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CROSS-BORDER SEISMIC RISK SCENARIOS (EASTERN PYRENEES)

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SUMMARY

Located on the border between Spain and France, the Pyrenees region is one of the most active seismic zones of the two countries. Its historical seismicity and recent tectonics data indicate a significant level of seismic hazard. Since 2003, the ISARD project (Information of Seismic Automatic Regional Damages) has been studying both the seismic hazard and vulnerability within the eastern part of Pyrenees in order to develop a common scheme for generating seismic risk scenarios that surpasses the countries' borders and provide preventive and operational information on the seismic risk to the local first-aid and crisis management organizations. This paper concentrates on the seismic risk scenarios developed for ISARD's pilot zones : Andorra and both Spanish and French Cerdanya regions. Seismic risk scenarios are developed using three levels of vulnerability assessment based on different levels of input data and methodologies. The vulnerability assessment for Level 0 is based on the classification of the building stock of a municipality according to the EMS-98 vulnerability classes according to the age, height and location of the building stock. The Level 0 damage estimation is calculated for each municipality within the region using the damage probability matrix methodology. The second vulnerability assessment level, or Level 1, implements the vulnerability index method taking account soil effects applied to geographical subdivisions of the building stock according to their structural typologies distribution. The third and final vulnerability assessment level, namely Level 2, applies the capacity spectrum method to determine the expected damage level or damage probabilities associated to a structure. This Level 2 method is only implemented for some essential buildings in the region. Seismic risk scenarios are expressed in terms of expected damages to the building stock and their consequences to the population such as the expected number of homeless, injured and casualties.

1. INTRODUCTION

The Pyrenees is one of the most active seismic zones of France and Spain. Its historical seismicity and recent tectonics data indicate a significant level of seismic hazard. The important crises of 1428 and 1660 provoked severe damages (I=VIII-IX). More recently, during the 20th century, several other destructive earthquakes (I=VIII) stroke the ridge.

Since 2003, the ISARD project (Information of Seismic Automatic Regional Damages), funded by the INTERREG IIIA program, has been studying both the seismic hazard and vulnerability within the eastern part of Pyrenees. It aims at developing a common scheme for generating seismic risk scenarios that surpasses the

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countries' borders and providing preventive and operational information on the seismic risk to the local first-aid and crisis management organizations. Inconsistencies between the two countries, appearing at all levels, should be overcome to reach this goal.
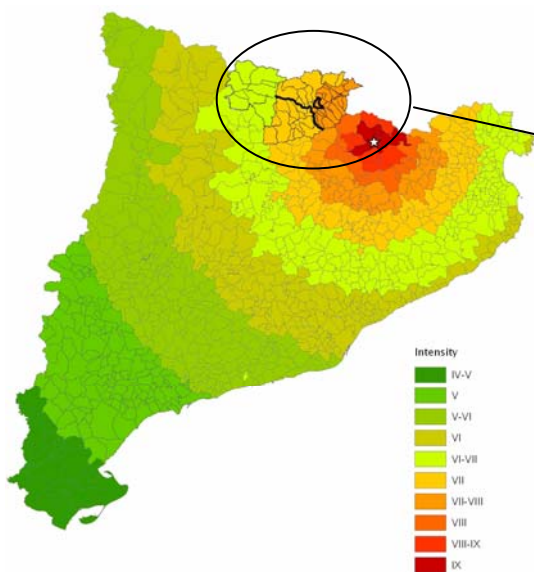
This paper deals with the vulnerability and seismic risk scenario evaluation for a pilot zone in the borders of France, Spain and Andorra. The seismic risk scenarios are developed using three levels of vulnerability assessment based on increasing precision of input data and methodologies, as summarized in Table 1. Level 0 approach is most suited to large ("regional") scale loss studies, as the inventory of buildings at stake and of their vulnerability is directly inferred from available statistical data. Level 1 may be more time-consuming as more detailed information on structural properties of the building stock is required. Finally, Level 2 approach is restricted to a few buildings only, chosen because they are "essential" in some way, or representative of one of the most common structural types identified in the region.

Table 1: Levels of application for the vulnerability assessment
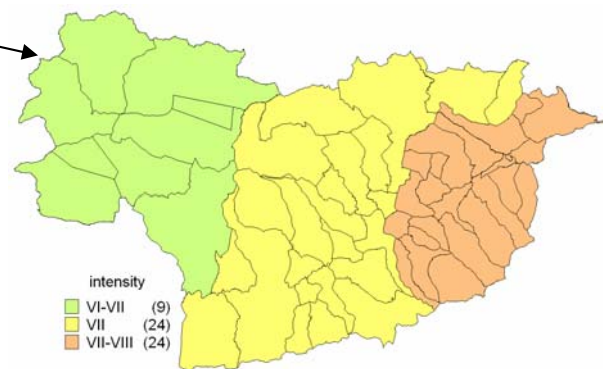
Method Level	Working Unit	Applied to…	Building Inventory	Hazard Input
0	municipality	Current buildings	Age and number of floors distribution	Intensity maps at regional scale
1	polygons	Current buildings	Age and structural typology distribution	Intensity maps at local scale (including soil effects)
		Essential buildings	Field investigation and structural plans	
2	Typologies	Typologies	Structural plans for representative structural typologies	Demand Spectrum (including soil effects)
	buildings	Essential buildings	Field investigation and structural plans	

2. DETERMINISTIC INTENSITY MAP

The 1428 earthquake, of estimated magnitude 6.5, is representative of major earthquakes that stroke and may strike again the region encompassed in the ISARD project area. The intensity map, that best fits the observed intensities inferred from the extensive historical study of Olivera et al. (2006), is presented in Figure 1 (covering the whole Catalan region) and Figure 2 (focusing on the pilot zone). This hazard map is used as the deterministic input of the damage scenarios.

Figure 1: ISARD deterministic scenario based on the 1428 earthquake

Figure 2: ISARD deterministic scenario based on the 1428 earthquake; focus on the pilot zone..

3. VULNERABILITY ASSESSMENT AND SCENARIO OF LEVEL 0

Level 0 approach is based on the classification of the building stock according to the EMS-98 [Grünthal, 1998] vulnerability classes in order to assess their damage state according to the methodology developed for Catalonia by Chavez (1998). Figure 3 shows the vulnerability classes assigned by the EMS-98 to the most common types of construction.

In order to obtain an inventory affordable both from the cost and the time point of view, Chavez (1998) established the distribution of the vulnerability classes among the building stock according to a limited number of data, all of them available from recent census (on both side of the France-Spain border), namely the age, height and location of constructions. The age and the height are clearly associated to the seismic vulnerability of the buildings. The age not only has importance by its effect on the process of loss of the resistance of the building but is indicative of constructive techniques and code enforcement, variable throughout time.

The distributions of EMS-98 classes according to these three parameters are summarized in Figure 4. From this table was derived the number of buildings of a given municipality in each vulnerability class, processing the data from the buildings census made in 1990 by the Institute of Statistics of Catalonia (IEC) and the BRGM from IGN/INSEE/field investigation for the French part. For Andorra, it was necessary to complement the data extracted from the Municipal Urbanism and Organization plans (POUP) with aerial photos and field surveys. The results of this Level 0 vulnerability assessment are presented in Figure 5, in the form of the vulnerability class distribution in each municipality of the pilot zone. As can be seen, the distribution obtained in all three countries are quite similar, being centred over the vulnerability class C and having important level of vulnerability class B (especially in Andorra and municipalities presenting an important historical centre, or little modern development connected with tourism industry).

Vulnerability Classes Percentages by Chavez (1998)					
	Until 1950		1951–1970		After 1970	
Levels	Urban	Rural	Center	Dissem	Center	Dissem
< 5	20A 80B	30A 70B	5A 50B 45C	15A 70B 15C	85C 15D	5A 20B 65C 10D
= 5	20A 80B	40A 60B	10A 60B 30C	20A 70B 10C	5A 20B 65C 10D	10A 30B 55C 5D
> 5	40A 60B	60A 40B	15A 70B 15C	30A 65B 5D	8A 27B 60C 5D	15A 45B 40C

Figure 3: EMS-98 vulnerability classes. **Figure 4: Distribution of vulnerability classes according to Chávez (1998)**

Knowing the number of buildings in each vulnerability class, the distribution of the damage due to a certain level of intensity can then be obtained by means of the probability damages matrices that have been determined for the classes of vulnerability A, B, C, D, E and F, the degrees of damages of 0 (no damage) to 5 (total collapse) and the degrees of intensity (VI to X) of the EMS-98 scale [Chávez, 1998; Chávez et al., 1998]. An example for intensity VIII is presented in Figure 6.
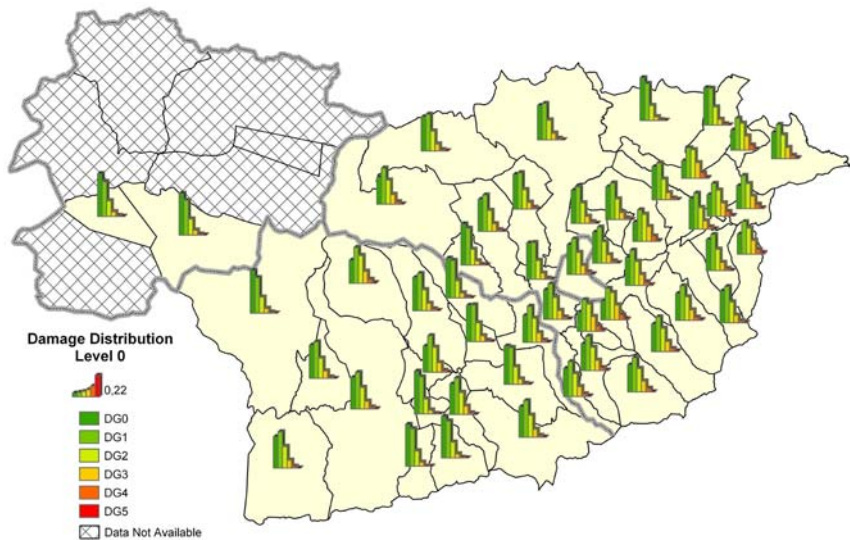
Figure 5: Distribution of vulnerability classes in the municipalities of the pilot zone
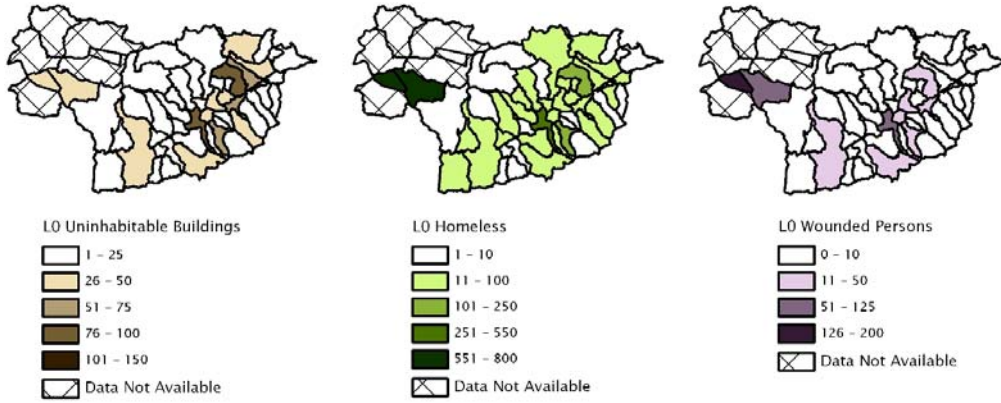
Figure 6: Probability damages matrix for intensity VIII

By convoluting the map of Figure 5 with that of input intensity (Figure 2), the Level 0 damage scenario can be derived in terms of the number of buildings of each municipality distributed according to the different damage degrees (Figure 7). As can be seen the most probable damages correspond to damage grades 0 and 1, inferring minor damages. Low percentages were obtained for damage grades 4 and 5, the most serious damages including collapse of buildings. It should be noted that the municipalities with the higher percentages for damage grade 3, that is moderate damages, are the eastern municipalities affected by higher intensities.

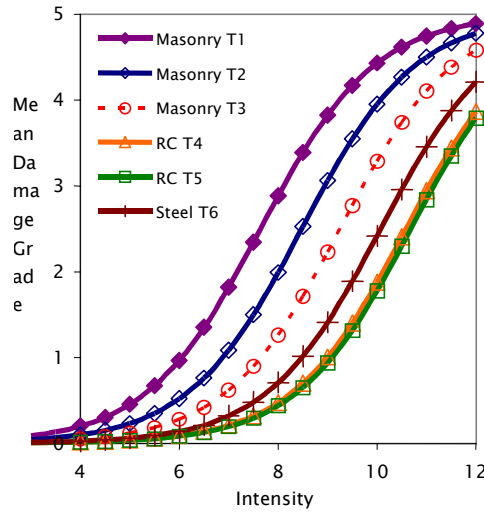**Figure 7: Distribution of damage degrees in the municipalities of the pilot zone**

An estimation of those buildings that are expected to be in uninhabitable conditions was calculated from the damage distribution, considering those that undergo damage degrees 4 and 5 as well as 50% of those that experience damage grade 3. These results are of maximum importance for the evaluation of the possible number of homeless after occurrence of the earthquake. The wounded persons and mortal victims were estimated as recommended by the ATC-13 (1985). Figure 8 shows the Level 0 results for uninhabitable buildings, homeless and total number of wounded persons. The highest losses estimated concentrate in Andorra and principal municipalities of the Cerdagne region. The considered deterministic scenario is expected to cause almost 1200 uninhabitable buildings, that is, a 6% of the total building stock of the region, and more than 500 wounded persons. This building loss would leave over 3,000 persons without home. These results only consider the residential population of the region, which can triple during the vacation season increasing the number of persons affected by a possible earthquake and making more difficult the emergency management.

L0 Uninhabitable Buildings

- [ ] 1 – 25
- [ ] 26 – 50
- [ ] 51 – 75
- [ ] 76 – 100
- [ ] 101 – 150
- [ ] Data Not Available

L0 Homeless

- [ ] 1 – 10
- [ ] 11 – 100
- [ ] 101 – 250
- [ ] 251 – 550
- [ ] 551 – 800
- [ ] Data Not Available

L0 Wounded Persons

- [ ] 0 – 10
- [ ] 11 – 50
- [ ] 51 – 125
- [ ] 126 – 200
- [ ] Data Not Available

Figure 8: Estimation of uninhabitable buildings, homeless and total wounded persons

4. VULNERABILITY ASSESSMENT AND SCENARIO OF LEVEL 1

The Level 1 damage assessment is now presented for both French and Spanish Cerdagne, its application to Andorra being still in progress. The vulnerability assessment of Level 1 is based on the vulnerability index method [Corsanego and Petrini, 1994; Bernardini, 2000; Giovinazzi and Lagomarsino, 2004] in which the building stock is classified according to structural typologies characterized by a vulnerability index. These vulnerability indices allow calculating the possible damages due to a certain earthquake by means of a vulnerability function as can be seen in Figure 9. The vulnerability function recommended within the RISK-UE for dwelling buildings was developed by Sandi and Floricel (1995) and is shown in Equation 1.

Figure 9: Mean vulnerability curves for the principal typologies in the pilot region

$$\mu_d = 2.5 \left[1 + tanh\left(\frac{I + 6.25V_I - 13.1}{3.0} \right) \right] \tag{1}$$

The structural typologies defined within the RISK-UE project [Mouroux and Lebrun, 2006] were used to construct building typology matrix for the pilot zone. Table 2 shows the structural typologies representative of the pilot zone along with its correspondence to RISK-UE typologies and the mean values of vulnerability indices recommended by Lagomarsino et al. (2002). Vulnerability index modifiers are also available in order to enhance the definition of the vulnerability of the building stock by increasing or decreasing the vulnerability as function of certain structural parameters. Milutinovic and Trendafiloski (2003) summarize the vulnerability index modifiers proposed within the RISK-UE project of which only those associated to the height, age, soft story condition and design code level will be applied in the pilot zone, according to Table 3.

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Table 2: Principal structural typologies for the pilot zone with their corresponding vulnerability indices from RISK-UE

Typology		Description	Risk-UE	Mean Vuln. Index
Unreinforced Masonry	T1	Stone masonry bearing walls made of rubble stone or fieldstone	M1.1	0.873
	T2	Unreinforced masonry bearing walls with wooden slabs	M3.1	0.740
	T3	Unreinforced masonry bearing walls with concrete slabs	M3.4	0.616
Reinforced Concrete	T4	Reinforced concrete frames with unreinforced masonry infill walls	RC3.1	0.402
	T5	Reinforced concrete shear walls	RC2	0.386
Steel	T6	Steel frame with unreinforced masonry infill walls	S3	0.484
Wood + Steel	T7	Wood structure supported on Masonry	N/A	0.550
Adobe	T8	Adobe structures	M2	0.840

Table 3: Vulnerability modifiers that applied for Level 1

Vulnerability Modifier	Typology	Indicator	Scores	
			Ancient (<1950)	Modern (>=1950)
State of preservation	Masonry (T2)	Good (>= 1950) Bad (<1950)	+0.04	−0.04
	Reinforced Concrete (LC)	Bad (LC)	+0.04	
Number of floors	Masonry	Low (1 or 2)	−0.02	
		Medium (3, 4 or 5)	+0.02	
		High (6 or more)	+0.06	
	Reinforced Concrete (LC)	Low (1 or 2)	−0.04	
		Medium (3, 4 or 5)	0.00	
		High (6 or more)	+0.08	
Soft-story	Masonry	Transparency	+0.04	
	Reinforced Concrete (LC)		+0.04	
Code Level	Reinforced Concrete (LC)	Pre or Low Code	+0.16	
		Mediun Code	0.00	
		High Code	−0.16	

Once typologies and their corresponding vulnerability indices and modifiers are well defined, it is necessary to address the issue of their distribution among the building stock. It is obviously almost impossible to individually identify each structure and a statistical approach must be preferred. It appeared clearly however, that the available building surveys did not provide the data necessary for a direct identification of the building on respect to the building typological classification of Table 2. Therefore inferences were established between categories of buildings, defined on the basis of more general information available from the census (height, age and location), and the structural typology. Table 4 presents the inference rules, determined for the municipalities of Spanish Cerdagne, according to the expert judgement of ISARD specialists and local architects and engineers. The
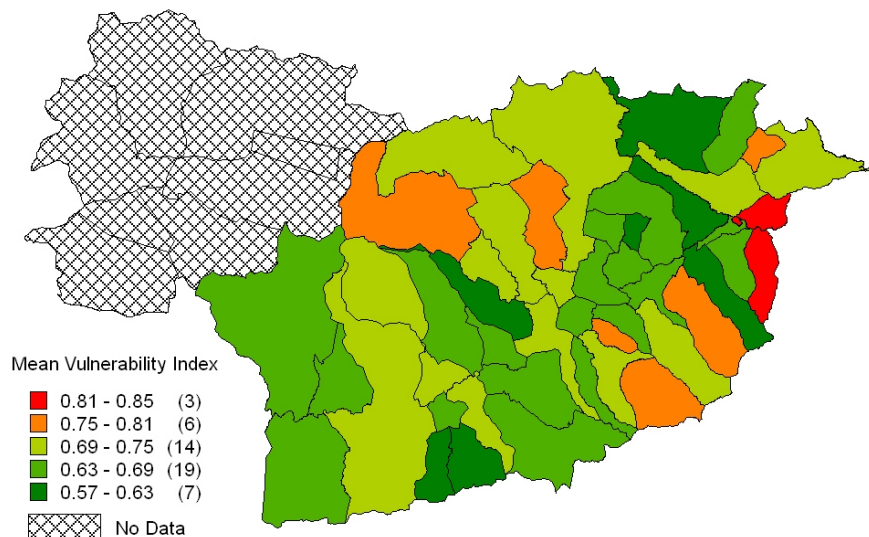
situation of the French Cerdagne required the development of specific distribution in each municipality, involving an extensive field survey.

Table 4: Distribution of building typology according to height, age and location, in Spanish Cerdagne, and in Saillagouse (French Cerdagne)

Height	Tipology	Other Spanish Cerdanya Towns			Puigcerda		
		Before 1950	1950–1970	After 1970	Before 1950	1950–1970	After 1970
<= 5	*T1*	15	10	0	15	10	0
	T2	75	25	5	75	15	5
	T3	0	65	60	0	75	55
	T4	0	0	25	0	0	30
	T5	0	0	0	0	0	0
	T6	0	0	10	0	0	10
	T7	0	0	0	0	0	0
	T8	10	0	0	10	0	0

Height	Tipology	<= 3			> 3		
		Before 1950	1950–1970	After 1970	Before 1950	1950–1970	After 1970
Saillagouse	*T1*	90	10	0	80	0	0
	T2	10	20	0	10	0	0
	T3	0	70	95	10	50	40
	T4	0	0	5	0	0	10
	T5	0	0	0	0	50	50
	T6	0	0	0	0	0	0
	T7	0	0	0	0	0	0
	T8	0	0	0	0	0	0

Level 1 vulnerability assessment is applied to the population entities (polygons) within each municipality. This could be made with good confidence in Spain, thanks to the availability of census data given in distinct polygons, defined according to their building density ("dense" or "disseminated"). In France, such polygons where drawn, and the number and characteristics of buildings in each polygon were estimated, by interpolating incomplete sources of information: the census data given at the municipality scale, the building database provided by IGN, and techniques using aerial photos, closely calibrated with field reconnaissance. The polygons for the population entities in the pilot zone are shown in Figure 11.
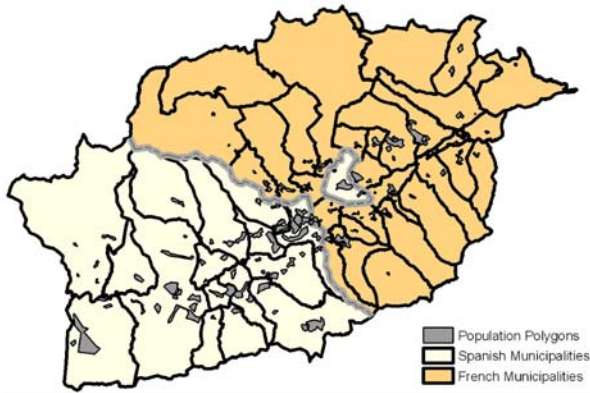
The typologies distribution allows obtaining a distribution of the vulnerability index for each population polygon that will be used for calculating its expected damages. Figure 10 illustrates the resulting mean vulnerability index, presented here at the municipality scale. The most populated municipalities, whose building stock widely grew beyond the limits of the old village core, have a similar overall vulnerability in Spain and in France, ranging from 0.6 to 0.7. A few French municipalities, located outside the main roads and hardly touched by the tourism development, have had their old stone masonry building stock almost unchanged for 50 years. Their singularly high mean vulnerabilities have no equivalent in Spanish Cerdagne.
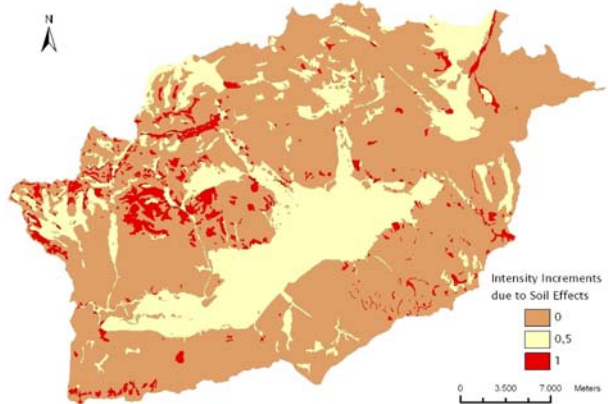

Figure 10: Mean vulnerability indices in the municipalities of the pilot zone

The vulnerability index distribution is then combined with the intensity map, in order to compute the distribution of damages through the vulnerability function. In order to take into account possible soil effects, i.e. possible amplifications of the seismic aggression due to local soil conditions, it is necessary to address the building stock at a local scale with respect to the fluctuations of the subsoil. Soil effects are considered in order to modify the mean intensity in each municipality and obtain the intensity with soils effects that affect each of the population polygons. A new methodology has been developed in the ISARD project, presented in this same issue by Macau

et al. (2006), in which the intensity increments are estimated taking into account the Arias Intensity computed from records obtained at the top of soil columns characterized using both geological and geophysical parameters. The results of this microzonation are presented in Figure 12. The intensity map to be used for the deterministic scenario is obtained by superimposing this map of increments to that of the intensity on rock (Figure 2).
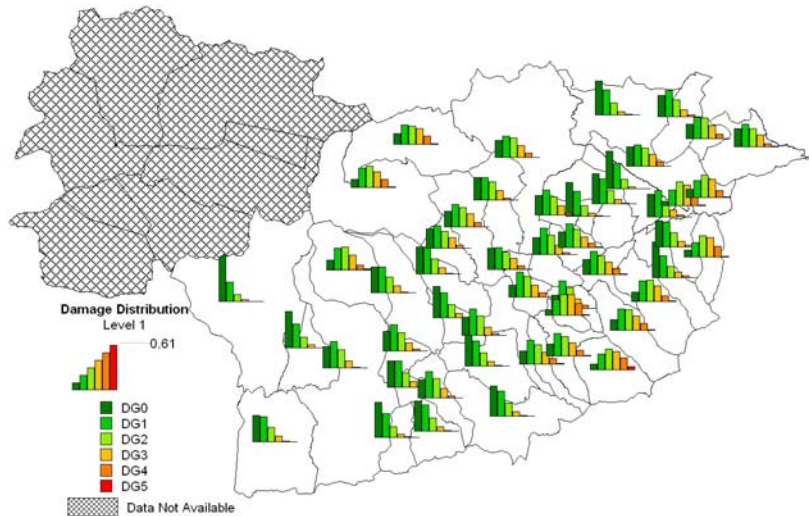

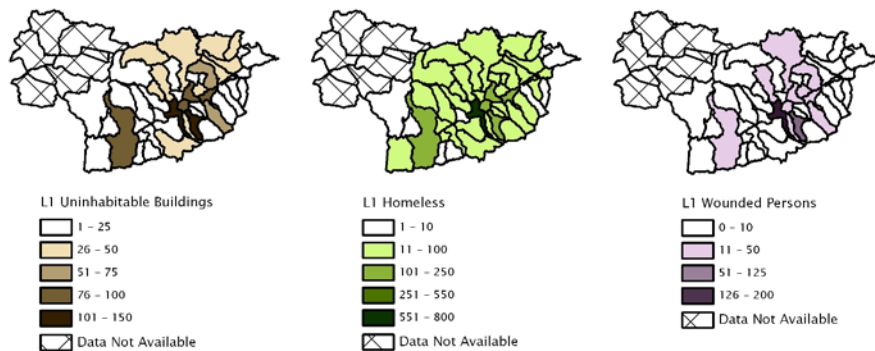**Figure 11: Polygons for the population entities for the pilot zone**

Figure 12: Map of seismic microzonation of the Cerdagne, proposed by Macau et al. (2006)

The damage distribution derived from Level 1 scenario is presented in Figure 13. By comparison with Level 0 scenario (Figure 7), we observe a slight shift towards higher damage grades, reflecting the soil effects on the one hand and a better consideration of the significant proportion of stone masonry buildings in French Cerdagne on the other hand. The same tendency applies to the estimated number of uninhabitable buildings, homeless and wounded (Figure 14); however, it should be noted that both scenarios give the same orders of magnitude.

Figure 13: Distribution of damage degrees in the municipalities of the pilot zone

Figure 14: Estimation of uninhabitable buildings, homeless and total wounded persons

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5. CONCLUSIONS

A seismic risk evaluation has been performed for a pilot border zone in the Pyrenees region that includes municipalities of Andorra, France and Spain. The vulnerability assessment has been performed using three methodologies depending on the kind of information available. Level 0 methodology based on the EMS-98 and applied at the municipality scale showed that the pilot zone is abundant in vulnerability classes B and C. The most representative structural typologies were identified within the region and its statistical distribution was developed through field investigations and expert judgments in order to apply Level 1 vulnerability index methodology. Level 1 vulnerability index methodology was implemented at the population entities scale to enhance the consideration of the soil effects in the region. Level 1 application revealed that the region is characterized by a mean vulnerability index of 0.67. Level 2 capacity spectrum method is still in the process of being applied to some essential buildings and some structural typologies.

Damages were calculated for a deterministic scenario inspired by the 1428 earthquake that affected the pilot zone with intensities between VII-VIII and VI-VII. Level 0 damages calculated for an average soil indicate that most of the region would mostly suffer minor damages but the eastern municipalities are affected by higher moderate damages due to their higher intensity values. On the other hand, Level 1 damage calculation including soil effects exposed an increase in the percentages of buildings expected to suffer damage grades 2 and 3 indicating moderate damages. The percentages of buildings with serious damages (damage grades 4 and 5) have also increased especially in the eastern part of the pilot zone characterized by high intensities, soil effects and vulnerable (field stone masonry) buildings

Losses were calculated for both Level 0 and Level 1 seismic scenarios although their results are not entirely comparable due to the fact that Andorra was not yet included in the Level 1 seismic scenario. The losses obtained for Level 1, which for now only includes the French and Spanish Cerdanya region, show that an 8% of the building stock would be uninhabitable, almost 600 persons can result wounded, and more than 2500 persons will lose their home. These figures will definitively increase when results for Andorra are included due to the high contribution of both buildings and persons that Andorra represents for the region. Another important fact to note is that these scenarios only consider the residential population of the region. Future scenarios will consider the floating population of the region during the vacation season in which the population of the region can triple.

Both Levels 0 and 1 have proven to be simple methodologies that can be applied for the development of seismic risk scenarios at regional scale requiring the identification of the principal structural typologies of the region and its correlation to simple available data. These two methodologies are being implemented into an automatic seismic information system developed for the region that will generate automatically a few minutes after the earthquake an informative note with the estimation of the possible damages for Civil Defense crisis managers [Goula et al., 2006].

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