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SEISMIC MICROZONATION IN TWO VALLEYS OF THE EASTERN PYRENEES: ANDORRA AND THE CERDANYA

Albert MACAU[1], Sara FIGUERAS[1], Bastien COLAS[2], Benoit LE BRUN[3], Adnand BITRI[2], Teresa SUSAGNA[1], Jordi CIRÉS[1], Marta GONZÁLEZ[4] and Agathe ROULLÉ[2]

SUMMARY

Within the framework of the ISARD (Information of Seismic Automatic Regional Damage) project two valleys located in the eastern part of the Pyrenees, with different geological features, have been selected as pilot zones for the study of seismic risk. The Andorra la Vella - Escaldes – Engordany basin where most of buildings, infrastructures and economic activity of the country are concentrated is characterized by a strong density of population. The Cerdanya Valley, located in French and Spanish territory, where the population distribution is spreader and is distributed in small urban nuclei. For the study of seismic risk a probabilistic seismic scenario has been chosen: for a return period of T=475 years a value of intensity VII and a value of PGA 0.12g for both zones for average soil conditions have been obtained within the framework of the same project.

Different approaches have been conducted in order to characterise the geological and geotechnical properties of the study area: use of geological maps, consulting reports from several geotechnical studies in the region, active seismic exploration to record Rayleigh wave for the SASW technique application to obtain shear velocity profiles and seismic noise measurements to obtain H/V spectral ratios. All this information allows us to constrain a realistic 1D soil columns to perform the computations of transfer functions. Spectral ratios from acceleration records recorded in this area are also used.

In Andorra, amplifications for frequencies higher than 1Hz are obtained, due to the thin sedimentary cover. In opposite, in the Cerdanya Valley the sediments that infill the basin, up to 800m thick, give rise to amplifications of the ground motion at smaller frequencies (<1Hz). The results of this study will be used, together with the building vulnerability assessment for the seismic risk estimation and the damage scenarios accomplishment.

1. INTRODUCTION

One of the objectives of the ISARD project is the estimation of the seismic risk and the accomplishment of damages scenarios in Andorra and the Cerdanya. The different studies carried out to perform a seismic microzonation in the zones of study are presented in this work.

Andorra is a mountainous country located in the Pyrenees, between Spain and France, characterized by quaternary glaciers valleys geology and exposed to many natural risks. Andorra la Vella basin has been selected as zone of study, it is a very narrow valley that includes the urban nuclei of Andorra la Vella, Escaldes-

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[1] *Institut Cartogràfic de Catalunya (ICC),* Parc de Montjuïc, S/N 08038, Barcelona, Spain
Email : amacau@icc.es
[2] *Bureau de Recherches Géologiques et Minières (BRGM)*
Email : b.colas@brgm.fr
[3] Previously at *BRGM*
Email: benoit.lebrun4@wanadoo.fr
[4] *Centre de Recerca en Ciències de la Terra de l'Institut d'Estudis Andorrans (CRECIT)*
Email : crecit@andorra.ad

Engordany, Santa Coloma and la Margineda, with a great density of population and a high concentration of buildings and infrastructures.

The region of the Cerdanya is also located in the Pyrenees it is a deep Miocene sedimentary valley, with a maximum thickness of 800m. The Cerdanya includes an extensive countryside where the distribution of the population is more dispersed and it is concentrated in small urban nuclei distributed between Spain and France, very crowded by the tourism of winter and summer. The study has been performed in different cross section profiles and in Puigcerdà, the main town of the region.

In both valleys a geological and geotechnical data summary, microtremors and surface wave measurements have been performed. That allows us to carry out experimental studies and 1D numerical simulation. In this work the results obtained in these studies are showed, that in addition, have allowed to perform a seismic microzonation that will be useful, with the studies of vulnerability, for the evaluation of the seismic risk in these valleys.

2. SEISMIC HAZARD AFFECTING ANDORRA AND CERDANYA

The historical seismicity and the recent tectonic data indicate a level of considerable seismic hazard in the Pyrenees the higher seismic activity is located in the western part of the mountain range. In 1373 a broad zone of the Ribagorça was affected by a destructive earthquake with an epicentral intensity of VIII-IX [Olivera et al., 2006]. In 1427 and 1428 Eastern Pyrenees was affected by a seismic crisis with maximum intensity of IX [Olivera et al., 2006]. In 1660 the Central part of the mountain range suffered a destructive shock (I=VIII-IX). During the XXth century, important damages have been produced in the 1923 Aran Valley (I=VIII) and 1967 Arette (I=VIII) earthquakes. Recently, with the increase of population and the economic activities, some moderate magnitude earthquakes have inflict considerable economic casualties, for example the earthquakes of Saint Paul de Fenouillet (M=5.2) in February 1996, Hautes Pyrénées (M=4.7) in May 2002 and Ripollès (M=4.0) in September 2004. Andorra was affected in 1970 by an important seismic crisis with epicentral intensities of V-VI [Susagna and Goula, 1999].

Within the framework of ISARD project a probabilistic study of the seismic hazard has been performed in the Pyrenees using an unified seismic catalogue, considering a sismotectonic zonation and an attenuation adapted to the zone. This study was carried out in two forms, from the point of view of the spectral accelerations and from the point of view of the intensities, considering a return period of 475 years. In Table 1 the Peak Ground Acceleration (PGA) and the Intensity values proposed by Secanell et al. (2006) for each zone are showed.

Table 1: Acceleration and Intensity values proposed for Andorra and la Cerdanya

	Cerdanya	Andorra
PGA		
T = 475 years	0.12 g	0.12 g
INTENSITY		
T = 475 years	VII	VII

The acceleration response spectra proposed in the hazard studies for the two zones are very similar therefore the same reference spectrum will be considered for both zones.

3. MICROTREMORS MEASUREMENTS

In the Andorra la Vella and Cerdanya basins microtremors measurements campaigns were carried out to obtain the soil fundamental frequency. For the measurement points selection, topography, geology, geotechnics and the easy access to the different measurement locations have been considered. The equipment used for the microtremors measurements is composed by a CityShark (LEAS) digitizer and a triaxial 5 seconds seismometer (Lennartz). Measurements were carried out in windows of three minutes with a sampling of 0.01 seconds. In each location several measures have been performed, repeating them in the cases that the record has been saturated or contaminated by urban noise.

In Andorra microtremors measurements have been performed in the urban nuclei of Andorra la Vella and Escaldes – Engordany municipalities. Most of the measurements have been performed at the bottom of the valley, but also measurements in slopes have been carried out to analyse possible topographic effects. In total microtremors measurements have been performed in 47 different locations.

In the Cerdanya region, being an extensive zone, the microtremors measurements have been concentrated in a set of cross-sectional profiles to the valley and in Puigcerdà, the main town of the region, (Figure 1). In total microtremors measurements have been performed in 115 different locations.

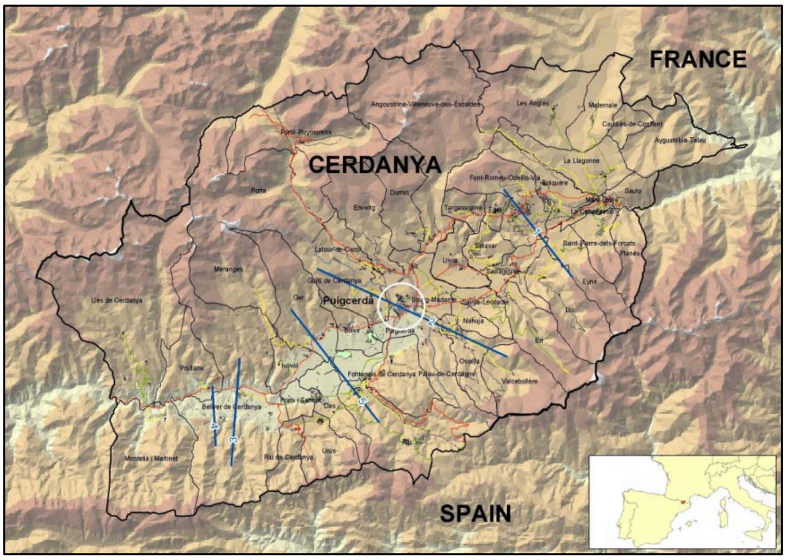

Figure 1: Cerdanya map with the sections in which microtremors measurements have been performed, Puigcerdà town is marked with a circle.

Nakamura's method [Nakamura, 1989] is applied to obtain the soil fundamental frequency in the locations of Andorra and the Cerdanya where the microtremors measurements are available. In Figure 2 the values of the fundamental frequencies obtained in the Andorra la Vella basin are showed.

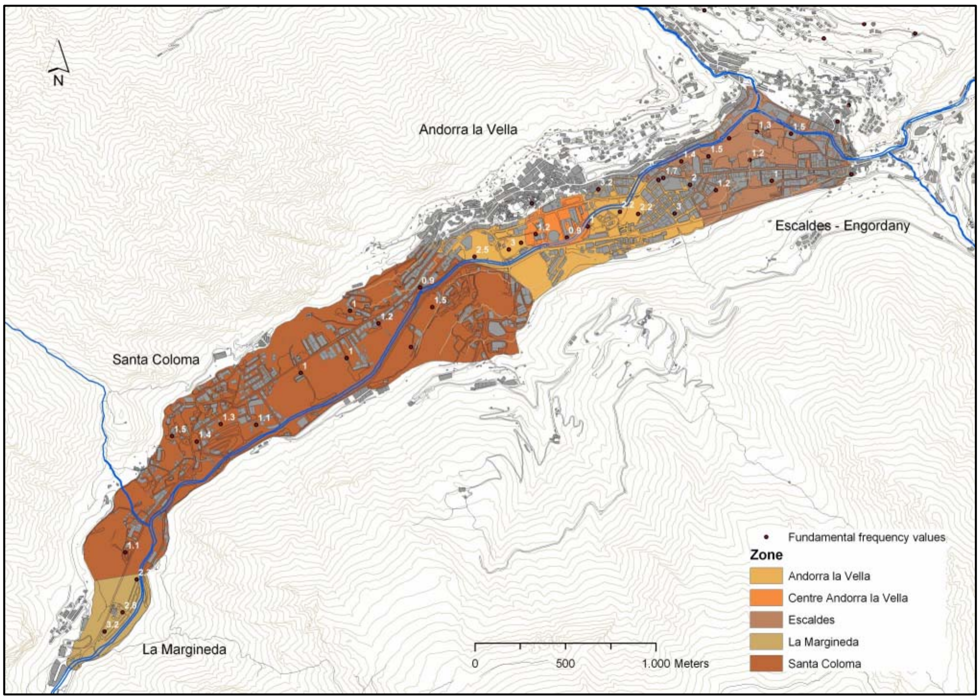

Figure 2: Andorra map with the zones defined considering the fundamental frequency values.

Considering these values five zones have been classified, showed in the figure 2. The variations of the fundamental frequency can be related to the variations of the bedrock depth or to the soil materials characteristics of the locations where the microtremors measurements have been carried out.

In Figure 3 the spectral ratios obtained applying Nakamura’s method in two profiles of the Cerdanya Valley are presented. The red curves follow the fundamental frequency values drawing the bedrock geometry in each profile. The maximum bedrock depth in the valley is around 800 meters so low fundamental frequency values are obtained, about 0.3 Hz.

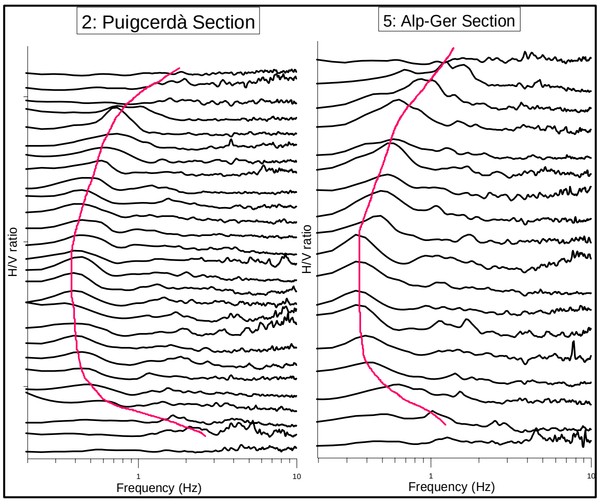

Figure 3: Spectral ratios in two profiles of the Cerdanya Valley, red lines indicate the fundamental frequencies.

Figure 4 shows the fundamental frequencies obtained in Puigcerdà, outstanding local effects are not noticeable, the low values of the fundamental frequency indicate a deep bedrock.

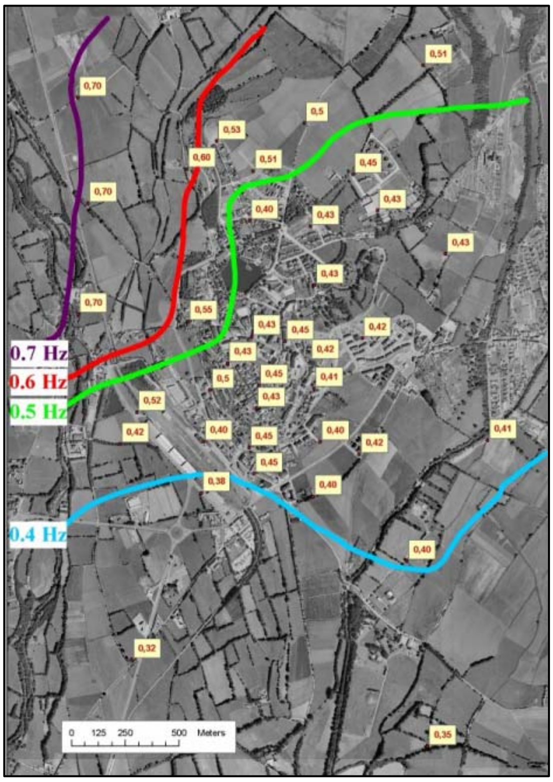

Figure 4: Puigcerdà map with zones of similar fundamental frequency values.

4. 1D NUMERICAL SIMULATION. EQUIVALENT LINEAR MODEL APPLICATION

In both study zones an equivalent linear method (ProShake) has been applied to obtain the transfer functions and the ground motion in locations with different soil characteristics. Previously to the method's application it is necessary to characterize suitably the soil columns and to select a reference acceleration record on rock.

4.1 Data collection and soil column definition

In order to define the soil columns that characterize the different locations, geologic and geotechnical information available has been compiled. In addition in both zones a surface waves measurements campaign has been carried out by BRGM (Bureau de Recherches Géologiques et Minières) geophysical team [Bitri et al., 2004] and SASW method has been applied to obtain shear velocity profiles [Bitri et al., 1997].

For the Andorra la Vella basin the information of superficial geology has been obtained from geologic map 1:50.000 [CRECIT, 2002]. The geotechnical information is obtained from the geotechnical data base of Andorra [CRECIT, 2001] that contains 118 drills pertaining to 19 geotechnical reports. These reports show the presence of little deep sedimentary filling, composed, in their superior part, by blocks and quaternary gravel in a sand-muddy matrix. In addition, the results obtained in a campaign of seismic and electrical prospecting in Andorra la Vella basin [Teixidó et al., 2003] have been considered. With all the available information, nine soil columns have been characterized in the Andorra the Vella basin, each one in the locations where results of the vertical electrical soundings were available, important contrasts of shear velocity are present between quaternary deposits and bedrock.

The data of the Cerdanya come from different studies. Geologic maps 1:50.000 of MAGNA series published by Instituto Geológico Minero Español (IGME). One of the most useful information of the geologic map is the Martinet zone geologic profile. From this profile it has been possible to define the depth of the soil columns as well as the materials that form each one of their layers. Different geotechnical reports are also available, the majority in the municipalities of Puigcerdà, Alp and Bellver de Cerdanya. From these data, values of the shear velocity, the density and the phreatic depth level in five soil columns have been obtained. In Figure 5 these soil columns are located on a representative geologic profile of the Cerdanya valley, the bedrock is constituted by slates and their depth ranges from 140m to 800m, the sedimentary materials of the valley are made up basically of conglomerates, sandstone and lutites of Neogene age.

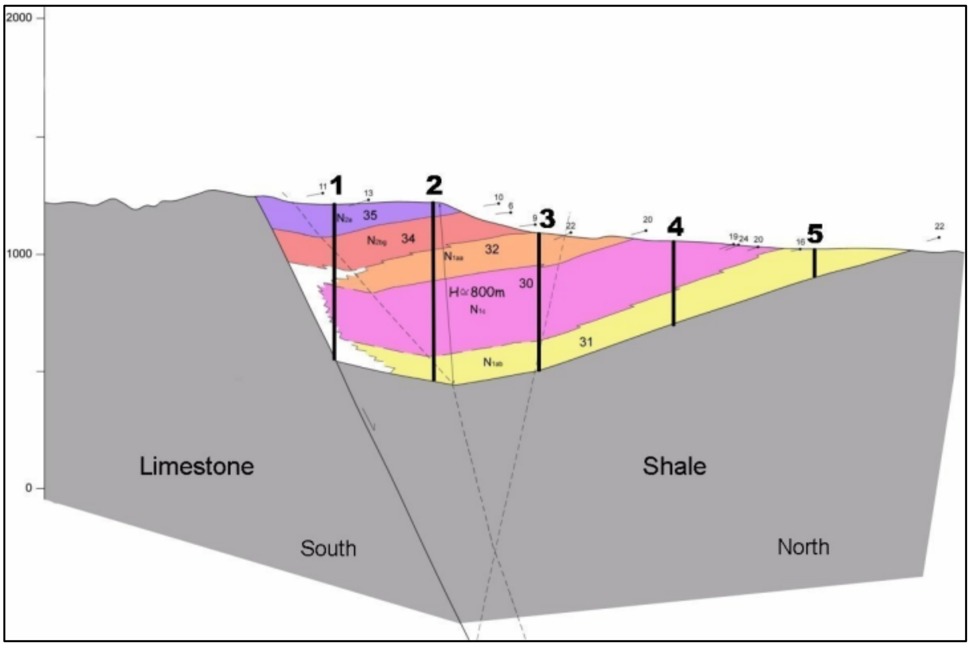

Figure 5: Geologic section of Cerdanya valley with the soil columns for the ProShake computations.

4.2 Selection of the reference rock acceleration records.

For soil columns transfer function computations ProShake program requires an acceleration record on rock that has a response spectrum similar to the obtained in the hazard computations mentioned in section 2. For this purpose a selection of acceleration records from European Strong-Motion Database [Ambraseys et al., 2000] has been performed. A total of four acceleration records are selected and their acceleration response spectra are within a 20% of difference from the target rock acceleration spectrum. Acceleration records obtained have been scaled to a PGA of 0.12g computed for a return period of 475 years in the study zones. Figure 6 shows the accelerations response spectra of the selected records and the target rock acceleration spectrum, notice that mean response spectra from the real acceleration records is always within 20% of difference from the target rock acceleration spectrum.

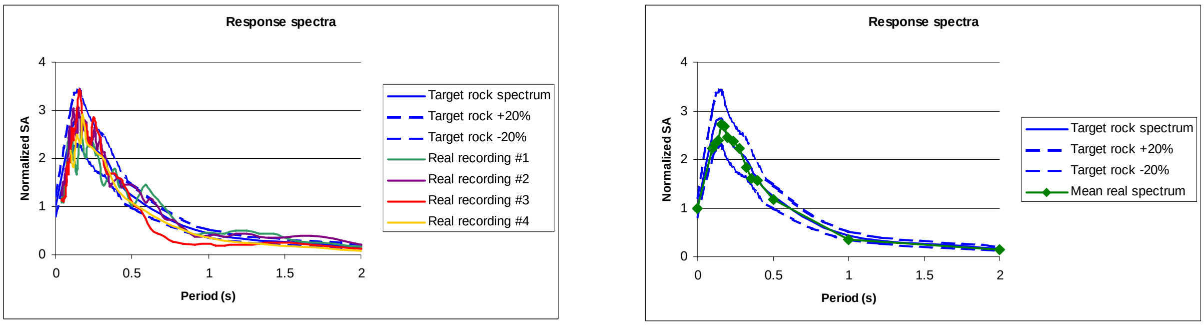

Figure 6: At left, response spectra of real records selected from Ambraseys et al. (2000) and target spectrum ±20%. At right, mean response spectrum and target spectrum ±20%.

4.3 Results obtained from numerical computations

Once the input motion on rock has been defined and the soil columns with their physical-mechanical properties have been characterized, the modelling program 1D ProShake has been applied. From these computations the transfer function and the ground motion for the soil columns defined in both study zones have been obtained.

Acceleration response spectra and Arias Intensity (AI) values of the different synthetic acceleration records obtained for the soil columns have been calculated. Arias Intensity and macroseismic intensity (I_L) can be related from empirical observations. The relation proposed by Cabañas et al. (1997) for the Mediterranean area, Eq. 1, is used.

$$Ln(\Delta I) = 1.50 \cdot I_L - 6.42 \qquad (1)$$

In this way, the intensity increment (ΔI_i) representative of each soil column can be obtained, using Eq. 2, from the soil to rock ratio of the Arias Intensity (AI_i/AI_R).

$$\Delta I_i = 0.66 \cdot Ln\left(\frac{AI_i}{AI_R}\right) \qquad (2)$$

These values will be used to increase the intensity for a reference soil for the both study zones.

4.3.1 Andorra la Vella basin results

A total of nine representative soil columns have been considered in Andorra la Vella basin. In Table 2 the fundamental frequency and the amplification value for each one of the nine soil columns defined in the Andorra la Vella basin are showed. In Figure 7 transfer functions computed in two soil columns are presented together with the fundamental frequencies obtained with the application of Nakamura’s method in sites located near these soil columns.

Table 2: Fundamental frequency and amplification values obtained in the soil columns defined in Andorra la Vella basin

Soil column	Fundamental Frequency (Hz)	Amplification
1	4.6	6
2	3.4	5
3	2.4	5
4	2.7	6
5	1.3	5
6	4.5	6
7	1.5	6
8	2.6	5
9	1.0	8

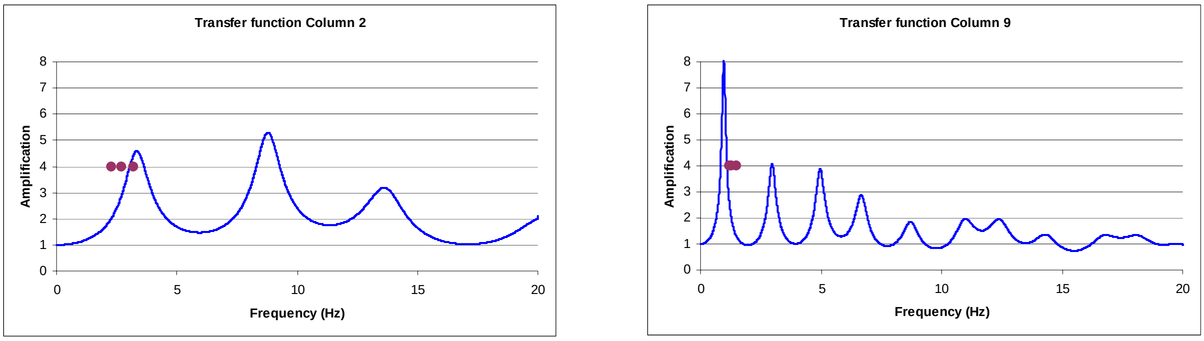

Figure 7: Transfer function for soil columns 2 and 9 together with fundamental frequencies (big dot) obtained by Nakamura's method in sites located near these soil columns

Variations of the soil's fundamental frequency are observed, these variations are associated to the bedrock depth. Amplifications observed in the ground motion are related to the contrast of shear velocity between the column layers and the bedrock. Fundamental frequency values obtained from Nakamura's method in locations near the soil columns agree with the fundamental frequency of the transfer function.

Acceleration response spectra of the different synthetic acceleration records obtained for the soil columns have been calculated. Figure 8 shows the acceleration response spectra computed in two soil columns and on rock.

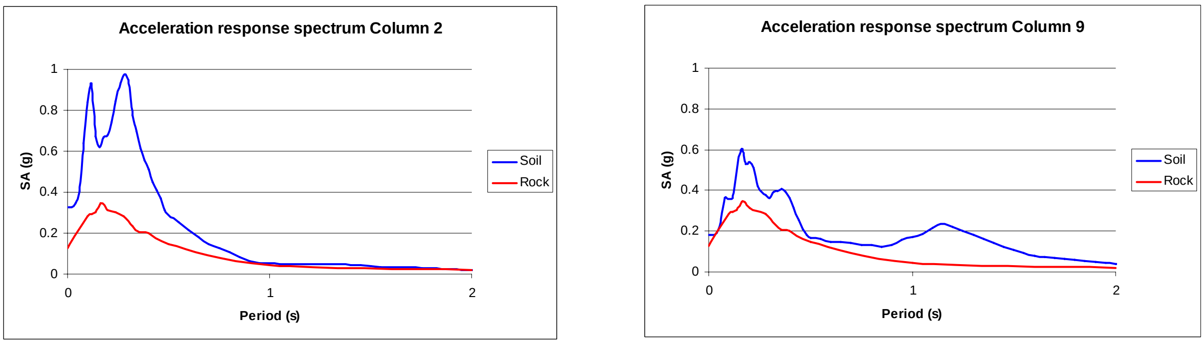

Figure 8: Acceleration response spectra for soil columns 2 and 9 together with acceleration response spectrum in rock

A seismic zonation of the Andorra la Vella basin has been performed based on the response spectra behaviour obtained in the different soil columns. The five zones proposed are shown in Figure 9.

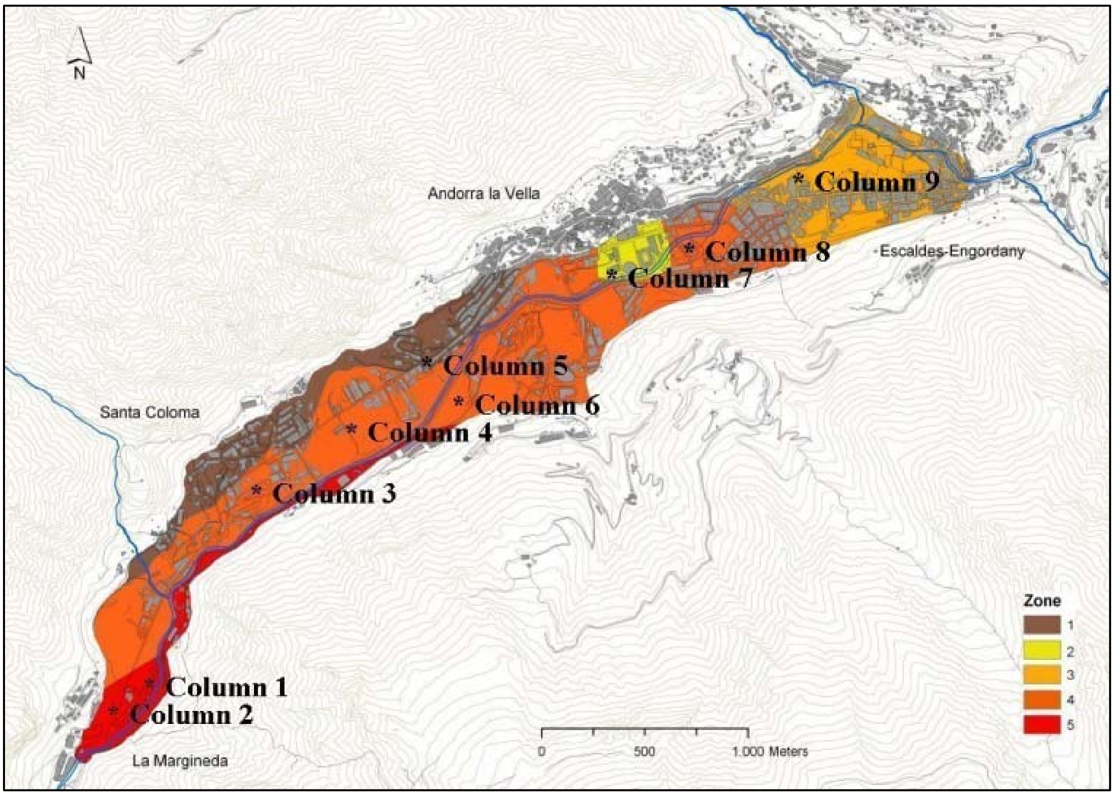

Figure 9: Andorra la Vella basin seismic zonation based on the response spectra behaviour

In zones 3, 4 and 5 amplifications take place in all the frequencies rank. In zones 1 and 2 amplifications take place in the low frequencies.

On the other hand the amplification has been characterized in terms of the macroseismic intensity increase produced by soil effects, using the methodology proposed in section 4.3. Table 3 shows the macroseismic intensity increase obtained in the five zones defined in Andorra la Vella basin in terms of acceleration response spectra.

Table 3: Macroseismic intensity increase (ΔI) obtained in Andorra la Vella basin

Soil zone	ΔI
1	+0.0
2	+0.5
3	+1.0
4	+1.0
5	+1.5

In this way the seismic zonation of Andorra la Vella has been characterized in terms of macroseismic intensity increase, four zones are defined with increase values from +0.0 to +1.5.

4.3.2 Cerdanya basin results

A total of five soil columns have been defined on a representative geologic profile of the Cerdanya basin. On the other hand soil columns of thick soft quaternary deposits have been defined to characterize the behaviour of these zones. Acceleration response spectra of the different synthetic acceleration records obtained for the soil columns have been calculated. Figure 10 shows the acceleration response spectra computed in two soil columns and in rock.

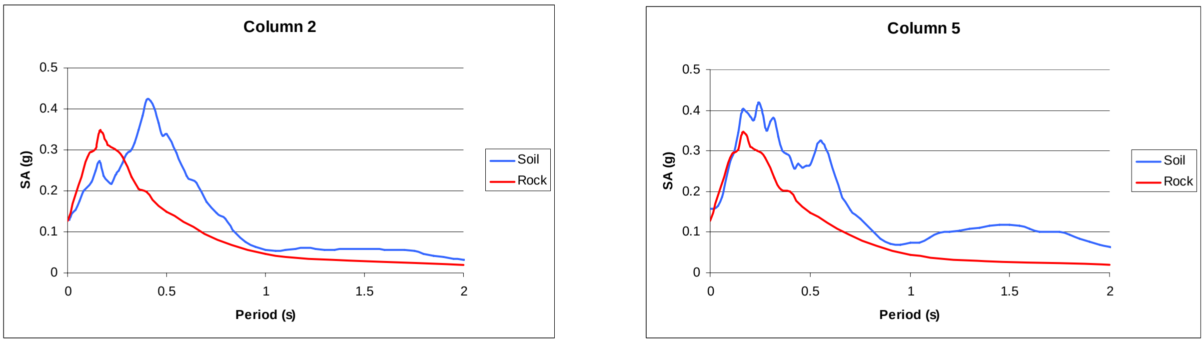

Figure 10: Acceleration response spectra for soil columns 2 and 5 defined in the geologic profile of the Cerdanya basin together with acceleration response spectrum in rock

Acceleration response spectra obtained in soil columns defined in the geologic profile of the Cerdanya basin have a similar behaviour, with variations in the frequency of the amplification pick, located in the low frequencies in the deeper columns and in the high frequencies in the less deep columns.

Response spectra of experimental acceleration records measured in two ICC accelerographic permanent stations (http://www.icc.es/sismes/catala/accenreg.html) installed in la Cerdanya have been computed. One of the stations is installed on rock, and the other is located on soil with similar characteristics to the soil column #5 of the Cerdanya basin geologic profile. The acceleration response spectra behaviour observed in the real records is similar to the results obtained in soil column #5.

Soil amplification has also been characterized in terms of macroseismic intensity increase, using the methodology proposed in section 4.3. Results obtained in the Cerdanya valley, showed in Table 4, are classified in terms of lithology class [Colas et al., 2006]. Figure 11 shows the seismic zonation of the Cerdanya Valley in terms of macroseismic intensity increase.

Table 4: Macroseismic intensity increase (ΔI) obtained in Cerdanya valley

Lithology	ΔI
Rock	+0.0
Miocene basin	+0.5
Soft quaternary deposits covering rock (thickness 5 – 20m)	+1.0

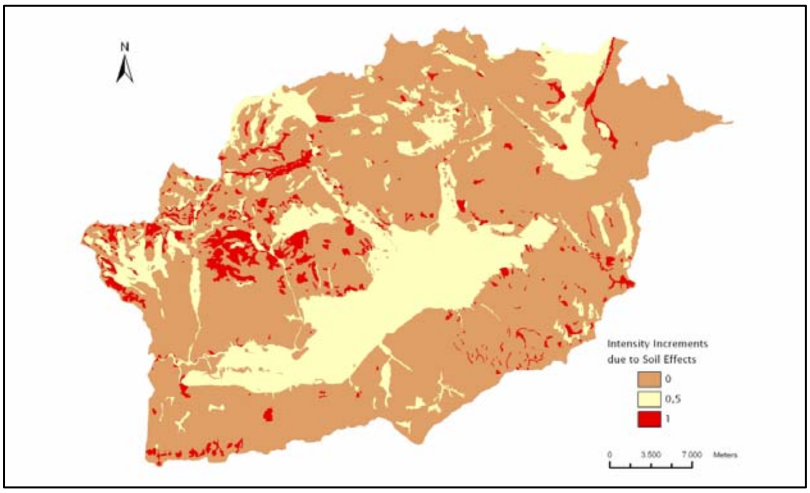

Figure 11: Cerdanya valley seismic zonation based on the macroseismic intensity increase

Most of the Cerdanya valley has a macroseismic intensity increase between +0.0 and +0.5. Only a few Quaternary deposits located on mountainous zones show intensity increases of +1.0.

5. CONCLUSIONS

Applying 1D equivalent linear method in soil columns defined in Andorra la Vella and Cerdanya basins soil transfer function and ground motion have been obtained for a probabilistic seismic scenario corresponding to a return period of 475 years. Taking into account these results acceleration response spectra and macroseismic intensity increases have been computed in each soil column. With these values, seismic zonation maps of Andorra la Vella and Cerdanya basins have been proposed.

Amplifications computed in Andorra la Vella basin are higher than the obtained in the Cerdanya valley. Soil fundamental frequencies obtained in Andorra la Vella basin ranges between 1.0 and 4.6 Hz, while in Cerdanya valley soil fundamental frequencies ranges between 0.2 and 0.65Hz. In terms of macroseismic intensity increase, results obtained in Andorra la Vella basin are higher than results in Cerdanya Valley.

Taking into account the results obtained in both study zones a simple methodology to obtain the macroseismic intensity increase (ΔI) due to soil effects can be proposed.

The amplification due to local effects obtained in both study zones will be considered in terms of spectral values and intensity, jointly with the buildings vulnerability evaluations, for the seismic risk estimation and the assessing of damage scenarios in both study zones.

6. REFERENCES

Ambraseys, N. N., Smit, P., Berardi, R., Rinaldis, D., Cotton, F. and Berge-Thierry, C. (2000), European Strong-Motion Database, CD-ROM collection *European Council, Environment and Climate Research Programme.*

Bitri, A., Le Bégat, S. and Balthassat, J.M. (1997), Détermination des vitesses de cisaillement des sols à partir de la dispersion des ondes de Rayleigh, *Bureau de Recherches Géologiques et Minières* Report n° R39877.

Bitri, A., Chardon, A. and Richalet, G. (2004), Micro Zonage sismique de la vallée de la Cerdagne et de la principauté d'Andorre. Évaluation de répartition en profondeur de la vitesse de propagation des ondes de cisaillement par la méthode SASW, *Bureau de Recherches Géologiques et Minières* Report.

Cabañas, L., Benito, B. and Herráiz, M. (1997), An approach to the measurement of the potential structural damage of earthquake ground motion, *Earthquake Engineering and Structural Dynamics*, n° 26, 79-92.

Colas, B., Cirés, J., Figueras, S., Roullé, A., Macau, A. and Fleta, J. (2006) Geological and Lithological characterization for a seismic zonation in a border region (Cerdanya, Spain-France), *European Congress on Regional Geoscientific Cartography and Information Systems*, Barcelona

CRECIT (2001), Base de Dades Geotècniques d'Andorra, *Institut d'Estudis Andorrans*, Andorra.

CRECIT (2002), Mapa geològic d'Andorra 1:50.000, *Institut d'Estudis Andorrans*, Andorra.

Nakamura, Y. (1989), A method for dynamic characteristcs estimation of subsurface using microtremors on the ground surface, *Quarterly Report of Railway Technical Research Institute*, 30-1, 25-33.

Olivera, C., Redondo, E., Lambert, J., Riera Melis, A., and Roca, A. (2006), Els terratrèmols dels segles XIV i XV a Catalunya, *Institut Cartogràfic de Catalunya*, Barcelona.

Secanell, R., Martin, C., Goula, X., Susagna, T., Tapia, M., Bertil, D., Dominique, P., and Fleta, J. (2006), Probabilistic seismic hazard assessment of the Pyrenean region, *Journal of Seismology*, (Submited).

Susagna, T. and Goula, X. (1999), Catàleg de sismicitat, Atles sísmic de Catalunya, *Institut Cartogràfic de Catalunya*, Barcelona.

Teixidó, T., Palomeras, I., Valls, P., and Martínez, P. (2003), Prospecció sísmica a la cubeta d'Andorra la Vella-Escaldes-Engordany, *Horitzó*, n° 4, 3-25.