13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 423

RISK SCENARIOS FOR BARCELONA, SPAIN

Lantada N.[1], Pujades L.G. [1] and A.H. Barbat [2]
[1] Geotechnical Engineering and Geosciences Department.
Technical University of Catalonia. Barcelona, Spain
[2]Structural Mechanics Department. Technical University of Catalonia. Barcelona, Spain

Keywords: dense urban environments, GIS, risk scenarios.

SUMMARY

An integrated GIS application is developed by using ArcView GIS software (Lantada [1]), in order to estimate risk scenarios for different seismic intensities and response spectra in Barcelona, Spain. Two seismic hazard scenarios are considered. The risk analysis of individual residential buildings is performed according to two methodologies developed within the RISK-UE Project of the European Commission RISK-UE [2]. The first methodology is based on the EMS-98 building typologies (Grünthal [3]) and vulnerability indices, the second one is based on fragility curves. Both methods are applied to the most representative residential building typologies of Barcelona, namely unreinforced masonry and reinforced concrete buildings. In the vulnerability index method, the specific residential buildings of Barcelona are classified in different classes characterized by a similar seismic behaviour. An average vulnerability index is associated to each building typology. This index is refined on the basis of behaviour modifiers, linked to the number of stories, the year of construction, irregularity in height, the position of the building within the aggregate and differences in the height between adjacent buildings. The damage probability distribution, corresponding to the vulnerability functions, is described by a beta distribution, characterized by a mean damage grade parameter, which is related to the vulnerability index and intensity by means of a single empirical equation. In the fragility curves method, we use specific fragility curves and Damage Probability Matrices, developed for the same two buildings typologies. The ability of GIS tools to store, manage, analyse, and display the large amount of spatial and tabular data involved in this study allows mapping hazard, vulnerability and damage at different levels: buildings, census areas, neighbourhoods and districts. Selected results, consisting of scenarios obtained for the seismic risk of Barcelona, Spain, are finally given. These results will be useful for preparing emergency plans for the city.

INTRODUCTION

Barcelona is the political and economical capital of Catalonia and the second city of Spain after Madrid. It is situated on the northeast coast of Spain and it concentrates a big percentage of the total population of the region (1.505.325 inhabitants in 2001). The city is located in a moderate seismic hazard area according to the Spanish seismic code (NCSE-02 [4]). However, most of its buildings were built between 1860 and 1940 with an unreinforced masonry structure, prior to the first Spanish Seismic Code, and show a high vulnerability. Moreover, it is well known today that the use of this structural typology is not adequate in a seismic area and that their seismic resistant retrofit is difficult and expensive.

Barcelona is organized into 10 districts: Ciutat Vella, Eixample, Sants-Montjuïc, Les Corts, Sarriá-Sant Gervasi, Gràcia, Horta-Guinardó, Nou-Barris, Sant Andreu and Sant Martí. Each district is subdivided into a number of neighbourhoods, with a total number of 38. All the available data have been integrated into a Geographic Information System (GIS), which in this case was ArcView GIS software (ESRI) (Lantada [1]). The data inventory for the buildings included in this study is composed of 63536 units (87 % of total buildings in the city), and information about their year of construction, structural typology (see Figure 1) and number of floors is available.

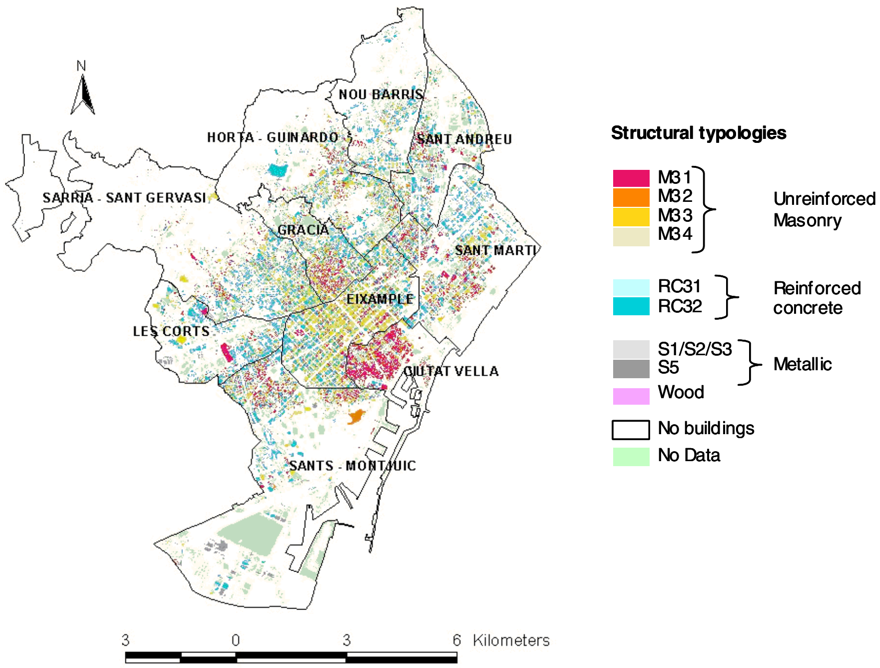

Figure 1. Distribution of buildings by districts, according to their structural typology.

SEISMIC HAZARD

In spite of the fact that Barcelona is located in a moderate seismic zone, the seismic hazard of the city has been intensively studied in the last ten years (Cid [5], Secanell [6], Alfaro [7], Irizarry [8]). A seismic microzonation for the city of Barcelona based on the simulation of local effects, was also performed by Cid [5], who computed complete transfer functions and spectral responses for a set of 70 columns corresponding to geotechnical borings. The four classified zones with similar behaviour roughly correspond to the main geological units of the soils of the city (see Figure 2). Zone R corresponds to rock outcrops (Palaeozoic and Tertiary), Zone I to Holocene deposits from the Llobregat and Besòs Deltas, Zone II to Pleistocene formations with a Tertiary base and Zone III to Pleistocene outcrops without the Tertiary basis, with sufficient thickness to have an influence on the soil amplification. Each zone is characterized by an average transfer function and by an amplification factor for spectral response spectra relative to each reference site.

The seismic scenarios here considered corresponds to a deterministic case and represents the maxima historical earthquakes that affected Barcelona. The seismic action will be modelled in terms of EMS-92 intensity and by using response and demand spectra. Local effects are included in the final seismic hazard maps. The basis intensity is increased by half intensity units while response or demand spectra are modified by means of amplification factors, which have been calculated by using the transfer functions developed by Cid [5]. Figure 3 shows the hazard maps. In the intensity case, the map reflects the proximity of the source, which is assumed to be at about 30 km. For the spectral values case the contribution of two historical eartquakes has been combined and we have considered average response spectra for each of the four zones (Irizarry [8]). The *Sa* values in the right side map in Figure 3 are the maxima *Sa* values wich correspond to the period range between 0.1 and 0.22 s.

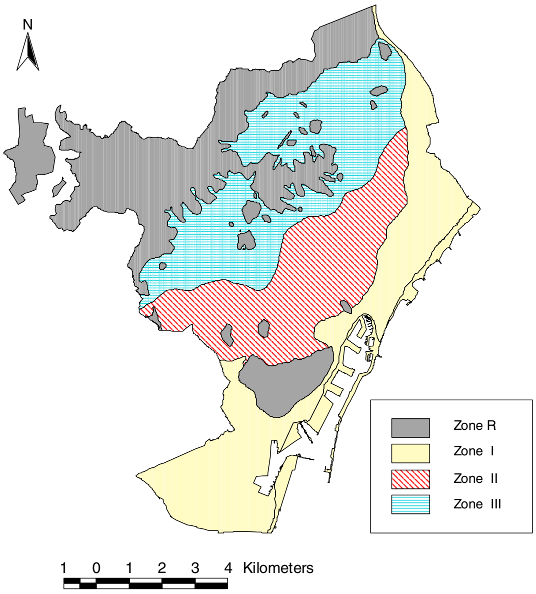

Figure 2. Seismic zonation of Barcelona (Cid [5]).

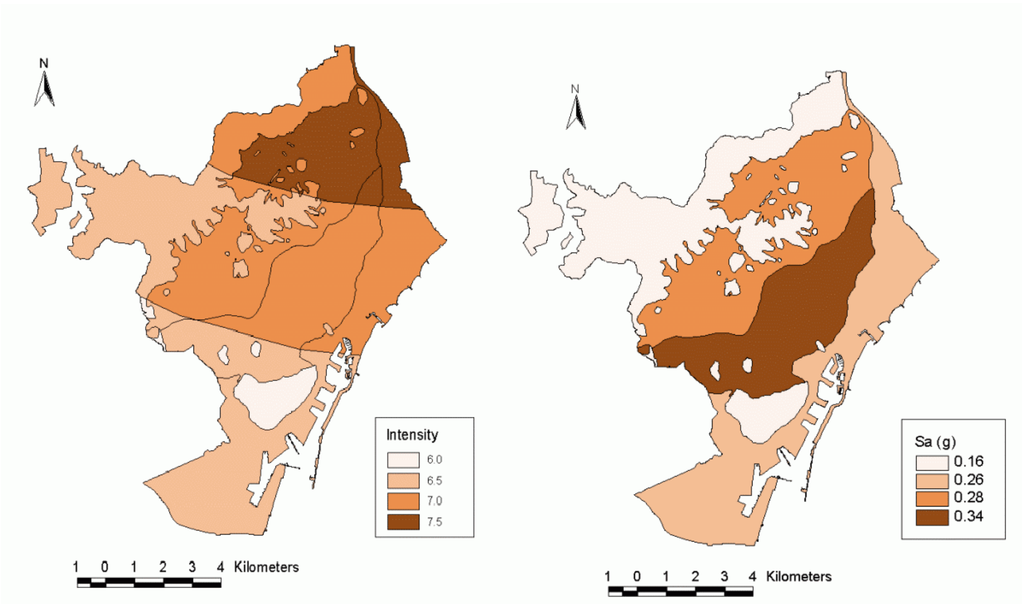

Figure 3. Deterministic seismic hazard scenarios, including local soil effects in terms of intensity and spectral acceleration.

VULNERABILITY INDEX METHODOLOGY

Traditionally, the methodologies used in Italy by GNDT (National Group for Defense from Earthquake) identify the existing building typologies within the studied area and define their class of vulnerability (i.e. A, B, C) (Giovinazzi [10]). For each vulnerability class, the relationship between intensity and damage may be defined by using Damage Probability Matrices (DPM). Alternatively, vulnerability functions, correlating damage factor (relationship between the cost of the repair intervention and the value of the structure) with the Peak Ground Acceleration (PGA) of the expected seismic input, can also be used to obtain the damage (Corsanego [11]).

According to the GNDT methodology, the specific buildings of Barcelona are classified in different groups characterized by a similar seismic behaviour. All the buildings belonging to each typology are cast within the most probable class (see Table 1). The six vulnerability classes denoted by A to F are arranged in a decreasing vulnerability order, according to the EMS-98 intensity scale (Grünthal [3]).

Concerning the vulnerability classes of Table 1, vulnerability indices (V_I) are assigned to the most representative typologies of the city. Their values are arbitrary, since this index represents only a score that quantifies the seismic behaviour of the building. However the vulnerability index ranges between 0 and 1, being their values close to 1 for the most vulnerable buildings and close to 0 for the buildings with high seismic resistance (i.e. high-code estructural design) (Giovinazzi [12]).

▭ most probable class ▯ possible class O Unlikely class (exceptional cases)	**BUILDING TYPOLOGY**		**VULNERABILITY CLASSES**					
			A	**B**	**C**	**D**	**E**	**F**
UNREINFORCED MASONRY	**M3.1**	Unreinforced masonry bearing walls with wooden slabs	O	▭	O			
	M3.2	Unreinforced masonry bearing walls with Masonry vaults	▯	▭	▯			
	M3.3	Unreinforced masonry bearing walls with composite steel and masonry slabs	O	▭	▯			
	M3.4	Reinforced concrete slabs		▯	▭	O		
REINFORCED CONCRETE	**RC3.1**	Concrete frames with unreinforced masonry infill walls with regularly infilled frames		▯	▭	▯		
	RC3.2	Concrete frames with unreinforced masonry infill walls with irregularly frames (i.e., irregular structural system, irregular infills, soft/weak story)		▯	▭	O		

Table 1. Building typology matrix used for Barcelona (Giovinazzi [12])

A first refinement of this average initial vulnerability index is performed by taking into account the age of the building. The building stock is grouped in 6 age categories by considering reasonable time periods in function of the existence of seismic codes in Spain and its level, as well as other specific construction features (see Table 2).

Further refinements of the vulnerability index V_I come from other behaviour modifiers, which are used to evaluate a global vulnerability index of each building, as follows:

$$V_I^{building} = V_I^{class} + \sum_{j=1}^{n} Vm_j \qquad (1)$$

where V_I^{class} is the vulnerability index corresponding to the category of the building, Vm_j is a vulnerability factor or a behaviour modifier and $V_I^{building}$ is the final vulnerability index of the building. These Vm_j modifiers in equation (1) are different for isolated and aggregate buildings.

Periods	Period of construction	Spanish Code	Obligation in Barcelona	Lateral bracing in constructive practice	Seismic Design level	Buildings (%)	Vulnerability Index (V_I)		
							M31 M32 M33	M34	RC32
I	<1950	-----	-----	Absent	Pre-code	50.69	0.938	--	--
II	1950-1962	-----	-----	Deficient	Pre-code	17.30	0.875	--	--
III	1963-1968	Recommendation MV-101 (1962)	No specified	Deficient	Pre-code	10.91	0.813	0.750	0.750
IV	1969-1974	Seismic code P.G.S.-1 (1968)	Yes	Acceptable	Low-code	9.80	0.750	0.625	0.625
V	1975-1994	Seismic code P.D.S. (1974)	Yes	Acceptable	Low-code	11.07	0.688	0.563	0.500
VI	1995 until now	Seismic code NCSE-94 (1995)	No	Acceptable	Low-code	0.23	0.688	0.563	0.500

Table 2. Vulnerability index for typologies and periods of construction according to seismic design level.

For isolated buildings we consider the following 4 modifiers: number of floors, irregularity in height, length of the façade and state of preservation. For building in aggregates we take into account the effects due to the different heights of adyacents buildings and the effects due to the position of the building in the aggregate (i.e. corner, header, or intermediate)

Concerning the damage, the methodology recognizes a no-damage state, labelled as *None* and five damages states, termed as *Slight, Moderate, Substantial to Heavy, Very Heavy* and *Destruction*. A sort of mean damage grade (μd) permits to characterize completely the expected damage for a building, known its vulnerability and for a given intensity. Equation (2) relates μd, intensity and the vulnerability index.

$$\mu_D = 2.5\left[1+tanh\left(\frac{I+6.25\cdot V_I\text{ - }13.1}{2.3}\right)\right] \quad (2)$$

Damage probability matrices, can be then easily obtained by assuming that the damage probability follows a beta probability density function (PDF) (see equation 3).

$$PDF:\ P_\beta(x)=\frac{\Gamma(t)}{\Gamma(r)\,\Gamma(t\text{-}r)}\ \frac{(x\text{-}a)^{r\text{-}1}\ (b\text{-}x)^{t\text{-}r\text{-}1}}{(b\text{-}a)^{t\text{-}1}} \qquad a \le x < b \quad (3)$$

In our case a is set to 0 (*None* damage state) and b is 6 (*Destruction* damage state). The parameter t affects the scatter of the distribution and its value is fixed to 8 in order the beta distribution to be similar to the binomial distribution. EMS-98 indicates that the damage distribution of a building follows a binomial distribution. (see also Giovinazzi [12]). Finally parameter r is given as a function of μd in the following equation.

$$r = t(\,0.007\mu_D^3 - 0.0525\mu_D^2 + 0.2875\mu_D\,) \qquad (4)$$

Then, the probability that the damage be less or equal to a damage grade $P_\beta(k)$ is obtained by integrating $P_\beta(k)$ in equation (3) between 0 and the k-damage grade. Finally, the probability of occurrence of the damage state k, p_k is obtained as follows:

$$p_k = P_\beta(k+1) - P_\beta(k) \qquad (5)$$

Figure 4 shows an example of the construction of p_k values for the case $\mu_d=2$.

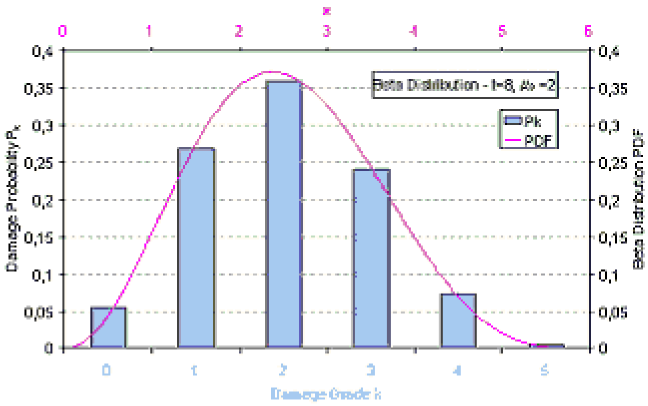

Figure 4. Evaluation of probabilities for each damage state (see explanation in the text).

All the collected data, vulnerability indices and damage factors have been used to build up a GIS application. We have used ArcView GIS. In this way, we may obtain detailed damage scenarios for each area or district and for any seismic intensity.

FRAGILITY CURVES METHODOLOGY

A more advanced method to analyse earthquake risk is based on the capacity-demand analysis and fragility curves. Of course, the application of this technique requires more information about the seismic action and buildings, because its application requires performing dynamic analyses of the buildings, in order to obtain the capacity and demand spectrum, which is based on the response spectrum. As said before, most of the residential buildings of Barcelona are reinforced concrete and masonry buildings, RC1 and M3.3 categories in Table 1, respectively. In order to apply this advanced methodology to Barcelona, specific fragility curves for low rise, mid rise and high rise, reinforced concrete and unreinforced masonry buildings have been developed (Moreno [13]). Obtaining the performance point for each analysed typology, allows obtaining the corresponding probabilities p_k.

This methodology considers building fragility curves for four damage states based on FEMA [14] and denoted as: *Slight*, *Moderate*, *Severe* and *Complete*. In fact, *Severe* damage state here, comprises *Substantial* and *Very Heavy* damage states in the previous methodology. Each fragility curve is assumed to follow a lognormal distribution and therefore may be characterized by a median and a standard deviation (β_{DSi}) value of seismic hazard parameter (i.e. *Sa* or *Sd*). For example, given the spectral displacement, *Sd*, the probability of being in, or exceeding a given damage state, DS, is modelled as:

$$P\left[DS > DS_i / Sd\right] = \Phi\left[\frac{1}{\beta_{DSi}} \ln\left(\frac{Sd}{\overline{Sd}_{DSi}}\right)\right] \qquad (6)$$

where $\overline{Sd}_{DSi}$ is the median value of spectral displacement at which the building reaches the threshold of the damage state, *DS*, β_{DSi} is the standard deviation of the natural logarithm of spectral displacement of damage state, *DS*, and Φ is the standard normal cumulative distribution function. The subscript *i,* represents the damage state, from slight (*i*=1), to collapse (*i*=4).

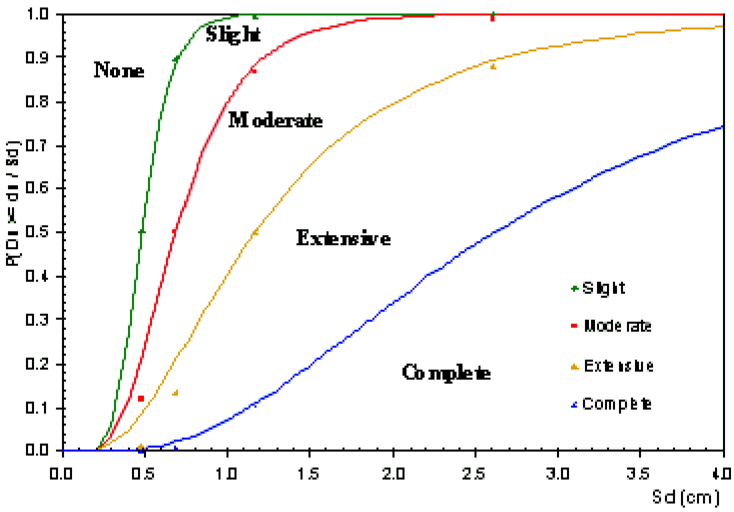

Figure 5. Fragility curves for M3.3 high-rise buildings of Barcelona (Moreno [13]).

	Zone	None	Minor	Moderate	Severe	Collapse	DS_m
Low-Rise	1	0,950	0,037	0,011	0,002	0,000	0,066
	2	0,737	0,189	0,063	0,009	0,001	0,349
	3	0,917	0,061	0,018	0,003	0,001	0,109
	R	1,000	0,000	0,000	0,000	0,000	0,001
Middle-Rise	1	0,003	0,166	0,399	0,353	0,079	2,339
	2	0,121	0,384	0,289	0,189	0,017	1,598
	3	0,273	0,364	0,215	0,139	0,009	1,247
	R	0,623	0,193	0,105	0,076	0,003	0,642
High-Rise	1	0,003	0,145	0,389	0,371	0,092	2,404
	2	0,135	0,388	0,281	0,178	0,018	1,556
	3	0,307	0,369	0,195	0,120	0,009	1,155
	R	0,647	0,205	0,086	0,059	0,003	0,566

Table 3. Probability damage matrices for masonry buildings (deterministic scenario).

Therefore, to calculate the probabilities starting from function Φ in equation (6), it is necessary to define $\overline{Sd}_{DSi}$ and β_{DSi} for each damage state. Fragility curves usually are represented in a coordinate system whose abscissas are i.e. the spectral displacement (*Sd*) and whose ordinates are the conditional probabilities that a particular damage state is meet ($P[DS=DS_i]$) or exceeded ($P[DS>DS_i]$). Figure 5 shows an example. By crossing the capacity and demand spectra of a given building, we find the performance point, getting the *Sa* or *Sd* of this building when it suffers the considered seismic action. Then from each fragility curve corresponding to a specific structural typology and elevation of the building, it is possible to obtain the probabilities of occurrence for each damage state. In this way, we are able to construct the damage probability matrices. Table 3 summarizes the distribution of probability for each damage state, for masonry buildings and for each zone of the map in the right side of Figure 2. The last column in Table 3, has the meaning of mean expected damage state, and is analogous to μd in the vulnerability index method. This is computed by the equation:

$$DS_m = \sum_{i=0}^{4} DS_i * P[DS_i] \qquad (7)$$

According to this equation, for example, a value DS_m=1.3 indicates that the most probable structural damage state of the corresponding building, ranges between *slight* and *moderate* states, being more probable the *slight* damage state. Thus, DS_m is a weighed average of different damage DS_i states where the probability to reach it, $P[DS_i]$, is the weight. Again, this sort of average damage state, permits to plot seismic damage scenarios, by using a single parameter. Of course, alternative maps, may plot the spatial distribution of the probability of occurrence for a determined damage state, it's to say, $P[DS_i]$ for a ginven *i*.

SEISMIC RISK SCENARIOS

The process to obtain the final seismic risk scenarios according to the vulnerability index methodology is: the behaviour modifiers are first calculated and associated with the vulnerability index of each building in the map of Figure 1. The deterministic seismic hazard map in terms of intensity (see Figure 3, left side map) and the map with information on the buildings are then overlaid in the GIS. The result is a new map with information on the seismic zone where the buildings are located. Finally, the mean damage grade is calculated by using equation (2) in order to obtain the damage scenario in Figure 6. We have adopted a graduated color scale to represent the 0 to 5 damage states. Namely: *No damage*-white, *Slight*-green*, Moderate*-yellow*, Substantial to Heavy*-Orange*, Very Heavy*-red and *Destruction*-black). In the same way, the damage scenarios coresponding to the analysis based on the fragility curves methodology are obtained by overlaying, in the GIS, the corresponding deterministic seismic hazard map in terms of spectral values (see, right side map in Figure 3) and building map with information about their typologies (see Figure 1). The information of damage probability matrices for each typology (see Table 3) is then associated in this final map. In this case the graduation of colors of the legend for each damage state from 0 to 4 are: *No damage*-white, *Slight*-green, *Moderate-yellow*, *Severe-red* and *Complete-black.*

Figures 6 and 8 present the obtained seismic risk scenarios. We can see how the expected damage for a relatively low seismic intensity is relatively high. About 50% percent of high rise masonry buildings located in Zone II, would present a damage state between *moderate* and *severe* (see also Table 3). This fact may be due to the high vulnerability of this typology. By another hand we can see how the damage follows a radial pattern from downton, in the center of the city, to the outskirts of Barcelona. This fact may be due to the historical evolution of the city, with old masonry buildings concentrated downtown and in the first city expansion represented by the Eixample district. It is also possible to see the influence of the nearness of the earthquake in the case analyzed in Figure 6 (sees also Figure 3).

Both maps, in figures 6 and 8, have been drawn showing a single value: the mean expected damage state for each building. Of course, we may also map other specific scenarios as for example, for each damage state, we may plot its probability spatial distribution. When doing this, we have maintained the same color-scale used in Figures 6 and 8, to identify each damage state, but the differences in the probabilities are now represented by different tones of the same color. Two examples of these damage state probability maps are shown in Figure 7 and Figure 9, for *moderate* and *severe* damage states respectively in the Eixample district. It must be noted that most of the buildings in this district are old unreinforced, high-rise buildings (more than 70%), and all of them are inside Zone II (see Figure 2). So, according to values in Table 3, the occurrence probability of the *moderate* damage state is about 28% (light-middle yellow in Figure 7), greater than occurrence probability of the *severe* damage state case, that is less than 20% (light pink in Figure 9).

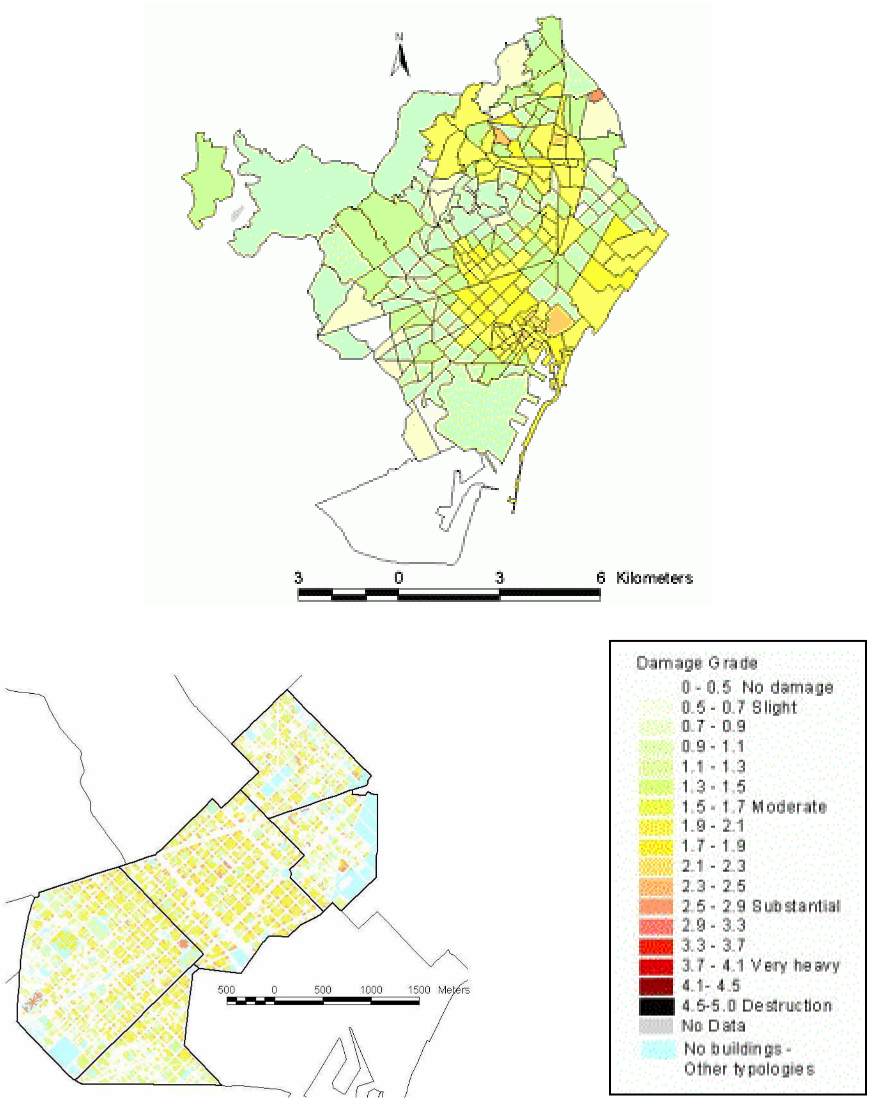

Figure 6. Damage scenario for census areas. A detail of the Eixample district is standed out (Vulnerability index method).

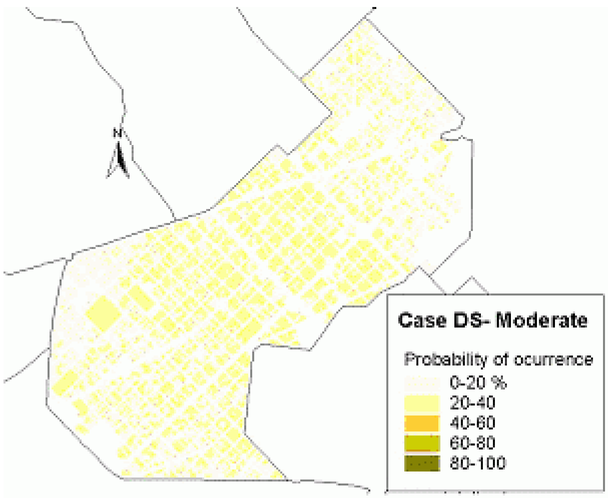

Figure 7. Probabilities of the *moderate* damage state in the Eixample District. (Fragility curves method)

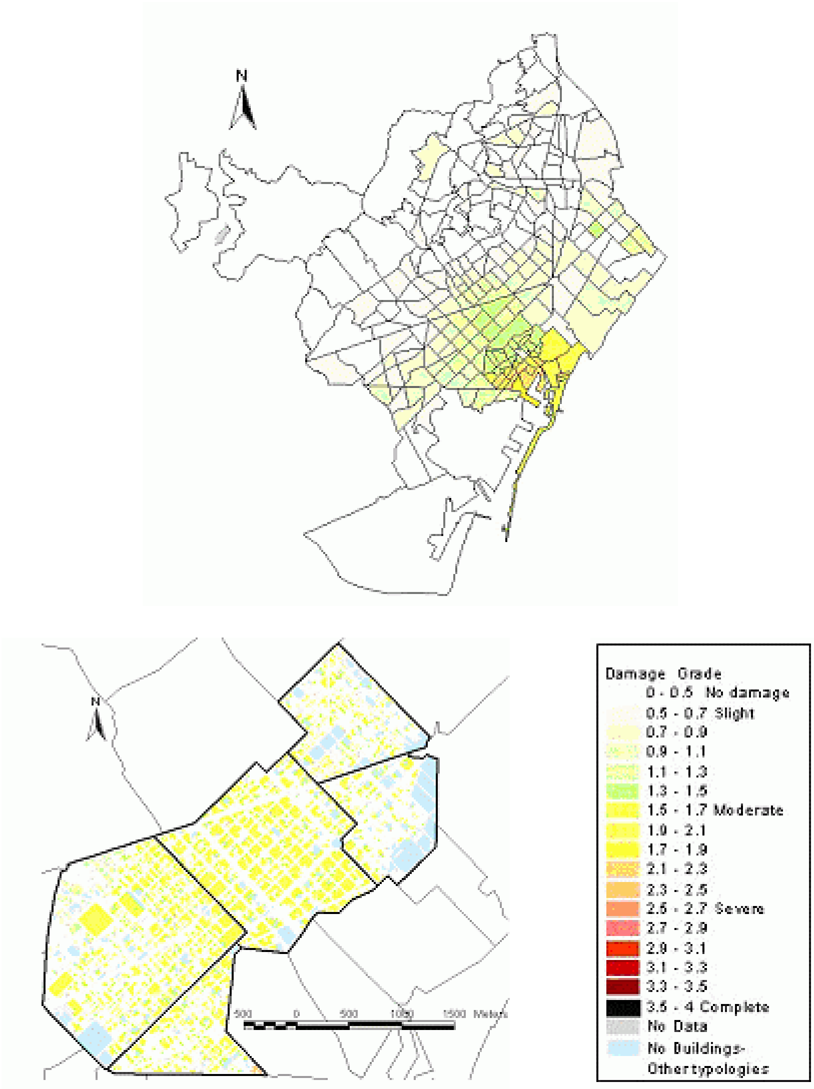

Figure 8. Damage scenario for census areas. A detail of the Eixample district is standed out (Fragility curves method).

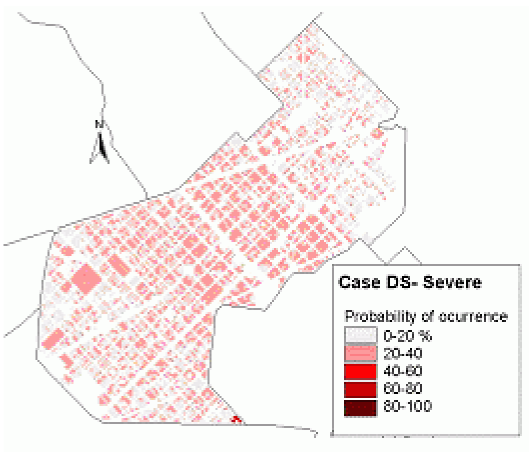

Figure 9. Probabilities of the *Severe* damage state in the Eixample District. (Fragility curves method)

DISCUSION AND CONCLUSIONS

In this paper we have implemented a GIS tool to obtain seismic risk scenarios in urban areas and we have analysed the case of Barcelona (Spain). Really it has been possible because of the great amount of information available about the seismic hazard of the city and the typology, age and other characteristics of almost the complete stock of buildings of the city. Our tool easily admits two methods. In the first one the seismic action is considered by means of e.g. EMS intensity and the fragility of the buildings is modelled by vulnerability indices. The second method uses fragility curves and requires determining the *Sa* or *Sd* parameters, in order to get the damage state probabilities, and therefore, it requires the computation of fragility curves, the capacity and demand spectra, and, finally the performance point. Therefore the first method requires less information and admits rough simplifications about both the seismic input and the vulnerability of the buildings. The second one is more advanced but requires more information about the seismic action (we really need response spectra) and about the buildings. Both the fragility curves and the capacity spectra require detailed structural plans and other design and construction details. Therefore, we feel that the results obtained by using the second method are more reliable.

Any way, in spite of the differences in the results shown in figures 6 and 8, we may say that both methods provide excellent results, showing an excellent correlation with the main features of the built-up environment of the city. It is clear in both cases that a city, like Barcelona, located in a low to moderate hazard region has paid no attention to the seismic performance of their buildings, and therefore it is expected a high seismic vulnerability and a considerable risk. In fact, the expected damage for a VI EMS intensity earthquake, would be close to the damage that seismic intensity scales anticipate for a VII intensity grade.

Another interesting feature of our seismic scenarios is their ability to draw the main characteristics of the built-up environment of the city, underlying the radial pattern of the damage. Downtown, where the population density is higher and the economy is more active, we find the highest vulnerability and damage.

The methods here described and the GIS tool here developed may be easily adapted to outline risk scenarios for other cities. Probably most of the vulnerability indices adopted for Barcelona, may be slightly modified and directly used for obtaining risk scenarios for other cities of Spain and, in particular, for those situated in the Mediterranean region. The application of the fragility curves method would need more data and more work.

Really the ability of GIS tools to store, manage, analyze, and display the large amount of spatial and tabular data involved in this kind of studies allows to map detailed and complete damage scenarios which may be used for emergency planning and civil protection. In the case here presented, final maps can be obtained at several detail levels: districts, neighborhoods, census areas and even for individual buildings. However it is important to have in mind the probabilistic meaning of the results.

ACKNOWLEDGEMENTS

The civil protection department of the Barcelona Municipality has provided most of the information and data used in this study. Sonia Giovinazzi and Sergio Lagomarsino, at the University of Genoa, have developed the methodology and guidelines of the vulnerability index method we have applied here. This work has been partially supported by the European Community Risk-UE project (Contract N. EVK4-CT-2000-00014) by the Science and Technology Ministry of Spain (Contracts N. REN2000-1740-C05-01 RIES, REN2001-2418-C04-01/RIES and REN2002-03365/RIES) and by the Civil Engineering School of Barcelona (UPC).

REFERENCES

1. Lantada, N. y Nuñez, M.A., Sistemas de Información Geográfica. Prácticas con ArcView. Politext. Barcelona: Edicions UPC, 2002. 1-226.
2. RISK-UE: An advanced approach to earthquake risk scenarios with applications to different European towns (Contract number EVK4-CT-2000-00014). 2003.
3. Grünthal, G., European Macroseismic Scale 1998: Cahiers du centre Européen de Géodynamique et Séismologie. Vol. 15. Luxemburg: G. Grünthal, 1998.
4. NCSE-02, Norma de Construcción Sismorresistente Española. Parte General y de Edificación, Comisión Permanente de Normas Sismorresistente, Real Decreto 997/2002 del 27 de septiembre de 2002, Boletín Oficial del Estado, 244, viernes 11 de 0ctubre de 2002. Ministerio de Fomento, 1994: 35898-35987.
5. Cid, J., Susagna, T., Goula, X., Chavarria, L., Figueras, S., Fleta, J., Casas, A., and Roca, A., Seismic Zonation of Barcelona Based on Numerical Simulation of Site Effects. Pure Applied Geophysics, 2001. 158.
6. Secanell, R., Avaluació de la perillositat sísmica a Catalunya: anàlisi de sensibilitat per a diferents models d'ocurrència i paràmetres sísmics., Tesis doctoral. Universidad de Barcelona. Barcelona, 1999: 335.
7. Alfaro, A.J., Estimación de periodos predominantes de los suelos de Barcelona a partir de microterremotos. UPC: Barcelona, 1997: 70.
8. Irizarry, J., Goula, X., and Susagna, T., Seismic Hazard Assesment for the City of Barcelona. Insitut Cartogràfic de Catalunya: Barcelona, 2002: 95.
9. Ambraseys, N.N., Simpson, K.A., and Bommer, J.J., Prediction of horizontal response espectra in Europe. Earthquake Engineering and Structural Dynamics, 1996. 25: 375-400.
10. Giovinazzi, S. and Lagomarsino, S. A methodology for the vulnerability analysis of built-up areas. in X National Conference on Earthquake Engineering. Potensa (Italy), 2001
11. Corsanego, A. and Petrini, V., Evaluation criteria of seismic vulnerability of the existing building patrimony on the national territory, Seismic Engineering. Vol. 1, 1994. 16-24.
12. Giovinazzi, S. and Lagomarsino, S., WP04:Guidelines for the implementation of the I level methodology for the vulnerability assessment of current buildings. Risk-UE Project: Genoa (Italy), 2002.
13. Moreno, R., Lantada, N., Bonett, R., Barbat, A.H., and Pujades, L.G., WP4: Vulnerability assessment of current buildings. Capacity and Fragility of the Barcelona's residential buildings. CIMNE: Barcelona, 2003: 14.
14. FEMA., HAZUS 99 Estimated annualised earthquake losses for the United States. Federal Emergency Management Agency (FEMA): Washington, 2000.