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A Simplified Method for Vulnerability Assessment of Dwelling Buildings and Estimation of Damage Scenarios in Catalonia, Spain

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Abstract. A simplified method for vulnerability assessment of dwelling buildings with a statistical approach at a regional scale based on the EMS'98 is proposed. It is presented some applications of this methodology in Catalonia, Spain: (i) tools for generation of damage scenarios for preventive purposes; (ii) simulation of damages of historical earthquakes if they would occur today; and (iii) territory zonation to establish the criteria for activating the different levels of earthquake emergency actions.

Key words: damage scenarios, emergency plans, risk assessment, seismic vulnerability

1. Introduction

In order to generate damage scenarios, several methodologies exist, some of which have been recently developed (Dolce *et al.*, 1994; FEMA, 1998, 2003; Freeman, 1998; Faccioli *et al.*, 1999; Faëh *et al.*, 2001; Erdik *et al.*, 2003, 2004; Giovinazzi and Lagomarsino, 2004), including those which provide detailed vulnerability and damage assessment at local scale. The methodology presented here consists of a simplified statistical approach for regional-scale assessment based on the EMS-98. This type of methodologies is useful for the preparation of national and regional emergency plans and other applications at this scale which do not require a very detailed analysis of the building characteristics. One can also apply these methods when preliminary results are required in a short time, when budget for detailed and costly studies is not available and when detailed data on buildings can not be obtained, as is particularly the case in developing countries.

This approach has been used to develop a regional emergency plan for Catalonia (Susagna *et al.*, 2006) and tools to simulate damage scenarios for specific earthquakes in Catalonia (RSE, 2003) and in Spain (Barranco and Izquierdo, 2002).

2. Methodology

The general characteristics of the proposed methodology are the following:

(i) It is a statistical method that can be used with few data on buildings characteristics that are generally available without needing field surveys.
(ii) It is based on the definition of the European Macroseismic Scale EMS-98 (Grünthal, 1998); this scale, in spite of being a measurement of the effects of the earthquakes that may involve a certain degree of subjectivity, has the advantage that it can be used in the complete analysis of the seismic risk, that is for an estimation of the input ground motion, of the hazard, of the vulnerability and of the damage.
(iii) The building structural typology has been expressed according to the typologies defined in the intensity scale EMS-98, and the damages expected for each intensity degree has been deduced using damage probability matrices.

Considering this hypothesis a methodology has been developed for the region of Catalonia in the Northeast of Spain, (Chávez *et al.*, 1998).

The methodology could be summarized in four steps:

(1) Classification of the dwelling existing buildings in vulnerability classes according to the EMS-98 using height, age and location of the building, simple statistical data available from general building census.
(2) Assessment of probable damages in buildings due to the action of the earthquake considered in each case. Due to the lack of enough detailed data on damages in Spain, Damage Probability Matrices (DPM), must be derived from data observed elsewhere; data from the Irpinia, Italy, 1980 earthquake provided by *Gruppo Nazionale Difesa dai Terremoti* (GNDT) have been used for this purpose.
(3) Estimation of earthquakes casualties using two different methodologies developed by Coburn *et al.*, (1992) and Applied Technology Council (ATC-13, 1985).
(4) Evaluation of the direct econòmic losses generated for the physical damage in dwelling buildings.

3. Classification of Dwelling Buildings According to EMS-98 Vulnerability Classes

The study started with the analysis of the most recent available buildings inventory of Catalonia, i.e. the census of 1990 prepared by the *Institut d'Estadística de Catalunya* (IEC, 1990) in order to propose vulnerability functions applicable to the dwelling buildings in the region (a total of nearly 935.000, for a population of approximately 6.1 million inhabitants).

The buildings of Catalonia are mainly composed by constructions of non-reinforced brick walls with reinforced concrete joints, which could be of wood or steel according to the epoch, and small prefabricated ceramic or concrete vaults that can be also constructed manually. In general, these constructions are regular in elevation, except for those corner buildings that have particular forms. Traditionally, dwelling buildings have been constructed to only support the gravitational loads, not being considered the seismic load in their design, not even after the introduction of the seismic Spanish code in 1964.

A first task of the study was to classify dwelling buildings of Catalonia in vulnerability classes, following the criteria defined in the EMS-98. The parameters available on the building census of 1990 retained for our classification are: age, height and zone of location of buildings (if it is located in urban area or disseminated). The state of preservation was also considered through a representative sample of the building population. Finally the judgement of different experts with a good knowledge of the particularities of the regional constructions was taken into account (Chávez, 1998).

Following their age, buildings have been grouped in three classes: built before 1950, between 1950 and 1970 and after 1970, on the basis of the facts that before 1950 vertical and horizontal structures were not well connected and the building code for concrete was introduced in 1970.

With respect to height, buildings have been classified in three ranges: low (up to 12 m; $\leq$ 5 floors), medium (15 m; = 5 floors) and high ($\geq$ 18 m; $\geq$ 5 floors) according to the margins of security to resist gravitational loads. Table I shows the distribution of buildings according to these three parameters.

The way to go from these three parameters to vulnerability classes A, B, C and D is carried out through the matrix represented in Table II, obtained by expert judgment taking into account the considerations on buildings characteristics above described (constructive techniques, level of connections, and state of conservation) and the definitions of these vulnerability classes in the EMS-98 scale.

For instance, a set of buildings in a urban area, constructed before 1950 with more than five floors is considered to be 40% of class A and 60%

Table I. Distribution of dwelling buildings of Catalonia by height, age and location.

Date of Construction		Pre-1950		1951–1970		Post-1970	
Geographic Situation		Urban	Rural	Urban	Rural	Urban	Rural
	< 5 stories	232740	31119	212070	16304	315504	37346
Height	= 5 stories	7065	9	14083	24	11937	22
	> 5 stories	12699	2	21963	33	22028	44

Table II. Classification of buildings in Catalonia in vulnerability classes according to EMS-98, Chávez *et al.*, (1998).

	<1950		1951–1970		>1970	
	Urban	Rural	Urban	Rural	Urban	Rural
< 5 floors	20% A + 80% B	30% A +70% B	5 % A + 50% B + 45% C	15% A + 70% B + 15% C	85% C + 15% D	5% A + 20% B + 65% C + 10% D
= 5 floors	20% A + 80% B	40% A + 60% B	10% A + 60% B + 30% C	20% A + 70% B + 10% C	5% A+20% B+ 65% C+10% D	10% A + 30% B + 55% C + 5% D
> 5 floors	40% A + 60% B	60% A + 40% B	15 % A + 70% B + 15% C	30% A + 65% B+ 5% C	8% A + 27% B + 60% C+ 5% D	15% A + 45% B +40%C

class B, while if it is constructed after 1970 and has less than five floors its vulnerability is much lower as it is considered to be 85% C and 15% D.

A summary of the result of applying the criteria shown in Table II to the complete building census of the region is presented in Figure 1. It can be seen that, from a total of 934.992 buildings, 9% belong to class A, 40% to class B, 45% to class C and 6% (the smallest amount) to class D (Chávez *et al.*, 1998).

The matrix in Table II has been applied to the building census data for each one of the 941 municipalities of Catalonia obtaining the percentage of building of each vulnerability class. The use of a geographical information system with all the census data allows to obtained different representations of the geographical distribution of buildings into vulnerability classes (Susagna *et al.*, 2005).

4. Damage Probability Matrices for EMS-98

In order to carry out damage scenarios for future earthquakes damage probability matrices (DPM) are needed. In Spain there is a lack of enough detailed data on damages for deriving specific DPM, thus they must be obtained from data observed elsewhere.

Between the several seismic zones of the world where exhaustive data of damages are available, Italy is the one that constructive typologies are more similar to those of our study region. Thus, DPM have been obtained from the analysis of data on damage to building collected in Italy soon after the Irpinia earthquake of 1980 provided by *Gruppo Nazionale Difesa dai Terremoti* (GNDT).

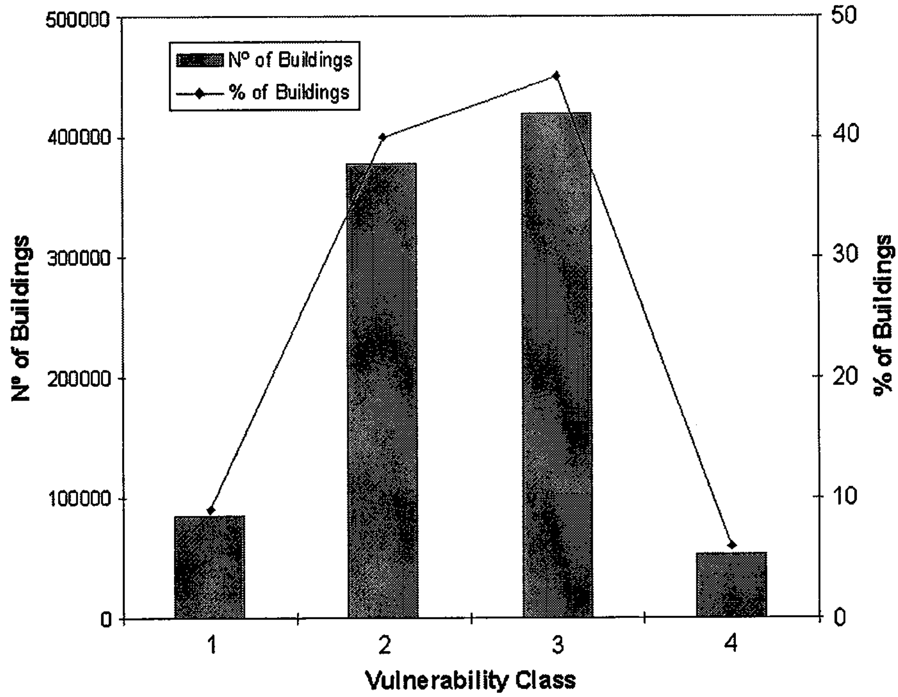

Figure 1. Classification of buildings in Catalonia in A, B, C, D classes.

In this survey, damage data had been classified in 15 typologies using a scale of 8 levels of damage (from no damage to collapse). For each municipality the distribution of buildings by typologies and by levels of damages is available. The used scale of damage was correlated to the series of damage defined in the MSK-76 scale (Braga *et al.*, 1982). The correlation and definition of each level of damage are presented in Table III.

A total of 15 structural typologies were identified by GNDT from the analysis of data of 32548 buildings in 41 Italian towns. Vertical (walls, columns) and horizontal (slabs, roofs) structures have been the essential elements in the definition of typologies. Other parameters characterising the vulnerability as the type of roof, height, age, and number of common walls with other building were available. The definition of the fifteen structural typologies and the total number of buildings in each one is given in Table IV.

These structural typologies have been grouped in the vulnerability classes defined in the EMS-98 (Chávez *et al.*, 1998). For this, the definitions of the vulnerability classes in EMS-98 and the seismic behaviours of the buildings are taken into account. The seismic behaviours of buildings is analysed in a statistic way; thus, an examination of the damage data for each typology individually by town and considering all buildings in it is executed.

Table III. Correlation and definition of damage in survey (Braga *et al.*, 1982) and MSK-76 scale.

MSK- 76 Damage Level	Survey Damage Level	Description of Damage
0	1	No damage
1	2,3	Slight: hair-line cracks, fall of small pieces of plaster
2	4,5	Moderate: cracks in many walls, fall of large pieces of plaster
3	6	Heavy: large and extensive cracks in walls, fall of chimneys
4	7	Destruction: gaps in walls, parts of buildings may collapse
5	8	Total damage: total collapse of buildings

Table IV. Typologies deduced from the survey and number of buildings for each one (Braga *et al.*, 1982).

Horizontal Structure	Vertical Structure							
	Fieldstone		Hewn stone		Brick masonry		Reinforced Concrete	
	Type	N. of buildings	Type	N. of buildings	Type	N. of buildings	Type	N. of buildings
Vaults	1	1540	5	618	9	17	–	–
Wooden	2	8996	6	3322	10	137	–	–
Steel	3	5375	7	2584	11	535	–	–
R.C. (1–3 floors)	4	945	8	3555	12	829	13	3186
R.C. (4–6 floors)	–	–	–	–	–	–	14	869
R.C. (>6 floors)	–	–	–	–	–	–	15	40

The classification adopted of the 15 typologies according to EMS-98 vulnerability classes adopted is reported in Figure 2, here the distribution of damage in each typology with its corresponding vulnerability class can be observed.

The first three typologies (8, 12 and 13) are considered as D vulnerability class; the following four (10, 11, 14 and 15), class C; the following three (3, 4 and 7), class B and the last five 1, 2, 5, 6 and 9, class A.

The last step in the process is to group the vulnerability classes belonging to towns with the same intensity values by level of damage. The distributions so obtained are the damage probability matrices for the A, B, C and D vulnerability classes, and represent the conditional probability of

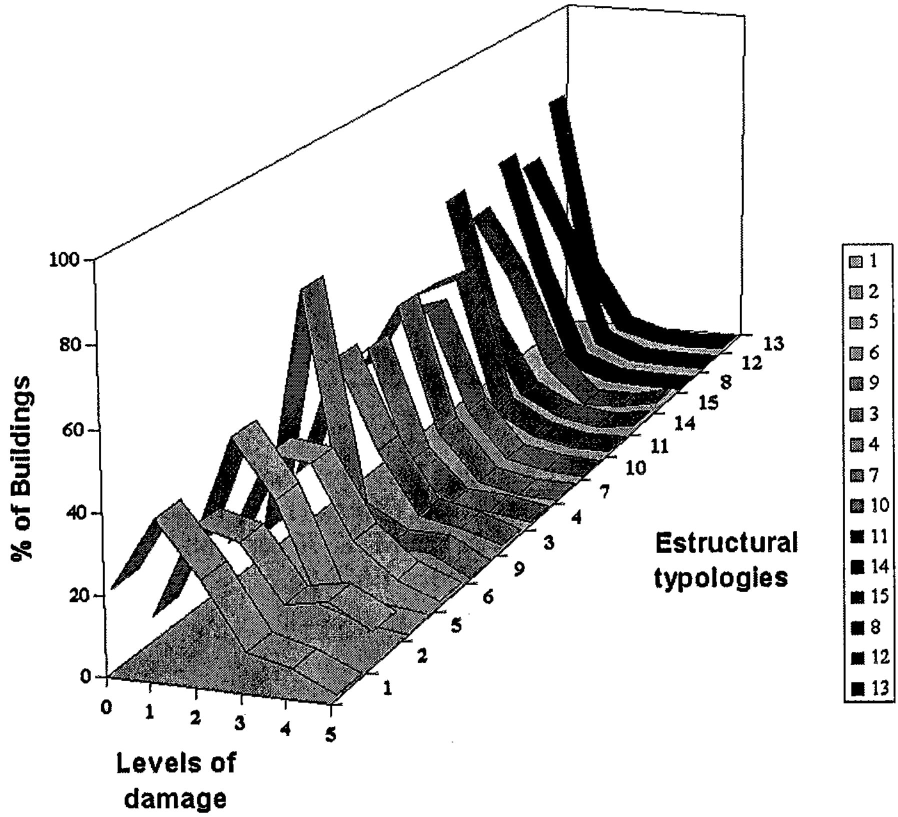

Figure 2. Distributions of damage observed in the fifteen structural typologies organized according to A, B, C and D vulnerability classes. From here on an evaluation of the intensity values in each town is necessary; for this a distribution of percentages of damage in each vulnerability class for each level of damage in all towns has been carried out and the intensity values are assigned according to EMS-98 patterns. A range of intensities from VI to IX was obtained.

that a given vulnerability class suffer a certain level of damage in the case of an earthquake of a particular intensity occurs.

These matrices have been adjusted to theoretical statistic distributions as Normal, Poisson and Binomial. The best results are obtained for Binomial distribution, which are the matrices proposed for the estimation of damage in buildings:

$$P_i = \frac{5!}{i!(5-i)!} p^i (1-p)^{5-i}, \tag{1}$$

where P_i is the probability of having damage of level $i (i = 0, 1, 2, 3, 4, 5)$ and p is the mean damage level.

Table V shows the parameter p of the obtained binomial distribution for A, B, C and D vulnerability classes and VI to IX intensities.

Table V. EMS-98: parameter **p** of the binomial distribution for A, B, C and D vulnerability classes and VI to IX intensities.

Intensity degree	Classes of vulnerability			
	A	B	C	D
VI	0.269	0.151	0.077	0.055
VII	0.396	0.269	0.151	0.077
VIII	0.603	0.396	0.269	0.151
IX	0.811	0.603	0.396	0.269

These damage probability matrices here proposed are comparable to other DPM obtained by Italian investigators (Braga *et al.*, 1982; Bramerini *et al.*, 1995) with the same data, based in the MSK-76 scale and more recently by Giovinazzi and Lagomarsino (2004) for EMS-98.

5. Risk Assessment for Preventive Plans

For the purpose of management of emergencies it is necessary to have risk maps for all the territory, that is the assessment of the probable damages taking into account values related to expected ground motion defined on a previous hazard analysis, for example, in terms of macroseismic intensity. Using the analysis of regional vulnerability of buildings and the DPM both above developed it is possible to proceed to estimation of probable damage to dwelling buildings, human injuries and related economical losses. In this issue, essential buildings, critical facilities and lifelines are not considered. Nor, indirect economical losses due to the loss of the economical activity are considered.

The estimation of the physical potential damage of the buildings can be carried out using the estimated damage probability matrices. The obtained possible damages that can suffer the different municipalities of Catalonia if an intensity associated to a return period of 500 years occurs (Secanell *et al.*, 2004) were used to prepare the Seismic Emergency Plan of Catalonia (Susagna *et al.*, 2006).

After the physical damage experimented by dwelling buildings for the action of an earthquake is determined the possible human victims may be estimated. The number of people injured as consequence of the occurrence of an earthquake depends on many variables, not only on the number of constructions affected and the number of inhabitants, but also on the season of the year, the day and the hour of the event. These variables can influence severely the results (Coburn and Spence, 1992). The knowledge of

Table VI. Correlation between damage level and cost of replacement (Chávez, 1998).

Damage level	% cost of replacement
1	1
2	20
3	40
4	80
5	100

the distribution of the population is of primordial importance to estimate human losses and the number of people that they could be injured or lose their housings.

Two methodologies can be used to carry out the estimation of human victims, one developed by Coburn *et al.* (1992) and the other proposed by the Applied Technology Council (ATC-13, 1985). Both methodologies were applied in all municipalities of Catalonia. The obtained results, even if very scattered, were used as a first estimation for the risk assessment included in the emergency plan (Susagna *et al.*, 2006).

A preliminary estimation of economic losses from earthquakes can be also obtained using a relationship between the level of damage and the global damage index considered equivalent to the percentage of the cost of replacement. The proposed equivalence shown in Table VI is a rough average of different equivalences obtained in different countries.

The proposed estimation takes only into account the damages to building by ground shaking (direct damage); hazards that follow the earthquakes, such as fire, landslides, etc, are not considered. Variations in economic value due to the inflation are included. However, adverse economic effects following the earthquake are not taken into account. A such effect could increase the replacement value due to the increase in the price of row materials or due to the increase of labour costs because of high demands (Kiremidjian, 1992); this means that losses may be underestimated by the proposed procedure we have followed.

6. Generation of Damage Scenarios for Emergency Plans

After the occurrence of an earthquake it is important for the organisation of the emergency services to have a quick estimation of possible consequences on the population, lifelines and buildings.

The above presented methodology, proposed and used for preventive purposes (risk maps), may also be adapted to be used for emergency management after a given event occurs. This methodology can be thus integrated in a complete process to generate damage scenarios in conjunction with a rapid determination of hypocentral parameters of the earthquake, immediately after occurring an earthquake (Erdik and Fahjan, 2005).

This methodology can be also used to simulate the damages of historical damaging earthquakes if they would occur today. As an example, the simulation of damages corresponding to an earthquake scenario similar to that of one of the largest earthquakes that occurred in the Pyrenees in historical times will be shown later.

Another application of the methodology will be the zonation of the territory in order to establish the criteria for activation of different levels of the earthquake emergency plan according to the severity of the estimated consequences of the events.

The methodology to generate damage scenarios consists of three steps:

(i) *Epicentral intensity estimation.* After receiving the information concerning the hypocentral parameters of the earthquake, coordinates, depth and magnitude it is possible to proceed to an estimation of the epicentral intensity using an empirical equivalence established between magnitudes and epicentral intensities deduced from intensities felt by the population in the last years on the study region.

(ii) *Intensity assignment to the municipalities likely affected by the earthquake.* It is necessary to adopt a law of attenuation of the intensity versus the distance. The relationship used is the one proposed by Sponheuer (1960):

$$Io - I = K^{*}\text{Log}\left(\frac{\sqrt{x^2+h^2}}{h}\right)^{b} + K^{*}\gamma^{*}\text{Log}e^{*}\left(\sqrt{(x^2+h^2)} - h\right) \qquad (2)$$

where K (factor that relates the intensity and the logarithm of the pick ground acceleration) adopted is 3; γ (inelastic attenuation) fitted to 0,001 km^{-1} and b (coefficient of geometrical spreading) is taken equal to 1 and an average value of h equal to 7 km for shallower earthquake and 12 km for the deeper ones.

The expression used for Catalonia corresponds to an average curve adjusted to the data of felt intensities of the most important earthquakes occurred in the region. An isotropic model of the inelastic attenuation has been used resulting isoseismal curves with circular forms.

For the assignment of the likely felt intensities a list of all municipalities of Catalonia (more than 900) with their geographical coordinates, the number of inhabitants and the area of each municipality has been used.

(iii) *use of GIS for damage scenarios.* A quick evaluation of the affected area and the number of people likely being felt the earthquake with different intensities is thus possible using a Geographical Information System (GIS). The results are expressed on a map distinguishing the municipalities areas with different colours according to the likely felt intensities and by a table with a list of municipalities, classified by likely felt intensities, with the number of inhabitants and the municipal area. In another table a summary of the results is also available for each intensity.

In the case that an earthquake occurred with an epicentral intensity equal or greater than V there exist some possibilities to observe damages. To asses the likely damage scenario the above presented methodology, may be adapted to be used. The likely felt intensities in each municipality are used as input to asses damages on buildings thorough the expression (4), above mentioned.

Two different tools using a GIS have been developed in Spain applying this methodology: *ESCENARIS V1.00* (RSE, 2003) for Catalonia and SES 2002 for the whole country (Barranco and Izquierdo, 2002). An example of a scenario map and list of municipalities obtained with *ESCENARIS V1.00* is shown in Figure 3.

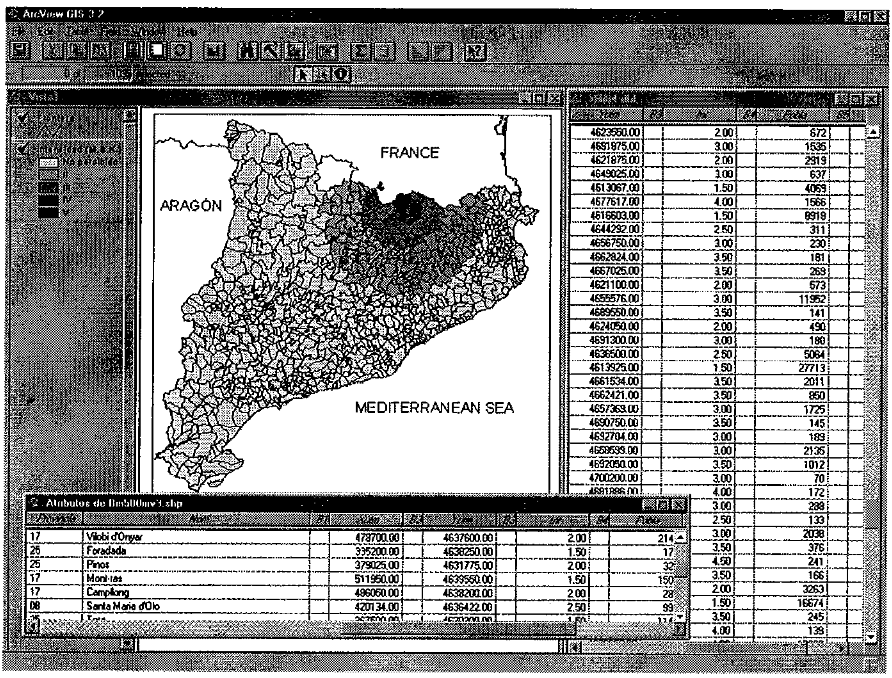

Figure 3. Example of a scenario map with the list of municipalities for an earthquake of M = 4.0 in the Pyrenees.

7. Damage Scenario for an Earthquake Similar to an Historical One

The earthquake that occurred in 1428 in the *Ripollès* (Girona) near the border between Spain and France is one of the greatest seismic events that the region has suffered in the past. Chronicles and other documents contemporary to the event report effects in a quite extensive way, including destruction of towns, churches, castles, etc., and the death of 800 people (Banda and Correig, 1984; Olivera *et al.*, 2005). This is the reason for the interest in the simulation of a scenario of the possible effects of an earthquake like this one of 1428 if it occurred at the present time.

An estimation of the different damage grades, affecting the dwelling buildings of each municipality as well as the number of homeless and victims has been done. A summary of damages for the whole of Catalonia has been completed (González *et al.*, 2001). The results are shown in Table VII. The estimated *destroyed area* refers to the probable surface with debris. The direct economic cost of the resulting damage – only referred to the dwelling buildings – is about 8% of the annual GNP of this community. Other direct costs related to installations other than dwellings and indirect costs (e.g. related to the interruption of services and interruption of economic activities) are not considered.

8. Criteria of Activation of a Seismic Emergency Plan. Application to Catalonia

The emergency plans include various levels of intervention, bringing out the adequate amount of resources, depending on the severity of the event.

These activation levels are defined in the current plan of Catalonia taking into account the ground shaking and the population density.

These activation levels can be defined taking into account not only the estimation of ground shaking but also other factors related to physical, human and societal vulnerability, such as the expected number of uninhabitable dwelling buildings, the number of homeless or the direct economical losses. All these parameters can be estimated for a regional damage

Table VII. Earthquake scenario simulation for an earthquake in the Ripollès of $I_{max} = IX$.

Uninhabitable buildings	Homeless	Economic losses (M€)
23.570	136.901	4 978
Economic losses (% GNP of Catalunya)		Destroyed Area (m²)
8		207.712

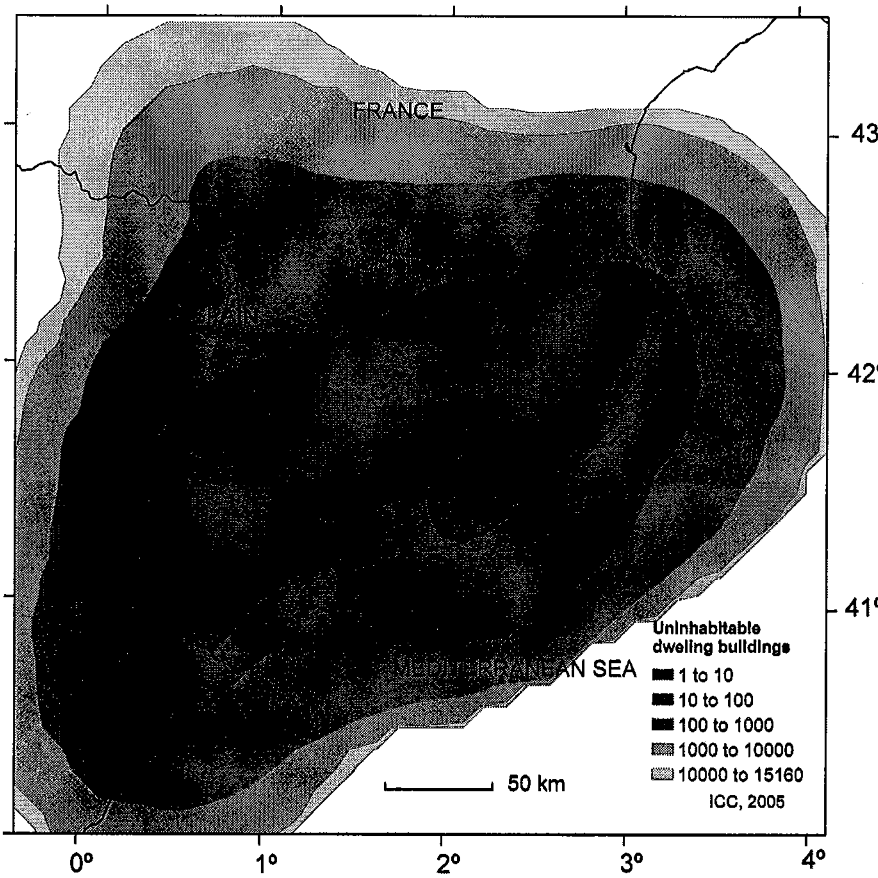

Figure 4. Number of uninhabitable dwelling buildings of Catalonia (contour plotted) that could result after an earthquake of M5.5, occurring at each point of the grid.

scenario developed previously for an earthquake occurring at any point of the territory with any magnitude.

The methodology proposed is based on a graphical representation (Pujades *et al.*, 2006) that concentrates all the regional damages estimated for an earthquake on its epicentre. Then, each point of the territory can be characterized by the severity of damages caused by an earthquake with epicentre in this given point, for each possible magnitude. The same methodology explained in the preceding sections has been applied to compute damages. As an example of the method, the number of uninhabitable dwelling buildings of Catalonia that would be observed after an earthquake of M5.5 is shown in Figure 4.

If the value of one parameter of damage is fixed, it is possible to construct new maps with the magnitude of the earthquake needed at any point of the grid to produce this damage.