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Trans-national study of site effects, the Cerdanya valley across French and Spanish Pyrenees

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ABSTRACT – The Cerdanya valley, located in the Eastern part of the Pyrenees range, between France and Spain, has been selected as a pilot zone for the elaboration of real-time seismic scenario directed to local authorities and emergency services. The elaboration of such scenarii implies a quantitative estimation of site effects at regional scale. The first step of site effects study was the harmonization of lithological typology and contours across the border and the elaboration of a simplified lithological map of the whole valley. This work has been completed by H/V measurements and SASW measurements on Quaternary deposits to provide resonance frequencies, information on substratum depth, and Vs profiles of superficial layers (up to 50 m depth). These data, combined with the analysis of earthquake data recorded during the Ripollès crisis of September, 2004, lead to a first order zonation of the valley using a soil classification based on lithology and layer thicknesses. For each zone, characterized by reference soil column(s), 1D numerical simulations using linear-equivalent models have been performed to obtain specific acceleration response spectra. Finally, soil amplification has been converted to macroseismic intensity increase for seismic scenario computation.

1. Introduction

The Pyrenees range is known as an active tectonic zone with moderate seismicity, that results from the collision between Eurasian and Iberian plates. Historical and instrumental seismicity indicate high seismic hazard level of the region. For memory, during the XVth century an important seismic crisis induced severe damage in the Eastern part of the range, destructive earthquakes hit the central Pyrenees in 1660 and 1750 (I0=VIII-IX and VIII), and the Western Pyrenees in 1967 (I0=VIII). More recently, moderate earthquakes like that of Saint Paul de Fenouillet in 1996 (Ml=5.6, I0=VI-VII) induced important economic losses due to the increasing number of inhabitants and economic activities in the area. In this context, seismic hazard mitigation becomes critical through prevention actions and effective post-seismic crisis management. However, one of the challenges for the Pyrenean range is the trans-national harmonization of methods and means between France and Spain.

ISARD is a European Interreg project which aims at providing homogeneous preventive and operational information on seismic hazard on both sides of the border. A pilot area for this experiment is the Cerdanya valley located in the Eastern part of the Pyrenees range between Spain and France. One of the main objectives of the project is to develop a methodology for real-time seismic scenarii that would deliver estimations of damage and losses to local authorities and emergency services. In this framework, an important work of harmonization, site effects assessment and mapping across the border has been undertaken. It is the object of this paper.

2. Harmonized geological map of Cerdanya valley

The Cerdanya valley is characterized by the presence of Quaternary deposits and a very deep sedimentary basin filled with up to 30 m depth Quaternary sediments and up to 800 m depth Miocene conglomerates, sandstones and lutites. The bedrock is made of schists. This particular structure is prone to induce important ground motion amplification. The first step of site effects estimation was the elaboration of a harmonized geological map over the two countries to locate the superficial formations which could induce a significant amplification of seismic ground motion during an earthquake.

Lithological harmonization work for the superficial formations was based on geological map data (French and Spanish scale: 1/50 000). Considering the difference of information level across the border, the developed process consisted in completing a lithological harmonization for both sides of the border separately using a specific typology created in the framework of the project. The cross border map has been built including natural geological choices and geomorphological interpretations around points of disharmony. This work lead to a final harmonized map described by 22 lithological entities (Colas *et al*., 2006).

3. Geotechnical zonation

The second step of site effects estimation over Cerdanya valley was the definition of homogeneous seismic response zones. This geotechnical zonation is based on a simplified litho-stratigraphic mapping including data of:

- geophysical measurements (SASW and H/V spectral ratio from noise records); which give the resonance frequency of the site from H/V spectral ratio (Nakamura, 1989), a Vs profile from SASW measurements (Bitri et al., 1997) and an estimation of EC8 criteria Vs30 (the average shear velocity for the first 30 meters of a soil column),
- boreholes data from BRGM Subsurface database (so-called BSS),
- geological and geophysical synthesis of the deep Miocene basin of Cerdanya.

3.1. SASW measurements and H/V results

Complementary geophysical data were collected to obtain information on resonance frequencies, sediments thickness and V_S values. To this effect, a SASW campaign and seismic noise measurements either on punctual sites or along linear profiles were performed (Figure 1).

The H/V spectral ratio results obtained by Macau et al., 2006a from noise measurements with Nakamura's technique show a good agreement between the Miocene basin structure and resonance frequencies with very low resonance frequencies (lower than 0.5 Hz, corresponding to yellow rectangles on Figure 1) in the deepest part of the basin (light blue and grey on Figure 1) and higher resonance frequencies (red rectangles on Figure 1) towards the borders, where Miocene deposits thin out (dark blue on Figure 1).

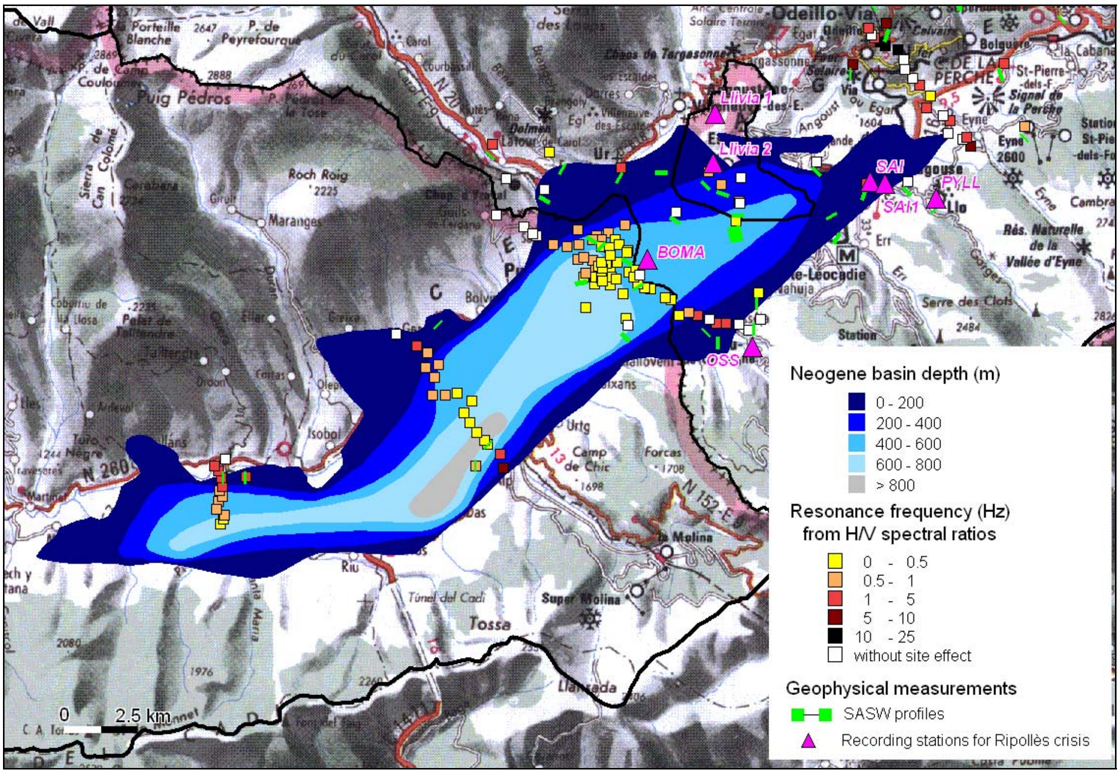

Figure 1 : Location and interpretation of the geophysical data and isopach curves of the Miocene basin of Cerdanya (Rivero, 1993). Topographical data are extracted from IGN map n°REG17 “Languedoc-Roussillon” at 1/250 000 (Institut Géographique National, France).

The H/V spectral ratios outside the basin show variable resonance frequencies, mostly superior to 1 Hz, corresponding to thinner superficial layers of soft sois.

The SASW profiles (in green in Figure 1) helped determine the shear velocity of superficial layers (Bitri *et al*.,2004) both inside and outside the Miocene basin and gave critical clues for the interpretation of H/V results relating the observed resonance frequency and the thickness of the layer responsible for the main resonance peak. It highlighted for example the importance of the Neogene formations which seem to induce stronger amplifications than the overlaying Quaternary deposits despite lower shear velocity values (about 350 to 500 m/s) for the soft Quaternary deposits compared to that of Miocene formations (about 1000 m/s at depth, below the altered zone).

3.2. Geotechnical zonation

Considering the geological, geophysical and geotechnical data, the zonation of Cerdanya valley was simplified to 9 soil classes identified as follows (Colas *et al.*, 2006, Figure 2):

- Soft Quaternary deposits on rock, from 5 to 20 m depth,
- Neogene deposits inside the Cerdanya basin, up to 800 m depth,
- Quaternary deposits in Neogene basin,
- Rock formations: mainly constituted by Paleozoic and Mesozoic substratum,
- Soft Quaternary deposits on rock and Stiff Neogene and Quaternary deposits on rock, up to 5 m depth,
- Stiff Neogene and Quaternary deposits on rock, from 5 to 50 m depth,

- Stiff Neogene deposits on rock, thicker than 50 m depth,
- Soft Quaternary deposits on stiff Quaternary deposits, thicker than 50 m depth,
- Stiff Quaternary deposits on rock, thicker than 50 m depth.

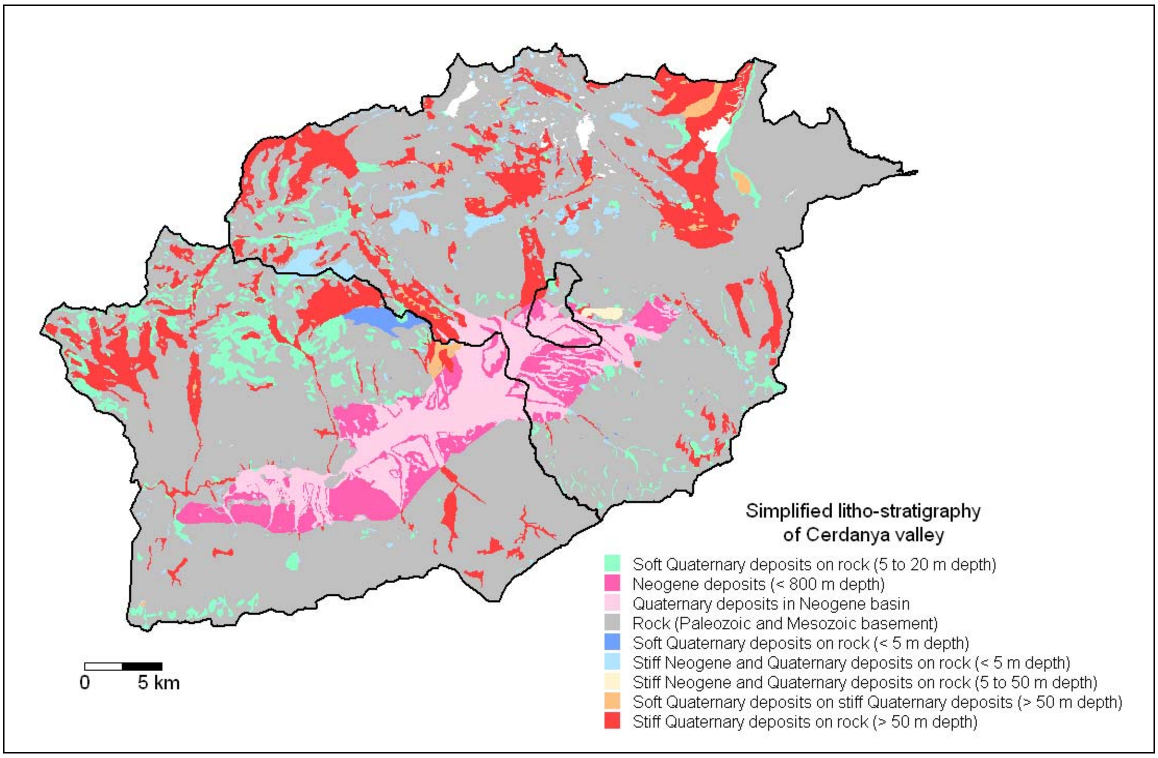

Figure 2 : Simplified litho-stratigraphic map of Cerdanya valley (Colas et al., 2006).

4. Seismic response spectra by 1D simulations

In order to perform a complete seismic zonation of the Cerdanya Valley, the seismic behavior of each geotechnical zone showed in Figure 2 has been characterized by a specific acceleration spectrum (response of a site to a given seismic aggression).

For each zone, a representative soil column has been defined compiling existing geological, geotechnical and geophysical data. A response spectrum has been computed for each soil column applying a 1D equivalent linear model with Shake (Schnabel *et al.*, 1972). For the input accelerograms, the selection has been done by fitting the input accelerograms response spectra with the reference spectrum adapted to the regional tectonic context and defined in a previous study by a probabilistic approach (Macau and Irizarry, 2005). A total of 4 accelerograms have been selected from the European Strong-Motion Database (Ambraseys *et al.*, 2002) with acceleration spectra within a 20% of difference from the target rock acceleration spectrum. The selected accelerograms have been scaled to a PGA of 0.12 g corresponding to a return period of 475 years (Macau and Irizarry, 2005).

All the acceleration response spectra calculated in the Miocene basin (Macau *et al.*, 2006a) have similar shapes with low frequency amplification in the deepest parts of the basin and higher frequency amplification at the borders. Outside the basin, the soil columns corresponding to Quaternary deposits over rock present higher frequency amplification compatible with the geological and geophysical available data.

5. Comparison of site effect estimations with real data

On the 21st of September 2004, an earthquake of magnitude Ml=4.0 hit the Ripollès area, at the East of Andorre, in the border region between Spain and France (Figure 3). The ensuing seismic crisis, occurring in September and October 2004, has been intensively recorded by a temporary network operated by ICC which gave precise locations of aftershocks (Table 2 and Figure 3). These aftershocks have also been recorded by 4 isolated temporary stations installed in the French part and operated respectively by BRGM (stations OSS and SAI, located in Osséja and Saillagouse) and CETE (stations SAI1 and BOMA, located in Saillagouse and Bourg-Madame). These stations and their characteristics are listed in Table 1 and located in Figure 3.

Three permanent accelerometric stations have also been used in this study: PYLL, located on a rock site in Llo and part of the French accelerometric network (RAP), and the Llivia 1 and Llivia 2 stations, located in Llivia and part of the Catalan accelerometric network.

Table 1 : Characteristics of the recording stations for the events listed in Table 2.

Station location	Llo	Osséja	Saillagouse	Bourg Madame	Saillagouse 1	Llivia (bedrock)	Llivia (Soil)
Station name	PYLL	OSS	SAI	BOMA	SAI1	Llivia 1	Llivia 2
Operating Institution	RAP	BRGM	BRGM	CETE	CETE	ICC	ICC
Latitude (°N)	42.45	42.41	42.46	42.44	42.46	42.479	
Longitude (°E)	2.07	1.99	2.03	1.94	2.04	1.974	
Recording period	Permanent	27/09/04-26/10/04	27/09/04-26/10/04	30/09/04 and 13/10/04	30/09/2004	Permanent	Permanent

Table 2 : Characteristics of the aftershocks of the 21st of septembre 2004 earthquake (Ripollès earthquake) recorded by the temporary and permanent stations listed in Table 1. Event locations was calculated by ICC (Institut Cartogràfic de Catalunya, Spain).

Date	Latitude (°N)	Longitude (°E)	Depth (m)	Magnitude (Ml)	Hour
23/09/2004	42.34	2.15	4	3.3	09h58'05
27/09/2004	42.35	2.14	4	<1.5	19h33'
28/09/2004	42.34	2.15	2	<1.5	7h12'
30/09/2004a	42.34	2.17	4	2	4h4'5.2s
30/09/2004b	42.34	2.18	5	1.5	4h51'4.3s
30/09/2004c	42.34	2.16	5	<1.5	22h27'
02/10/2004	42.33	2.16	4	1.4	4h46'12.4s
07/10/2004	42.33	2.16	4	1.2	0h35'20.9s
24/10/2004	42.33	2.14	4	2	0h39'20.8s

These real data permit to compare site effect assessment from earthquake data first to the results obtained from noise measurements and second to the results obtained from numerical 1D simulations.

5.1. Temporary experiment in French Cerdanya after the Ripollès crisis

A total of 8 aftershocks, with local magnitudes smaller than 2.0 and epicentral distances from 10 to 20 km, recorded both by the temporary stations and the permanent station PYLL, have been processed.

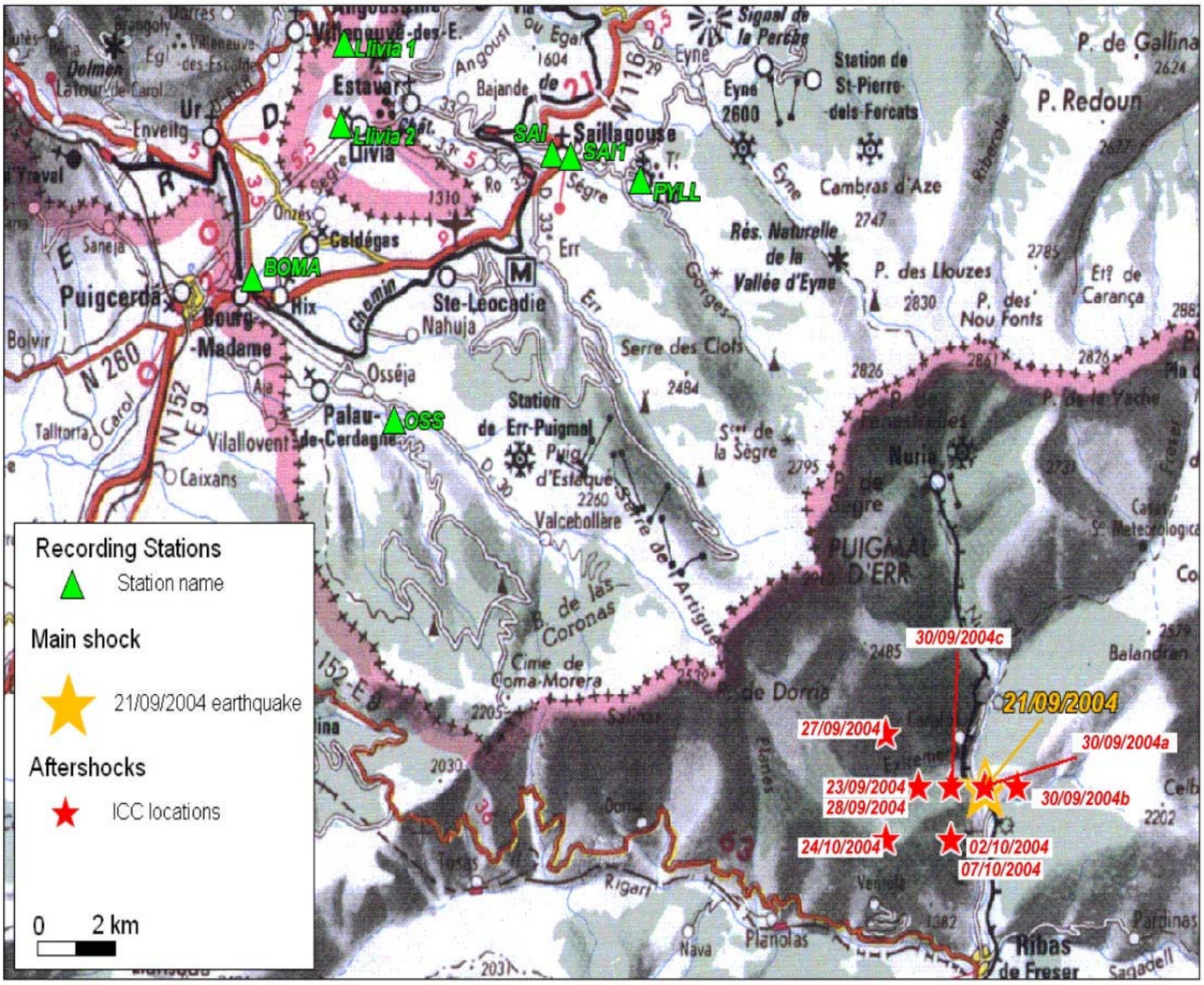

Figure 3 : Location of stations listed in Table 1 and aftershocks listed in Table 2. Topographical data are extracted from IGN map n°REG17 “Languedoc-Roussillon” at 1/250 000.

Aftershock data have been first processed using the H/V spectral ratio method adapted from Nakamura’s technique (1989) for earthquake data as explained by Lermo and Chávez-García (1993). Second, site to reference spectral ratios have also been computed following Borcherdt (1970) and considering the PYLL station, located on rock, as the reference station.

As expected, the H/V spectral ratio of PYLL station does not present any site effect and can be used as a reference station (Figure 4). Stations SAI, SAI1 and OSS, located respectively at the border of the Miocene basin and outside the basin, present high resonance frequencies (superior to 4 Hz; Figure 5) compatible with the superficial geology and the noise measurements results obtained in sites located close-by. For station BOMA, results are more complex. This station is located in a deep part of the basin (from 400 to 600 m depth) where Quaternary deposits overlay Neogene formations. The earthquake data results (Figure 5) at that station show a high frequency amplification (with resonance frequency higher than 3 Hz) whereas noise measurements (Figure 1) show a low frequency resonance (lower than 0.5 Hz). This apparent discrepancy is discussed later.

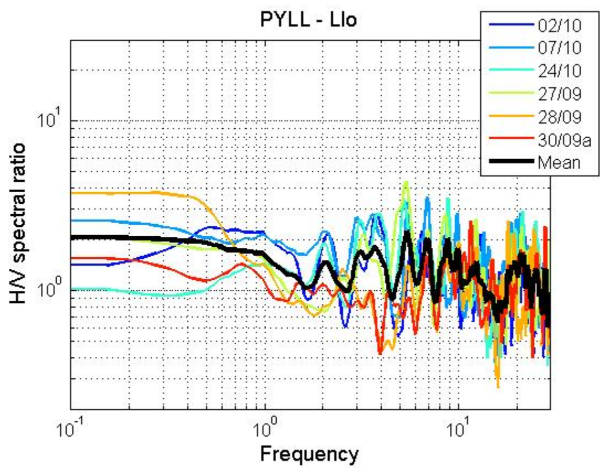

Figure 4 : H/V spectral ratio of station PYLL computed on the earthquake data listed in Table 2.

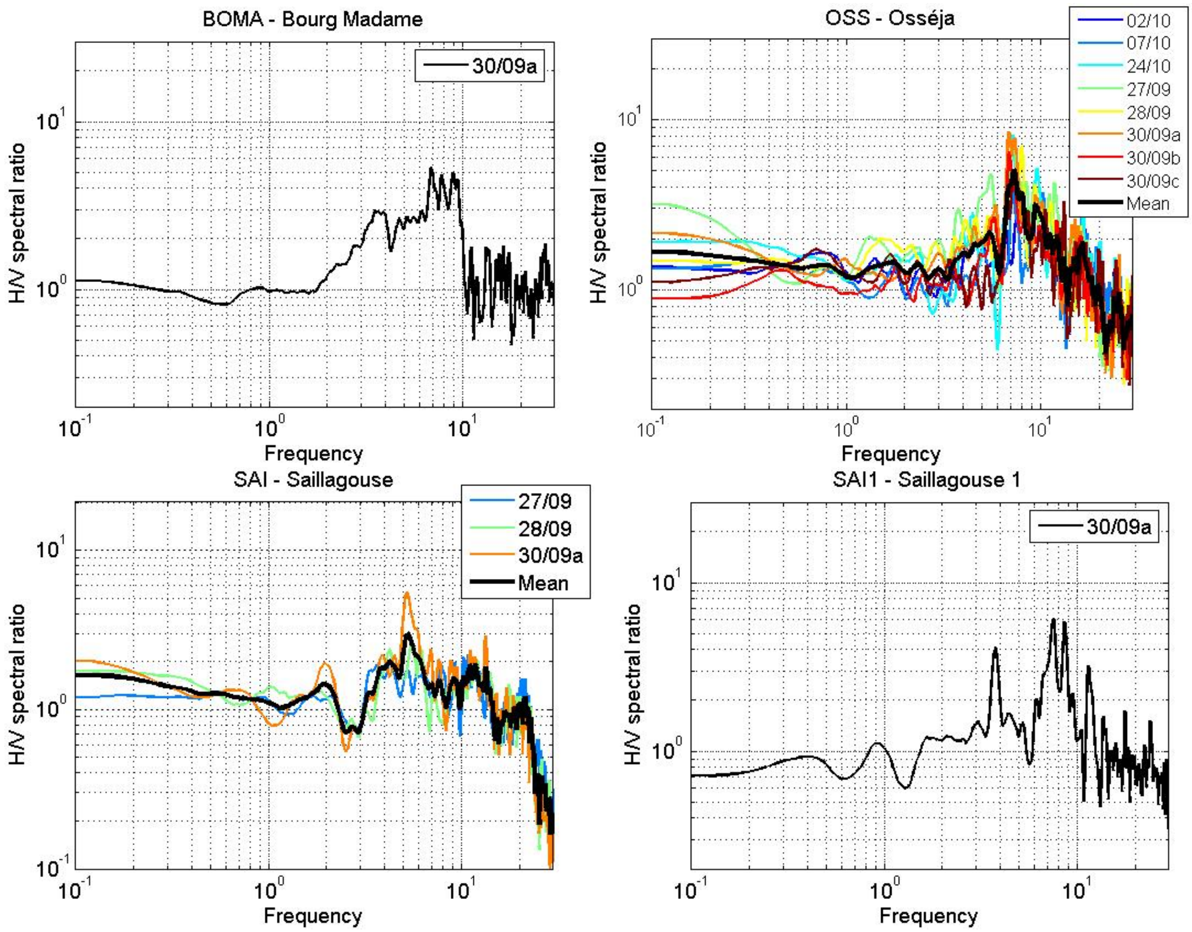

Figure 5 : H/V spectral ratio of stations BOMA, OSS, SAI and SAI1 (Table 1) computed on the earthquake data listed in Table 2.

5.2. Permanent accelerometric stations in Llivia

In the Llivia district, located in the North of Cerdanya valley, 2 accelerometric stations have been installed in the framework of the Catalan accelerometric network: Llivia 1 and Llivia 2. The first one, Llivia 1 is located on bedrock while the second one, Llivia 2, is located on soft soil 2 km away from Llivia 1. The Llivia 2 site is characterized by the presence of 10 m of Quaternary deposits overlaying 150 m of Miocene materials. Both stations have recorded simultaneously 8 moderate earthquakes that occurred in the Eastern Pyrenees between the 26th of February 2003 and the 7th of February 2006. These have local magnitudes from 2.4 to 4.0 (with stronger magnitudes than the events recorded by the temporary network described previously) and epicentral distances from 10 to 27 km. Among these quakes, the stations have recorded the main shock and several aftershocks of the Ripollès crisis of September 2004. Assuming that propagation effects are similar for these two close stations, we compared their respective response spectra with those obtained from the numerical 1D simulations.

The seismic response spectra of station Llivia 2, located on soft soil, (e.g. for the data of the 23/09/2004 aftershock, Figure 6) show a low frequency amplification compared to the bedrock station Llivia 1 with peaks at 0.25 s, 0.5 s and 1 s with amplification coefficient up to 5. This observation can be easily related to the presence of a thick layer of soft soil on Llivia 2 site, which is located at the northern border of the Miocene basin (Figure 1 and Figure 3). The observed seismic response for Llivia 2 is similar to that calculated for the soil column characterized by a single layer of 150 m of Miocene deposits overlaying the bedrock (Macau *et al*., 2006a; Figure 7). This column corresponds to the zone bounding the basin. Since there is no high frequency peak in the response spectra, thin Quaternary deposits are not excited and do not induce significant ground motion amplifications.

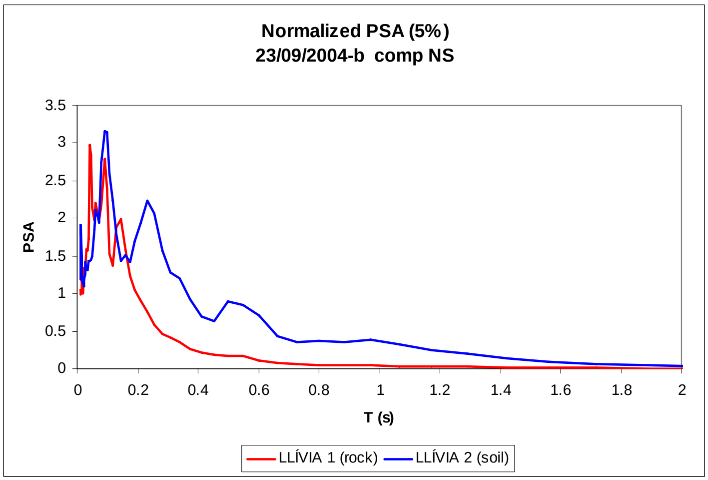

Figure 6 : Response spectra of NS components of Llivia station for the 23rd of September aftershock (Macau et al., 2006a).

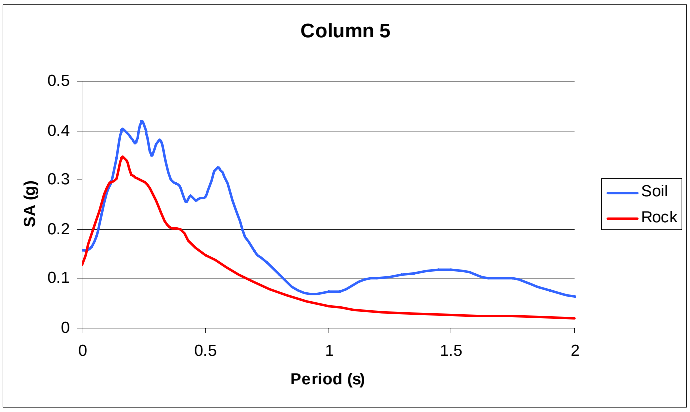

Figure 7 : Acceleration response spectra for the soil column corresponding to Llivia 2 configuration and bedrock (Macau et al., 2006a).

The results obtained from the temporary network stations (H/V spectral ratio) are quite different from those obtained from the Llivia permanent accelerometric stations (Soil/Rock). For the 1st case, Quaternary deposits seem to induce the strongest amplification characterized by high-frequency resonance peaks whereas, for the 2nd case, Miocene deep deposits seem to be responsible for the main low-frequency resonance peaks. This discrepancy can be explained by the difference of magnitude range of the studied events and by the method used in each case. In the 1st case, the studied aftershocks have magnitudes smaller than 2.0: the low-frequencies are not excited so that these events are only susceptible to excite the superficial layers. At the contrary, in the 2nd case, local magnitudes reach 4.0: a broader range of frequencies are excited and these events are susceptible to excite both the superficial Quaternary deposits and the deep Miocene structure which induce the strongest amplification.

These results emphasize the importance of taking into account both the very superficial and the deep geological structures susceptible to induce soil amplifications in site effects studies.

6. Site effects mapping of Cerdanya valley

The computed seismic responses allowed us to perform a complete seismic zonation with specific response spectra that will be used for seismic scenarii purposes (this is one of the final goal of the project) and for future seismic risk studies in the area.

For each soil columns, soil amplification has also been characterized in terms of macroseismic intensity increase through Arias intensities computation (Arias, 1970) following the relation between local MSK intensity (I) and Arias intensity (AI) found by Cabañas et al. (1997) for the Mediterranean area.

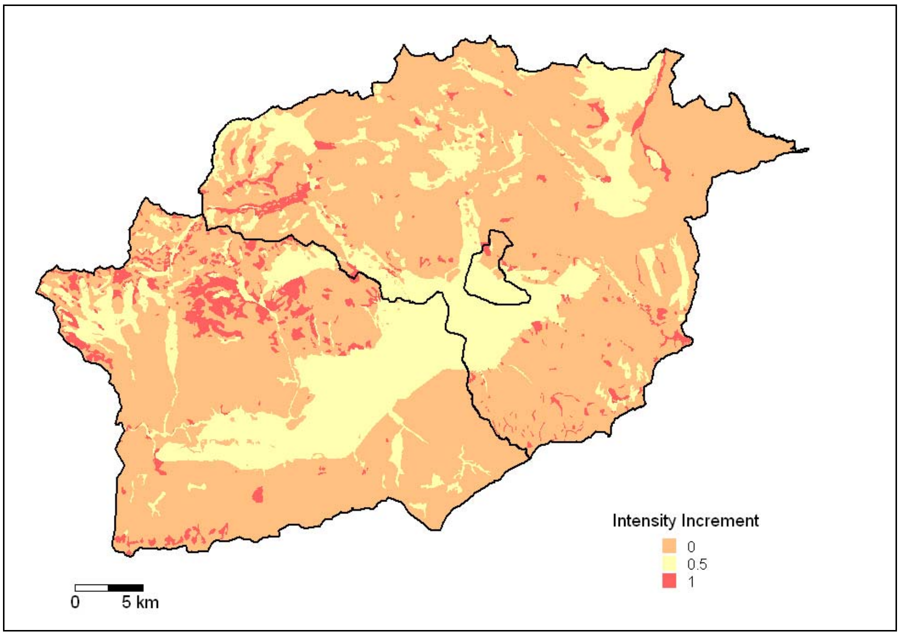

Figure 8 : Site effects mapping of Cerdanya valley (from Macau et al., 2006b).

The resulting site effects map of Cerdanya valley predicts macroseismic intensity increment (Figure 8; Macau *et al*., 2006b). The strongest increment (one degree) corresponds to zones where soft Quaternary deposits overlay bedrock. This is indeed where velocity contrast is strongest. Miocene deposits induce an increase of intensity by a half of a degree. Elsewhere, because bedrock outcrops, there is no amplification of intensity.

7. Conclusions

A harmonized litho-stratigraphic zonation of superficial formations, combined with geophysical data analysis and site effects quantification from 1D numerical simulations and real data analysis has permitted to obtain a harmonized map of site effects in Cerdanya valley. This site effect quantification has been performed both through specific acceleration response spectra calculations and macroseismic intensity increase derived from Arias intensity computations. Real data analysis shows the importance of taking into account both the superficial and the deep structures for site effects assessment. They also have permitted to validate the seismic response spectra calculated from 1D numerical simulations. The resulting site effects mapping will provide an efficient tool for the elaboration of regional seismic scenario and real-time damage estimation in case of earthquake.

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