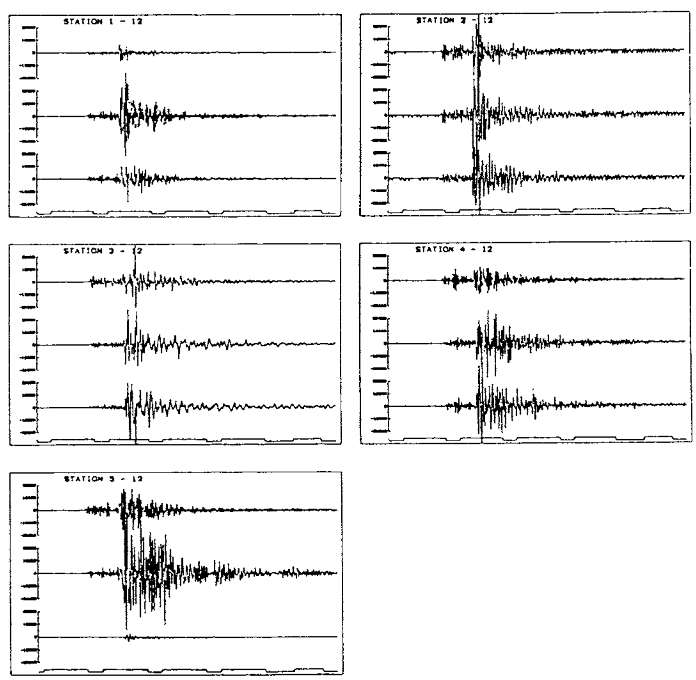

Figure 5: Same as Figure 4 for a smaller earthquake. The duration of the signal is 5 sec. Note the variation of spectral content.

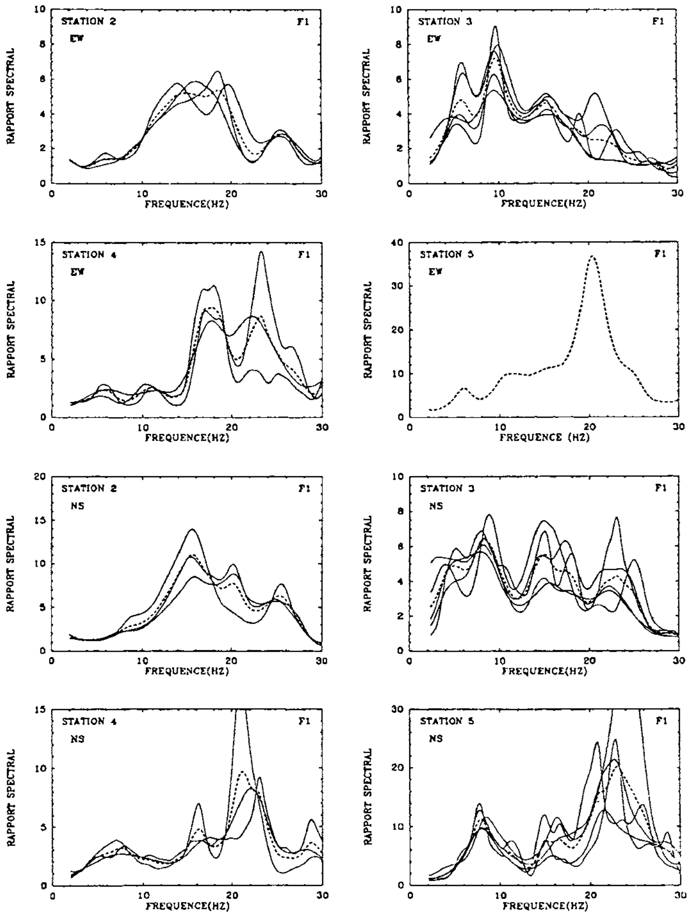

Figure 6: Spectral ratios between records at the reference station and at the sites in the valley for the event of Group 1. The ratio were are shown for the two horizontal components. The mean value is plotted as a dashed line.

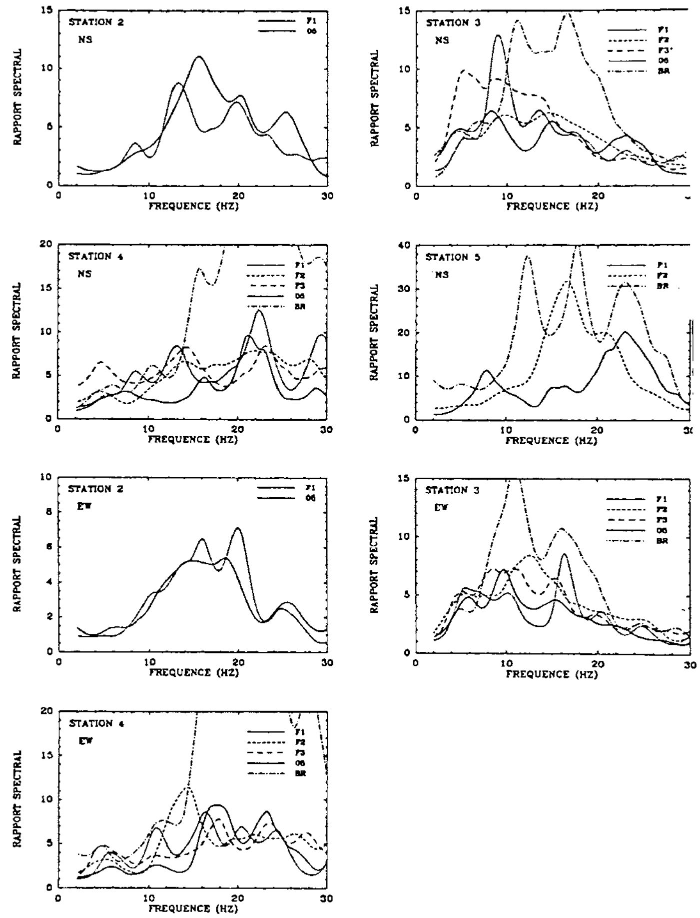

Figure 7: Comparison between the mean spectral ratios computed for the different groups of earthquakes. The curves corresponding to Group 1 to 3 are labelled F1 to F3. The dashed line (BR) is the mean ratio computed from the seismic noise.

From the examination of these figures we can draw the following conclusions:

- the spectral amplifications vary from one station to the other both in terms of maximum value and of shape of the response curve, - the values of amplification and the position of the peaks change
from one horizontal component to the other,
- the spectral ratios are also dependant on the group of earthquakes considered.

In order to further understand the amplification effects and their variability, we have compared these observations with theoretical predictions under simple assumptions.

1D modeling

On the basis of the seismic surveying, one may expect to have a good knowledge of sub surface ground conditions in the valley. The quantitative data obtained were used to set up a one-dimensional model beneath each seismological station and we computed the response of such a stack of layers to incident SH and SV waves.

The spectral amplifications at each station are shown in Figure 8 and indicate that important variations of the curves occur only for very large values of the incident angle. For moderate incidence (up to 30 degrees) the curves remain very stable. When we compare

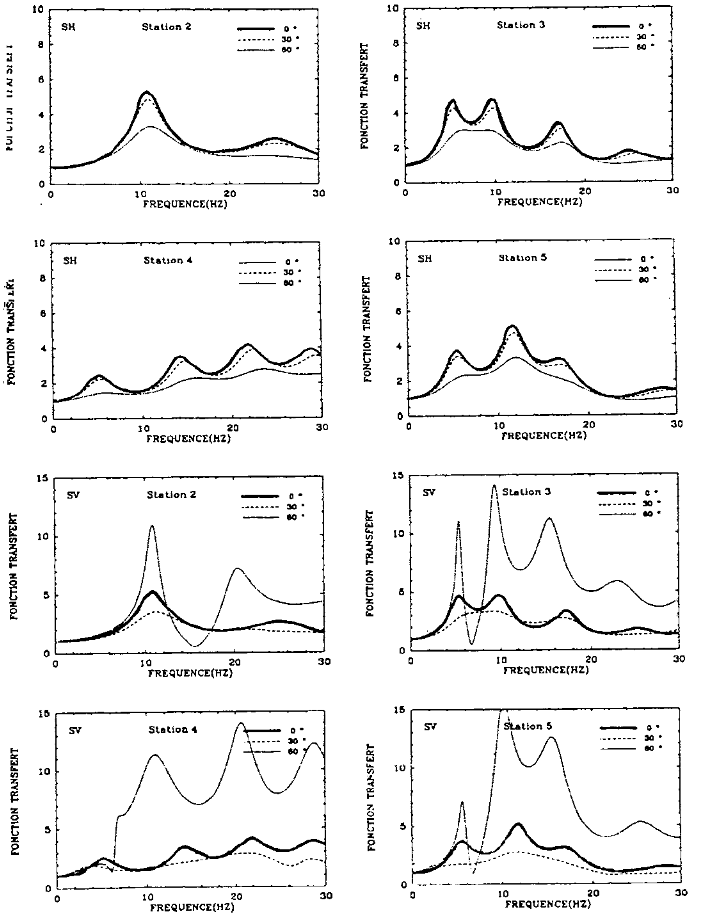

Figure 8: One dimensional response of the soil beneath the stations plotted for 3 different incidence angles on each graph. The upper part of the figure corresponds to the case of SH waves while the lower part shows the response at each site for incident SV waves.

these computations with the experimental results of Figure 7, we can find global agreement for some features such as the magnitude of the amplifications or the shapes of the spectral ratios at stations 3 and 4 for example. Nevertheless, 1D modeling fails to explain experimental results such as the broad band amplification at Station 2 or the variations of the locations of the spectral peaks for the different groups of earthquakes. We therefore investigate the possible effect of lateral changes of the structure under the assumption of a two-dimensional model.

2 D modeling

To compute the response of a two dimensional structure given by the results of the prospection (Figure 3), we used a boundary integral equation method in a formulation described by Bouchon et al. (1989). This method allows to consider steep interfaces and high frequency waves. In the present application, we restricted the computation to the case of vertically incident SH waves. We considered frequencies between 0 and 25 Hz. The model was simplified in order to give a local analytic representation of the interfaces

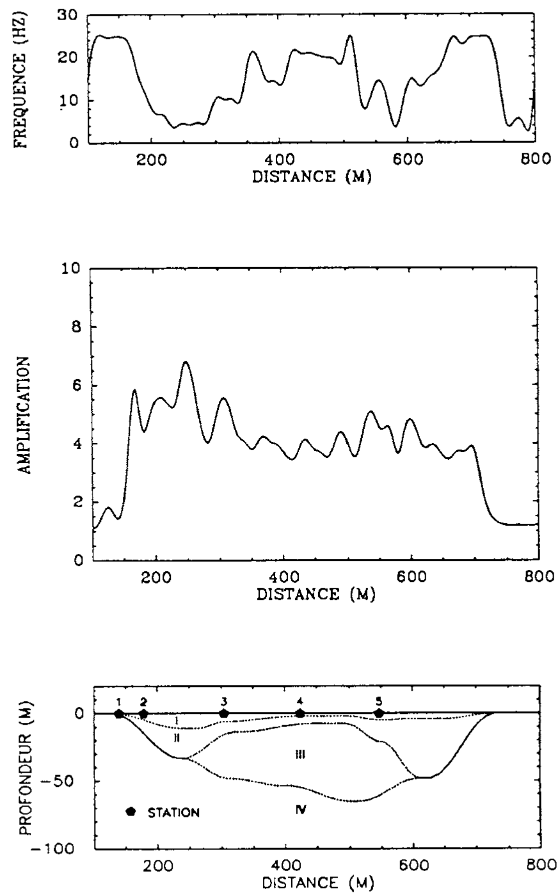

Figure 9: a) 2D model used in the computations. Characteristics of the layers are given in Table 3. b) Maximum amplification and c) frequency corresponding to this maximum.

in terms of cosines. It is presented in Figure 9 together with the maximum values of amplification and the corresponding frequencies. The parameters of the medium used are given in Table 3. The quality factors are those inferred from surface wave analysis.

formation n°	description	V_s(m/s)	Q_s	ρ
1	Surficial layers (alluvium, colluvium)	250	10	1.8
2	Alluvial deposits	600	10	1.9
3	Moraines, weathered bedrock	1100	20	2.0
4	Limestone	2400	200	2.6

Table 3 Dynamic characteristics of the formations used for 2D modeling.

The results obtained indicate the existence of low frequency amplification above deep soft deposits. The maximum values of amplification are less than 7. The wave propagation in the valley can be seen in Figure 10 where is plotted a section of synthetic seismograms computed across the structure. These synthetics correspond to an incident

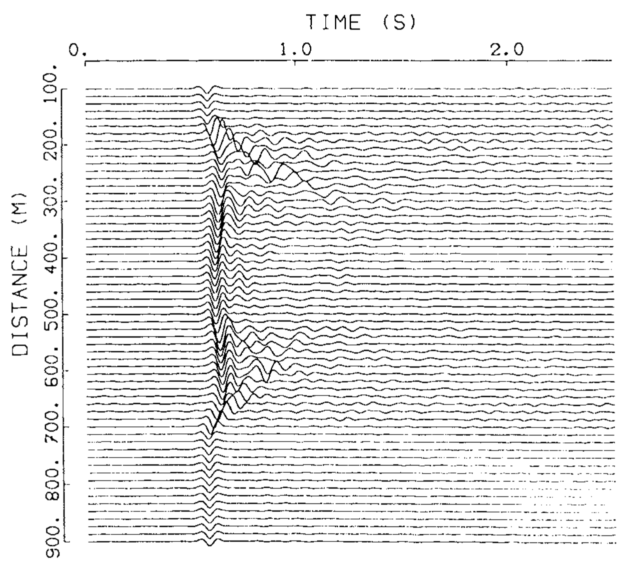

Figure 10: Example of synthetic seismograms computed for the model shown in Figure 9. The source time function is a Ricker wavelet of central frequency 10 Hz.

Ricker wavelet whose central frequency is 10 Hz. It is not possible to identify waves that propagate from one edge of the valley to the other. Thus we cannot expect to observe a lateral resonance of the structure. On the contrary, in each of the two zones where th layers 1 and 2 are thick, we can see travellin waves that contribute to increase the duratior of the signal and, therefore, that are the cause of the spectral amplification shown ir Figure 9.

Comparison between observed and predicter amplifications

To be able to compare our computation with actual observations we have to select data that are compatible with the restrictive assumption of our theoretical modeling. First, we limited our calculus to the two-dimensional case. The shape of the valley allows this hypothesis when we consider earthquakes aligned with the seismological stations. As mentioned before, this is the case with earthquakes of group I. Second, we only considered SH waves in the computation. With respect to the configuration of our experiment, this means that we must use the EW component of the motion to make the comparison.

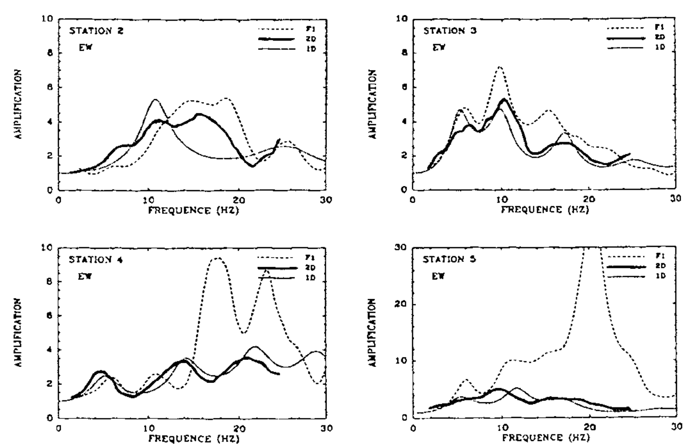

Figure 11: Comparison between observed amplification for Group 1, 1D and 2D modeling.

The results are summarized in Figure 11 which presents (a) the spectral ratios computed from the EW components of earthquake records of group I and (b) the theoretical spectral amplifications for the 1D and 2D computations. The most striking effect of considering a 2D model in place of a 1D one is visible for the case of Station 2. As this is observed, the two-dimensional modeling predicts a broad-band mplification of the motion while a flat ayered structure would result in a peaked pectrum. For station 3, our results are lmost similar whatever model is considered. he prediction slightly underestimates the mplification beneath the station but gives an cceptable description of the location of the eaks of amplification. For Station 4 the odels and the observations are in good greement for frequency smaller than 10 Hz. At igh frequency, the large discrepancy is robably explained by our poor knowledge of the ost superficial layers, that might play a rominent part in the response for frequency arger than 15 Hz. Similar remarks can be made n the case of Station 5. One must note that he two-dimensional model is still too simple ecause each layer is defined with given wave elocity, density, ... while, as shown in igure 3, our prospection experiments indicate ome lateral variations of the elastic modulus n the layer in addition to the variations of epth of the interfaces.

Even if the entire valley is not subject o resonance, 2 D effects cannot be ruled out, n particular to explain local effects at the edges of the structure (Station 2).

Another aspect which may be pointed out by he 2D-SH modeling of the structure is the nfluence of the incidence angle likely to explain some of the fluctuations of the amplification curves for the different groups of events.

This is illustrated in Figure 12 which compares the amplification corresponding to angles of incidence of 0 and 30 degrees respectively. In this case one can notice changes in the positions of the amplification peaks as an effect of the variation of the incidence angle. In the same time, a similar test made for one-dimensional model shows almost no shift in frequency (Figure 8).

These results show the need for at least a two-dimensional modeling to explain the amplification in the valley and its variability from one group of earthquakes to another. In addition, further examination of the data indicates that a 2D-SH modeling is not sufficient. For example, the different behavior between the two horizontal components is an important point that cannot be addressed at this stage of the simulation. The full elastic modeling and the 3D case must be the next goals of our study.

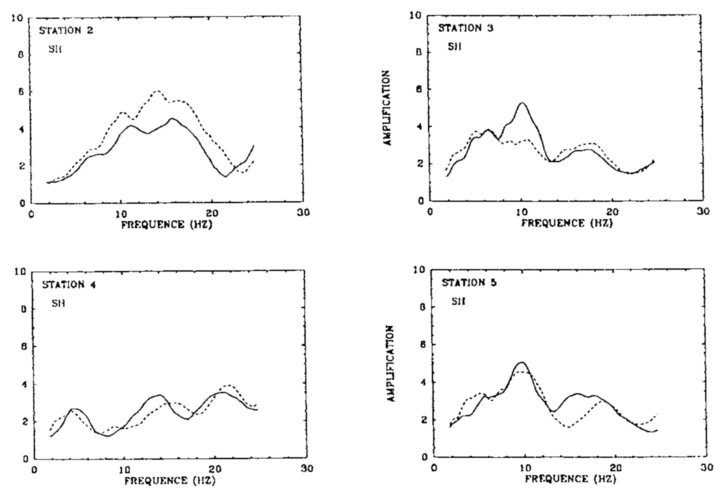

Figure 12: Amplification curves computed in the two-dimensional case for two incidence angles: vertical (continuous line) and 30 degrees (dashed line).

CONCLUSIONS

The study of the Ubaye valley has been initiated with the aim to test our capability to predict amplifications effects for a given site.

The geological structure of the valley was unknown and the first step was to investigate it thoroughly with different seismic methods (refraction tests, reflection profile and surface wave inversion). P and S wave velocities as well as quality factor values were inferred from these experiments.

At the same time, earthquakes have been recorded by five stations (3 components) located in the valley and on a rock outcrop. The spectral ratios have indicated a great variability of the responses (a) between the different stations, (b) between the two horizontal components of the same records and (c) for different groups of earthquakes at the same station. This last observation suggests an azimuthal dependence of the site response towards the earthquake location.

On the basis of geophysical data, numerical simulations (1D and 2D modeling) were performed for the SH case. In most cases, observed and synthetic spectral ratios show a good agreement for a frequency lower than 10 Hz.

If these results are promising, modeling at this stage is however limited to a specific input motion (incident SH waves) and reality clearly appears to be more complex. An important point to stress is that all the experimental amplifications which have not been simulated tend to be higher than those predicted in the SH case.

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