URBAN SEISMIC RISK EVALUATION THROUGH GIS TECHNIQUES. APPLICATION TO BARCELONA CITY,SPAIN

N. Lantada[1], **L.G. Pujades**[1] and **A.H. Barbat**[2]

[1] *Professor, Dept. of Geotechnical Engineering and Geosciences, Technical University of Catalonia, Barcelona, Spain.*
[2] *Professor, Dept of Structural Mechanics, Technical University of Catalonia, Barcelona, Spain.*

Email: lluis.pujades@upc.edu

ABSTRACT :

This study contributes to the development and application of the seismic risk assessment in big cities. It has been structured into two parts. The first part details the model to evaluate the physical damage on residential buildings and their impact on the population and population-related aspects. The second part describes its application to Barcelona. The method, namely Vulnerability Index, defines five damage states; the action is expressed in terms of the macro-seismic intensity and the seismic quality of the buildings by means of a vulnerability index. In order to apply this method to Barcelona a deterministic and a probabilistic scenario are used. A powerful and versatile tool based on Geographic Information Systems (GIS) was created. Throughout the years, detailed information on the design of buildings has been obtained by collecting and completing the database of the dwellings of the city of Barcelona. The results obtained showed the peculiarities of individual buildings and were consistent with the historical evolution of the populated city and with the characteristics of soils, thus establishing the solidity of this method. The damage to the population is significant and its evaluation strongly depends on casualty models. In this sense, it is necessary to consider the specific numerical values as a prediction of the order of magnitude of the evaluated quantities. The obtained results and conclusions offer a great opportunity to guide the action and decision making in seismic risk prevention and mitigation in big cities.

KEYWORDS: Risk scenarios, GIS, building's vulnerability, damage probability assessment, loss estimation

1. INTRODUCTION

The exponential increase in the world's population, together with the growth of big cities, which is characterized by the inadequate occupancy of the soil, contributes augment the expected damage due to seismic catastrophes. The high concentration of population, buildings, infrastructures and valuables exposed, turn these zones into high risk areas. The major part of losses and casualties due to earthquakes has its origin in the deficient seismic behaviour of structures.

2. VULNERABILITY AND DAMAGE EVALUATION

The vulnerability index method, in its version developed in the framework of the European project Risk-UE (Mouroux et al., 2004), has been applied in this article to evaluate the seismic risk for the city of Barcelona (Spain). This method, also called "macro-seismic method", is based on observed damage data and on the European Macro-seismic Scale EMS'98 classification of buildings (Grünthal, 1998). It considers five non null damage states labelled as *Slight, Moderate, Substantial to Heavy, Very Heavy and Destruction*, The seismic action is defined in terms of macro-seismic intensity and the building by means of a vulnerability index.

The VIM method classifies each building in similar seismic behaviour classes and identifies a Vulnerability

Index V_I from each class. Its values are normalized taking values between 0 for high seismic resistance buildings, and 1 for most vulnerable buildings. Further refinements of this index come from a regional modifier, and from two kinds of behaviour modifiers: the *building modifiers* refer to the isolated building and quantify properties such as the number of floors, the length of the façade, the preservation state, horizontal and elevation irregularity; and the *location modifiers* take into account those characteristics of the building referring to the aggregate they belong to. Therefore, for instance, the difference in height between adjacent buildings is taken into account, as well as their position in the aggregate or block they belong to.

The estimated mean damage grade, μ_D, permits to characterize completely the expected damage for a building, and it is measured by a semi-empirical function (Eqn. 2.1.) depending on the intensity I, and the vulnerability index V_I (Giovinazzi and Lagomarsino, 2002):

$$\mu_D = 2.5\left[1+tanh\left(\frac{I+6.25\cdot V_I\text{ -}13.1}{2.3}\right)\right] \tag{2.1}$$

The probabilities of damage states are obtained estimating a binomial or beta-equivalent probability distribution. Then, a weighted mean damage index, DS_m, can be calculated by using the following equation:

$$DS_m = \sum_{k=0}^{5} k\cdot P\left[DS_k\right] \tag{2.2}$$

where k takes the values 0, 1, 2, 3, 4 and 5 for the damage state k considered in the analysis and $P[DS_k]$ represents the corresponding probabilities of occurrence for the damage state k. This damage index is equivalent to the mean damage grade, μ_D, and It can be considered that is close to the most likely damage state of the structure. DS_m , as well as μ_D , is useful for mapping and analyzing damage distributions by using a single parameter.

3. IMPACT ON THE POPULATION

The direct physical damage is the starting point for other aspects of risk, such as damage to population, as well as to the economical and social system functions of the city. ATC-13 (1985), Coburn and Spence (2002) or Vacareanu et al. (2004) provide models to incorporate to the physical risk analysis, the number of casualties and deaths, homeless population and the economic cost, among others. These models, in general, use empirical functions, developed starting from observed data during past earthquakes and are usually based on the knowledge of the occurrence probabilities of the physical damage state.

3.1. Casualties

To evaluate the expected number of deaths and injured people, the casualty model given by Coburn and Spence (2002) has been applied:

$$K_S = C\cdot\left[M1\cdot M2\cdot M3\cdot\left(M4+M5\cdot\left(1-M4\right)\right)\right] \tag{3.1}$$

In this equation, K_S is the number of casualties; C is the number of collapsed buildings, evaluated by summing, for all building classes, the number of buildings of the class multiplied by the very heavy and destruction damage state or collapse probability; $M1$ is the occupancy rate, that is, the number of inhabitants per building; $M2$ is the occupancy at time of earthquake; $M3$ is the percentage of occupants trapped by collapse; $M4$ is the percentage of fatalities among the trapped persons during the earthquake and strongly depends on the building typology; finally, $M5$ represents the post-collapse mortality. The cases of light injured people, injuries requiring hospitalization, the life threatening cases and the death people are considered here as different cases of casualties.

3.2. Homeless

The model proposed by Risk-UE European Project and applied in this study to compute the number of uninhabitable dwelling units and the number of displaced households is based on HAZUS'99 (FEMA/NIBS, 1999). The number of uninhabitable dwelling units due to structural damage is determined by combining: a) the number of uninhabitable dwelling units due to actual structural damage, and b) the number of damaged units that are perceived to be uninhabitable by their occupants. Therefore, the total number of uninhabitable units (UNU$_{SD}$) due to structural damage is calculated by the following relationship:

$$\begin{aligned} \%MF &= w_{MFH} \times \%MF_{H} + w_{MFVH} \times \%MF_{VH} + w_{MFD} \times \%MF_{D} \\ UNU_{SD} &= MFU \times \%MF \end{aligned} \tag{3.2}$$

Where %MF$_H$, %MF$_{VH}$ and %MF$_D$ are, respectively, the damage state probability for *substantial to heavy*, *very heavy* and *destruction* structural damage state in the multi-family residential occupancy class. The values of weighting factors are 1.0 for w$_{MFD}$ and w$_{MFVH}$, and 0.9 for w$_{MFH}$. And MFU is the total number of multi-family dwelling units.

The total number of persons displaced from each building with a given typology (P_{UNU}), is then obtained with Eqn. 3.3., where P_h is the number of persons who are assumed to live in each household of the building:

$$P_{UNU} = P_h \cdot UNU_{SD} \tag{3.3}$$

4. APPLICATION TO AN URBAN AREA

The Vulnerability Index Method (VIM), proposed by the Risk-UE Project has been applied in this article to evaluate the seismic risk for the city of Barcelona (Spain).

4.1. The city of Barcelona and its housing buildings

Barcelona is the second city of Spain after Madrid and it is located on the north of the Mediterranean coast, a low to moderate seismic hazard area. According to the Statistics Institute of Catalonia, it concentrated about 1.606 million inhabitants and an average density of 15,903 inhabitants per square km in 2006. And it had 757,928 housing units and 75,932 residential buildings, with an average of about 2.53 inhabitants in each according the 2001 population census.

Barcelona is divided into 10 districts. Each district consists of a small number of neighbourhoods that sum up to 38 for the entire city. Each neighbourhood is subdivided into census zones (238 in total), as these zones constitute the basis for the census (Figure 1). These zones are composed by a set of blocks and are used for administrative purposes.

A great amount of information about its residential buildings has been collected along years by the Municipality of the city. Afterwards the Technical University of Catalonia integrated this data in a GIS and completed it with the geometrical, structural, uses and constructive and situation characteristics of the housing buildings of the city. The development of reliable risk scenarios for Barcelona has been possible thanks to the details and quality of this GIS.

There are two main structural typologies representing about 97% of residential buildings in Barcelona. The most representative corresponds to un-reinforced masonry buildings. This building type was designed only for vertical static loads, without any consideration of seismic design criteria. According to the Building Typology Matrix (BTM) proposed by Risk-UE, codes M31, M32, M33 y M34 correspond to masonry buildings with the following types of floors respectively: wooden, masonry, vaults and steel beams with masonry vaults. The second building class are reinforced concrete structures with irregular structural system

(RC32 code), without moment-resisting frames, but typically column and slab buildings in their waffled-slab-floor version. In addition, many of these buildings have soft first storeys (Barbat et al., 2006; 2008). Almost 80% of this building stock was built prior to the first Spanish Seismic Code (PGS-1, 1968). In general, buildings are part of aggregates, forming building blocks.

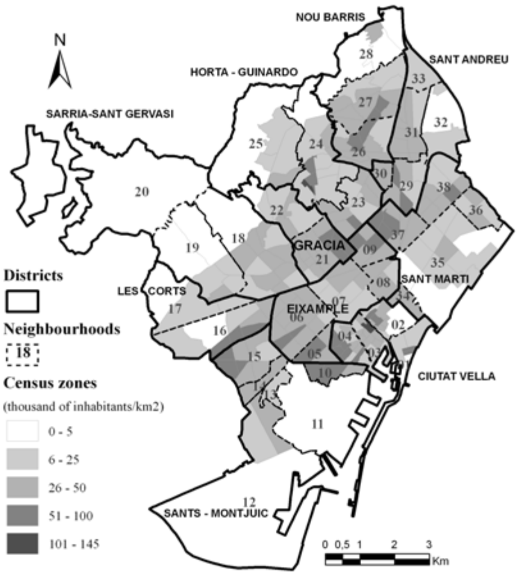

Figure 1 Administrative zones of Barcelona. Population density is also shown. Numbers in this Figure correspond to the 38 neighbourhoods.

4.2. Earthquake scenarios

In order to apply the VIM method to Barcelona a deterministic and a probabilistic scenario are used. In both assessments the effects of soils are taken into account by means of the seismic micro-zoning of the city of Barcelona performed by Cid et al.(2001) and based on the simulation of local effects.

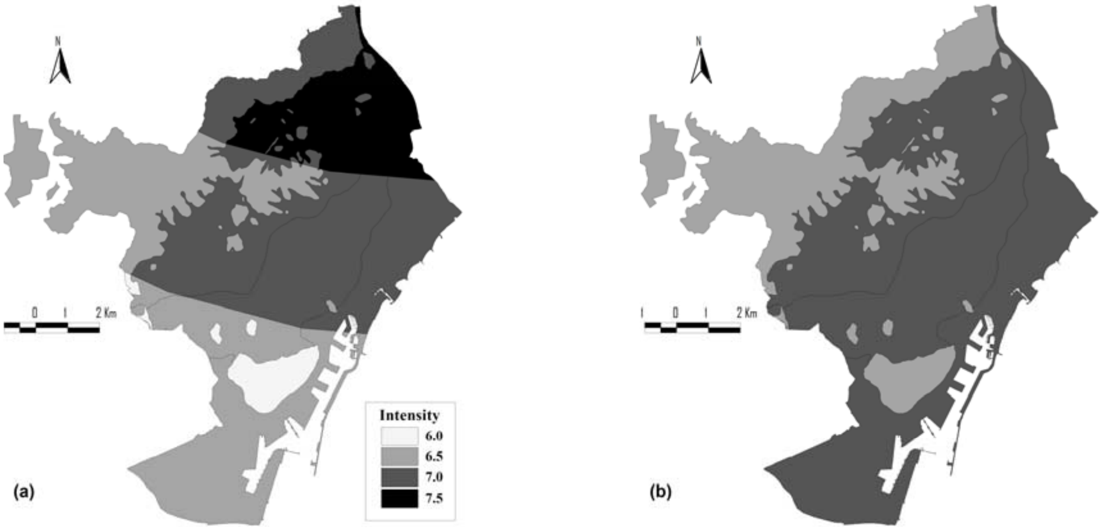

Figure 2. Earthquake scenarios: a) deterministic and b) probabilistic.

Figure 2a shows the deterministic earthquake scenario map based on the historic earthquake occurred in 1448 in *Cardedeu* (local magnitude of 5.5), 25 km away from Barcelona and with a focal depth of 7 km (Irizarry, 2004). The effect of seismic attenuation is observed southwards and the soil effects amplify the signal eastwards, towards the sea front. For this scenario, Intensities in Barcelona vary from VI, in the rock outcrops of *Montjuïc,* to VIII, northeast of the city, in soft soils zones closer to the epicentre.

The probabilistic earthquake scenario is based on the ground motion with a 10% probability in 50 years, equivalent to an earthquake with an intensity of VI to VII MSK in the rock outcrops (Secanell et al., 2004). In this case, intensities vary between VII, in rocky outcrops zones, and VIII in deltaic and coastal soft soils. Figure 2b shows this probabilistic hazard scenario in terms of intensity taking into account the zoning of the soils.

4.3. Seismic risk

4.3.1. Physical damage

The vulnerability indexes obtained for masonry buildings have values from 0.7 to almost the unit, with a mean value of 0.87, while indexes for reinforced concrete buildings are smaller, ranging between 0.4 and 0.85 (mean value of 0.65).

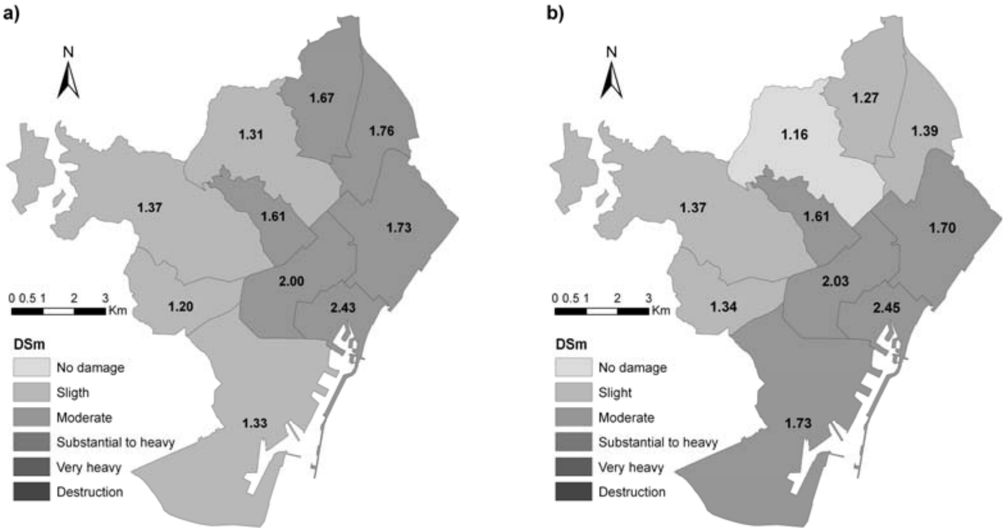

Figure 3 Distribution of mean damage state (*DSm*) among districts: a) deterministic scenario and b) probabilistic scenario.

The mean damage grade for the entire city is 1.65 and 1.59 for the deterministic and the probabilistic scenarios, respectively (Figure 3), which correspond to a moderate damage state.

4.3.2. Damage to population

The factor M1 in Eqn. 3.1., that is, the number of inhabitants per building, has been calculated for each census area and for each type of building. The occupancy rate M1 has been re-evaluated by assuming that reinforced concrete buildings contain more dwellings and therefore more people because of its bigger size. Attending the total floor area of masonry and reinforced concrete buildings, reasonable weights of 45% and 55% were assumed for masonry and concrete buildings, respectively. The results obtained (Figure 4) correspond to night scenarios, with occupancy at time of earthquake of 80% for residential buildings (*M2* parameter in Eqn. 3.1.).

Table 4.1 Summary of damage to population by districts.

	Deterministic hazard scenario			Probabilistic hazard scenario		
Districts	Fatalities	Injured	Homeless	Fatalities	Injured	Homeless
Ciutat Vella	110	333	18896	466	1384	35328
Eixample	249	800	22632	1339	4169	64612
Sants-Montjuïc	169	544	14522	516	1578	30872
Les Corts	69	223	3180	235	751	7945
Sarrià-StGervasi	13	37	5100	369	1169	17751
Gràcia	38	120	7125	325	999	21135
Horta-Guinardó	13	37	5727	241	757	15752
Nou Barris	13	41	6528	389	1249	17156
Sant Andreu	68	219	5205	366	1158	17395
Sant Martí	493	1603	19416	1126	3622	33322
Total	1235	3957	108331	5372	16836	261268

Figure 4 Distribution of injured people: a) deterministic and b) probabilistic scenarios.

In general, we obtain higher values for casualties and injured people for the deterministic scenario. The *Sant Martí* district shows the highest values in both scenarios (Table 4.1.). This area contains a high amount of low quality high-rise reinforced concrete buildings, representative of the outer suburbs in big industrial cities and with a class and cost below the average of the city. All this aspects increase their vulnerability.

5. CONCLUSIONS

The seismic risk for current residential buildings in Barcelona city has been evaluated using the Vulnerability Index Method defined within the Risk-UE Project (VIM). Reasonably expected seismic actions have been considered in terms of intensity. Two earthquake scenarios have been considered including soil effects. These two seismic scenarios have been constructed according to a deterministic and a probabilistic point of view. Intensities vary from VI to VII-VIII for the deterministic approach and from VII to VII-VIII for the probabilistic one.

The results obtained are coherent with the historical evolution of the city and with its current state, as well as with the characteristics of the soils, which demonstrates the solidity of the method. Generally, we obtain a radial structure of the expected damage, showing greater damage in the downtown (*Ciutat Vella* district) and lesser damage in the outskirts. For the deterministic and probabilistic scenarios, the global average damage state is moderate.

L'Eixample district stands out for showing the highest risk due to the vulnerability of its buildings, to its high buildings and population density and also due to the valuables exposed. It is well demonstrated that, in cities like Barcelona, located in low-to-moderate seismic regions, the scarce-to-inexistent awareness of seismic hazard and the absence of seismic protection measures lead to the high vulnerability of buildings and, thus, to considerable risk. In fact, significant damage is expected for relatively moderate scenarios, with intensities ranging from VI to VII. Expected damage to population is significant but its evaluation strongly depends on casualty models.

A significant contribution of this research is the creation of a powerful and versatile tool, whose design is based on Geographic Information Systems (GIS). This GIS application allows integrating, exploitation and managing a great amount of geo-referenced data. We are able generating any other kind of information useful to evaluate expected physical damage and other aspects related to seismic risks in great cities. On the other hand, this type of software is essential to map spatial scenarios, which are useful to highlight and discriminate the strong and weak points of the social and residential urban network. In fact, this tool go beyond the specific application here described, as it can be updated fast and is easily adapted to the study of other types of risk in the same or in other cities. Finally, in the case of Barcelona, the quality of data allowed a great resolution of results, thus being able obtaining damage scenarios "à la carte".

The scenarios analyzed, the results obtained and the conclusions and suggestions gathered in this study offer a great opportunity to guide the action and decision making in the field of seismic risk prevention and mitigation in Barcelona. We have developed a useful tool for planning, optimizing and managing the civil response to an eventual seismic emergency. However, given the high uncertainties involved in these methods and models, it is worth mention that the specific numerical values have to be carefully interpreted and, in any case, they should be interpreted, from a probabilistic point of view, as average values expected for credible seismic scenarios.

ACKNOWLEDGEMENTS

This work has been partially sponsored by the Spanish Ministry of Education and Science and with FEDER funds (projects: CGL2004-22325-E, CGL-2005-04541-C03-02/BTE, HABITAT 2030-PSS-380000-2005-14 and SEDUREC-CSD2006-00060) and by the European Commission (RISK-UE Project -EVK4-CT-2000-00014).

REFERENCES

ATC-13 (1985). *Earthquake damage evaluation data for California, ATC-13*, Applied Technology Council. Redwook City, California.

Barbat, A. H., Pujades, L. G. and Lantada, N. (2006). Performance of buildings under earthquake in Barcelona, Spain. *Computer-Aided Civil and Infrastructure Engineering*, **21**, 573-593.

Barbat, A. H., Pujades L. G. and Lantada, N. (2008). Seismic damage evaluation in urban areas using the capacity spectrum method: application to Barcelona. *Soil Dynamics and Earthquake Engineering,* special issue *Urban earthquake risk and damage assessment,* **28: 10-11**, 851-865 (doi: 10.1016/j.soildyn.2007.10.006).

Cid, J., Susagna, T., Goula, X., Chavarria, L., Figueras, S., Fleta, J., Casas, A. y Roca, A. (2001). Seismic Zonation of Barcelona Based on Numerical Simulation of Site Effects. *Pure Applied Geophysics* **158,** 2559-2577.

Coburn, A. and Spence, R. (2002). *Earthquake Protection*, John Wiley & Sons, Chichester, UK.
Departament d'Estadistica. (2007). *La població de Barcelona, 2006.* Ajuntament de Barcelona, Barcelona (in catalan).

FEMA/NIBS. (2002). Earthquake *Loss Estimation Methodology, HAZUS-99 Service Release 2 (SR2)* Technical Manual. National Institute of Building Sciences for the Federal Emergency Management Agency, Washington, D.C.

Giovinazzi, S. y Lagomarsino, S. (2002). WP04: Guidelines for the implementation of the I level methodology for the vulnerability assessment of current buildings. Genoa (Italy).
Grünthal, G. (1998). *European Macroseismic Scale 1998.* Centre Européen de Géodynamique et de Séismologie, Luxemburg.

Irizarry, J. (2004). *An Advanced Approach to Seismic Risk Assessment. Application to the Cultural Heritage and the Urban System Barcelona*. PhD Thesis, Universitat Politècnica de Catalunya, Barcelona (Spain).

Mouroux, P., Bertrand, M., Bour, M., Brun, B. L., Depinois, S., Masure, P. and Risk-UE team (2004). *The European Risk-UE Project: an advanced approach to earthquake risk scenarios.* Proceedings of the 13th World Conference Earthquake Engineering, Vancouver B.C (Canada), CD-ROM, Paper No. 3329.

PGS-1 (1968). *Decreto 106/1968, de 16 de enero, por el que se aprueba la aplicación de la «Norma Sismorresistente PGS 1 (1968), parte A»*. Presidencia del Gobierno. BOE 30/1968.

Secanell, R., Goula, X., Susagna, T., Fleta, J. y Roca, A. (2004). Seismic hazard zonation of Catalonia, Spain integrating uncertainties. *Journal of Seismology* **8: 1,** 24-40.

Vacareanu R., Lungu, D., Aldea, A. and Arion, C. (2004). *WP07. Report Seismic Risk Scenarios Handbook*, Risk-UE Project, Bucarest.