Probabilistic Seismic Risk Assessment of Barcelona, Spain

Omar D. Cardona[1], Mabel C. Marulanda[2], Martha L. Carreño[2], and Alex H. Barbat[2]

[1]*National University of Colombia, Manizales, Colombia*
[2]*International Center for Numerical Methods – CIMNE, Technical University of Catalonia, 08034, Spain*

Summary

Understanding disaster risk due to hazard events, such as earthquakes, creates powerful incentives for countries to develop planning options and tools to reduce potential damages. The results of the seismic risk assessment of the city of Barcelona using CAPRA (Comprehensive Approach for Probabilistic Risk Assessment) presented in this paper involve the evaluation of probabilistic losses of the exposed elements using probabilistic metrics, such as the exceedance probability curve, the expected annual loss and the probable maximum loss, which are useful for multi-hazard/risk analyses. The outcomes obtained with techno-scientific methodologies like CAPRA are oriented to facilitate decision-making. Using CAPRA, it is possible to design risk transfer instruments; evaluation of probabilistic cost-benefit ratio, to consider the net benefits of risk mitigation strategies; land use planning, loss scenarios for emergency response, early warning, on-line loss assessment mechanisms and holistic evaluation of disaster risk based on indicators. These applications facilitate the integrated risk management by the different stakeholders involved in risk reduction decision-making.

KEYWORDS: probabilistic seismic risk assessment, average annual loss, pure premium, loss exceedance curve.

1. INTRODUCTION

A disaster is the materialization of existent risk conditions. The risk level of a society is related to its development achievements and its capacity to intervene the existing risk. Hence, urban planning and efficient strategies are necessary to reduce risk and improve sustainable development. Risk management is a fundamental development strategy that considers four principal policies: risk identification, risk reduction, disaster management and risk transfer.

From the financial point of view, it is essential to estimate and quantify potential losses in a given exposure time given that the budget for both emergency response and recovery and reconstruction could mean a fiscal exposure and a non explicit contingent liability for governments at city and country levels (Pollner 2001; Andersen 2002). Estimation of contingent losses provides information and permits to set out strategies *ex ante* for reducing or financing them (Marulanda et al 2008a, 2010a; Cardona 2010a; Cardona 2010b). Assessment of potential losses allows budget allocation for structural retrofitting to reduce damages and implementation of effective financial protection strategy to provide loss coverage of public infrastructure and private buildings to protect government resources and safeguard socioeconomic development; in summary, to achieve the greater awareness, security culture and economic prosperity, the financial protection must be a permanent and long term policy (Freeman et al. 2003).

Thus, one of the key strategic activities of disaster risk management is the assessment of the risk of disaster or of extreme events, which requires the use of reliable methodologies that allow an adequate calculation of probabilistic losses in exposed elements. The use of catastrophic risk models and the results obtained from risk analysis make feasible determining the potential deficit existing in case of the occurrence of an extreme event. Catastrophe risk models –based on metrics such as the Probabilistic Maximum Loss or the Average Annual Loss– are used to estimate, building by building, the probabilistic losses of different portfolios of exposed elements.

This paper performs a seismic risk assessment of the city of Barcelona, Spain. The probabilistic methodology Comprehensive Approach for Probabilistic Risk Assessment, CAPRA (Cardona et al. 2010a), is considered to be the most robust for this type of modeling and identifies the most important aspects of catastrophe risk from the financial protection perspective according to the fiscal responsibility of the states.

Vulnerability and risk analysis for Barcelona were developed starting from the seismic hazard information available for the city and the detailed cadastral information provided by the city administration in order to obtain the probable maximum losses (loss exceedance curve) and the pure risk premiums (average annual loss) of each building of the city. These risk metrics help to the knowledge of the contingency liabilities of the public sector and of the economic impact of the private sector, facilitating thus the consideration of risk transfer strategies for financial protection. Additionally, potential scenarios of damage can be obtained with the model, that can be used to develop emergency response plans and to implement risk reduction measures from physical, social and organizational point of view.

2. THE MODEL

The frequency of catastrophic seismic events is particularly low and this is the reason why very limited historical data are available. Considering the possibility of future highly destructive events, risk estimation has to focus on probabilistic models that can use the limited available information to best predict future scenarios and consider the high uncertainty involved in the analysis. Therefore, risk assessments need to be prospective, anticipating scientifically credible events that might happen in the future. The earthquake prediction models use the seismological and engineering bases for its development, allowing the assessment of the risk of loss given a catastrophic event. Since large uncertainties related to the severity and frequency characteristics of the events are inherent in models, the earthquake risk models have to use probabilistic formulations that incorporate this uncertainty into the risk assessment. The probabilistic risk model built upon a sequence of modules (Woo 1999, Grossi and Kunreuther 2005; Cardona et al 2008a/b/c/d), quantifies potential losses arising from earthquake events as shown in the Fig. 1.

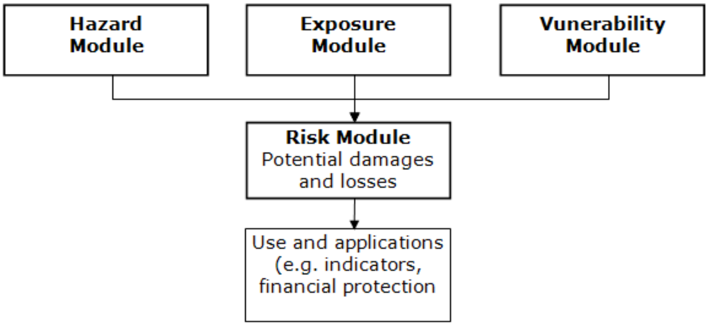
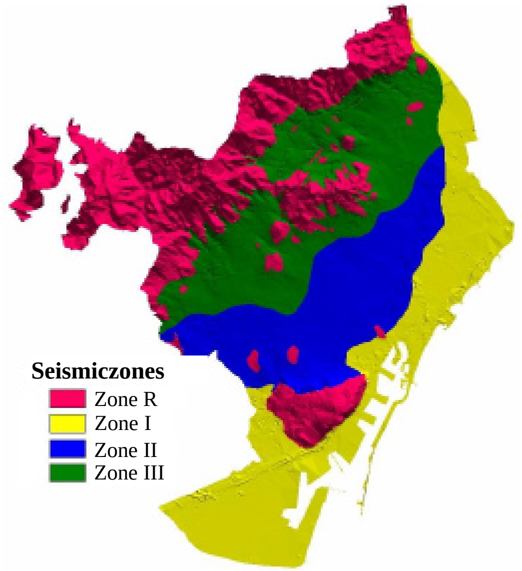


Figure 1.Probabilistic risk model

3. SEISMIC HAZARD MODULE

The hazard module of the probabilistic risk modeldefines the frequency and the severity of a hazard at a specific location. This is completed by analyzing the historical event frequencies and reviewing scientific studies performed on the severity and frequencies in the region of interest. Once the hazard parameters are established, stochastic event sets are generated which define the frequency and severity of thousands of stochastic events. This module can analyze the intensity at a location, once an event of the stochastic set has occurred, by modelling the attenuation of the event between its location and the site under consideration, and evaluates the propensity of the local site conditions to either amplify or reduce the impact. The seismic hazard is quantified in terms of return periods (or exceedance rates) and the module provides the relevant seismic intensities necessary to evaluate the behavior of the structures. Its calculation includes the contribution of the effects of all seismic sources located in a certain influence area.

The application to the city of Barcelona takes into account the seismic sources for the Catalonia region of Spain identified by Secanell et al. (2004). Additionally, it considers the effects of the attenuation of the seismic waves by means of probabilistic spectral attenuation laws that include different source types Ambraseys (1996), as well as the local amplification effects based on microzonation studies. The site effects, considering the amplification of seismic hazard parameters according to the geological characterization of Barcelona, were established by Cid et al (2001) where a transfer function and an amplification factor for the acceleration level at the rock level characterized each zone (see Figure 2).



Soil zone	Vs (m/s)	Eurocode subsoil class
R	225	C
I	384	B
II	405	B
III	800	A

Figure 2. Seismic zonation based on local effects (Cid et al. 2001)

The seismic hazard was simulated by using the CRISIS 2007 code. The code allows estimating the hazard associated to all possible events that can occur, or to a group of selected events, or even to a single relevant event. Using the hazard module, it is possible to calculate the probable maximum value of the intensity, characterized for different exceedance rates or return periods. An .ame file type is created in this module (.ame comes from amenaza –hazard- in Spanish) which includes multiple grids on the area of study, of the different parameters of intensity of the considered phenomena. Each grid is a scenario of the intensity level obtained from historical or stochastic generated events, with their frequency of occurrence. For this case, the parameter of seismic intensity selected is the spectral acceleration.

Further, the desired risk parameters such as percentages of damage, economic losses, effects on people and other effects are evaluated, in a probabilistic framework, for each of the hazard scenarios and then these results are probabilistically integrated by using the occurrence frequencies of each earthquake scenario. For Barcelona, 2058 seismic hazard scenarios were generated.

4. EXPOSURE MODULE

The *exposure* is mainly related to the infrastructure components or to the exposed population that can be affected by a particular event. The exposure module is based on files in *shape* format corresponding to the exposed infrastructure included in the risk analysis. To characterize the exposure, it is necessary to identify the individual components, including their location, their main physical, geometric and engineering characteristics, their vulnerability to hazardous events, their economic value and the level of human occupation that can have in a given analysis scenario. The exposure value of assets at risk is usually estimated from secondary sources such as available databases. The degree of precision of the results depends on the level of resolution and detail of exposure information.

The information used was compiled by Lantada (2007); the economic value of the exposed elements was supplied by the Cadastral Office of Barcelona, and 70655 buildings were considered (Figure 3). They are distributed in 10 municipal districts (Figure 4), 73 neighborhoods, 233 Basic Statistical Areas (in Spanish AEB– Áreas Estadísticas Básicas) and 1061 census sections. For each one of the buildings, the geographic location, economic value, year of construction, number of levels, structural type and human occupation, were defined. In order to proceed with the risk calculations, the results were calculated building by buildings, but they can be presented by considering any geographical level according to the required resolution.

In order to calculate the social impact, the general information related to building occupation is also estimated. Maximum occupancy and occupancy percentage at different hours of the day are also defined, allowing establishing different time scenarios of the event’s occurrence. When no specific occupation information was available, an approximate occupation density by construction class was used to complete the information.

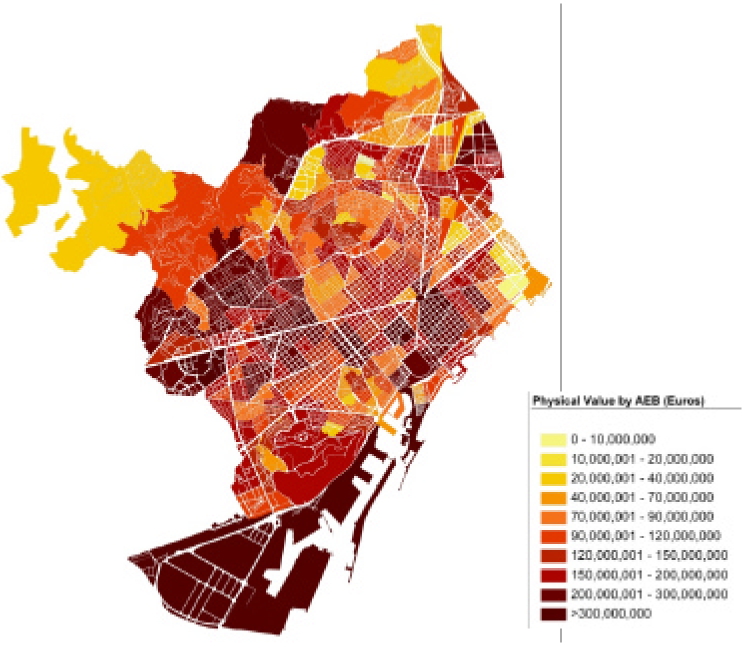


Figure 3. Exposed value of Barcelona by AEBs

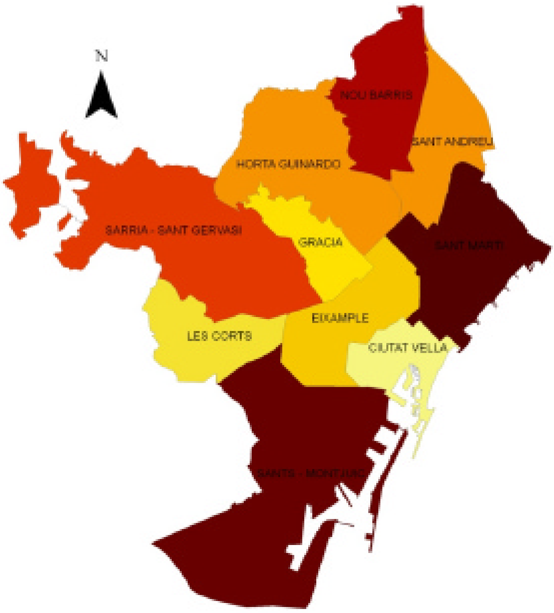


Figure 4. Administrative division of Barcelona

5. VULNERABILITY MODULE

The vulnerability module quantifies the damage caused to each asset class by the intensity of a given event at a site (Miranda, 1999). The classification of the assets is based on a combination of construction material, construction type (i.e. wall & roof combination), building use, number of levels and age. Estimation of damage is performed in terms of the mean damage ratio, MDR, which is defined as the ratio of the expected repair cost to the replacement cost of the structure. A vulnerability curve is defined relating the MDR to the earthquake intensity that can be expressed in terms of maximum acceleration (e.g. useful for 1-2 story buildings), spectral acceleration, velocity, drift or displacement (e.g. useful for multi-story buildings) at each location.

Most part of the building stock of Barcelona was constructed when no seismic-resistant construction codes existed. The combination of very old buildings constructed without seismic code with a highly populated and active produced a high vulnerability which can generate a significant risk even under the effects of a moderate earthquake. The vulnerability module of the ERN-CAPRA platform defines the vulnerability of the buildings in the city by using vulnerability functions. The assignment of the vulnerability function to each exposed element is carried out in the exposure module by means of a shape format file. There is a vulnerability function corresponding to each building typology; the most common structural system used in Barcelona is the unreinforced masonry, followed by the reinforced concrete, whose construction has increased rapidly in recent decades. Steel structures are less used and they are not usually used for residential buildings but for industrial buildings, markets, sports areas, among others. The used typologies were defined in RISK-UE (2004) and are shown in Table 1.

Each structural type is subdivided into 3 classes according to the height:

- *Low, L.* 1 to 2 floors for masonry and wood structures; and 1 to 3 floors for reinforced concrete and steel buildings.
- *Medium, M.* 3 to 5 floors for masonry and wood structures; and 4 to 7 floors for reinforced concrete and steel buildings.
- *High, H.* 6 or more floors for masonry and wood structures; and 8 or more floors for reinforced concrete and steel buildings.

Table 1. Building typology matrix for Barcelona (RISK-UE 2004)

UNREINFORCED MASONRY	M3.1	Unreinforced masonry bearing walls with wooden slabs
	M3.2	Unreinforced masonry bearing walls with masonry vaults
	M3.3	Unreinforced masonry bearing walls with composite steel and masonry slabs
	M3.4	Reinforced concrete slabs
REINFORCED CONCRETE	RC3.1	Concrete frames with unreinforced masonry infill walls with regularly infill frames
	RC3.2	Concrete frames with unreinforced masonry infill walls with irregularly frames (i.e., irregular structural system, irregular infill, soft/weak storey)
STEEL MOMENT FRAMES	S1	A frame of steel columns and beams
STEEL BRACED FRAMES	S2	Vertical components of the lateral-force-resisting system are braced frames rather than moment frames.
STEEL FRAMES WITH UNREINFORCED MASONRY INFILL WALLS	S3	The infill walls usually are offset from the exterior frame members, wrap around them, and present a smooth masonry exterior with no indication of the frame.
STEEL AND RC COMPOSITE SYSTEMS	S5	Moment resisting frame of composite steel and concrete columns and beams. Usually the structure is concealed on the outside by exterior non-structural walls.
WOOD STRUCTURES	W	Repetitive framing by wood rafters or joists on wood stud walls. Loads are light and spans are small.

Figure 5 shows the vulnerability functions used for unreinforced masonry buildings and Figure 6 shows the functions for other building typologies, for low (L), medium (M) and high (H) buildings. These functions relate the severity of the event, represented by the spectral acceleration with the average damage in the building.

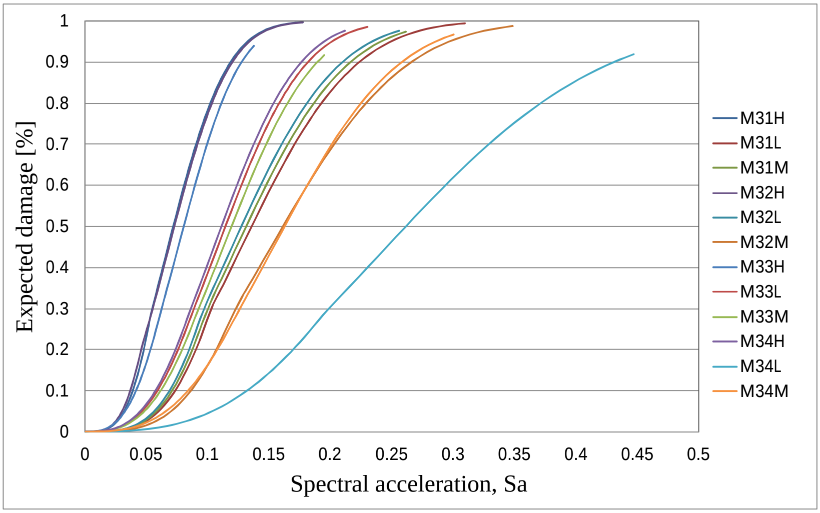


Figure 5. Vulnerability functions for unreinforced masonry buildings

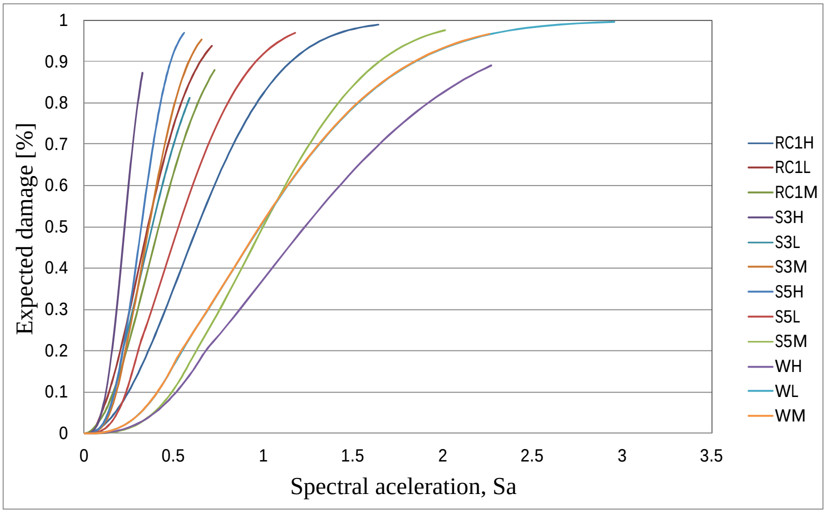


Figure 6. Vulnerability functions for reinforce concrete, steel and wood buildings

6. RISK MODULE

The physical seismic risk is evaluated by means of the convolution of the hazard with the vulnerability of the exposed elements; the results are the potential consequences. Risk can be expressed in terms of damage or physical effects, absolute or relative economic loss and/or effects on the population.

Once the expected physical damage is estimated (average value and its dispersion) as a percentage for each of the assets or infrastructure components included in the analysis, one can make estimates of various parameters useful for the proposed analysis. Risk metrics calculated by using the model provide risk managers and decision makers with essential information required to manage future risks. One measure is the Average Annual Loss and the other is the Loss Exceedance Curve. Other measures, such as the Pure Risk Premium and the Probable Maximum Loss, can be computed based on the former.

- *Average Annual Loss.* AAL is the expected loss per year. Computationally, AAL is the sum of products of event expected losses and event annual occurrence probabilities for all the stochastic events considered in the loss model. In probabilistic terms, AAL is the mathematical expectation of the annual loss.
- *Pure Risk Premium.* PRP is the AAL divided by the replacement value of the asset, usually expressed as a rate per mill of monetary value.
- *Loss Exceedance Curve.* LEC represents the annual frequency with which a loss of any specified monetary amount will be exceeded. This is the most important catastrophe risk metric for risk managers, since it estimates the amount of funds required to meet risk management objectives. The LEC can be calculated for the largest event in one year or for all (cumulative) events in one year. For risk management purposes, the latter estimate is preferred, since it includes the possibility of one or more severe events resulting from earthquakes.
- *Probable Maximum Loss.* PML represents the loss amount for a given annual exceedance frequency, or its inverse, the return period. Depending on the stakeholder's risk tolerance, the risk manager may decide to manage for losses up to a certain return period (e.g. 1 event in 300 years). For that stakeholders (e.g. a public or private agency), the PML is the 300-year loss. For others, it may be 150 years or 500 years. It is noteworthy that it is frequent that certain stakeholders set the insolvency criterion at return periods between 150 years and 200 years. However, other involved stakeholders (e.g. governments or regulation agencies) have chosen much longer return periods, such as the Mexican Insurance Commission, which uses a return period of 1500 years to fix solvency margins of insurance companies in Mexico.

As previously said, the probabilistic risk analysis is done based on a series of hazard scenarios that adequately represent the effects of any event of feasible magnitude that can occur in the area of influence. Each of these scenarios has an associated specific frequency or probability of occurrence. The probabilistic calculation procedure comprises the assessment using appropriate metrics, in this case the economic loss, for each exposed asset considering each of the hazard scenarios with its frequency of occurrence, and the probabilistic integration of the obtained results.

The Average Annual Loss for physical assets, fatalities and injuries are calculated for each building of the city. The probabilistic results for of Barcelona are shown in tables 2, 3 and 4. Figure 7 shows the PML curve obtained for Barcelona. Figure 8 shows the expected annual loss for each AEB of Barcelona. As it was previously mentioned, the expected annual economic loss was calculated building by building and Figure 9 shows the obtained results at this resolution. Figure 10 and Figure 11 show the expected annual loss for injured and deaths by AEB in Barcelona.

Table 2. Physical exposure

PHYSICAL EXPOSURE		
Exposed value	€ $x10^6$	31,522.80
Average Annual	€ $x10^6$	72.14
Loss	‰	2.29‰
PML		
Return period (Years)	Loss	
	€ $x10^6$	%
50	729.35	2.31%
100	1,770.16	5.62%
250	3,699.35	11.74%
500	5,172.26	16.41%
1,000	6,510.67	20.65%
1,500	7,021.14	22.27%

Table 3 Dead people

DEAD PEOPLE		
Exposed value	Inhab.	1,639,880.00
Average Annual	Inhab.	28.27
Loss	‰	0.017‰
PML		
Return period (Years)	Loss	
	Inhab.	%
50	101.41	0.01%
100	654.30	0.04%
250	2,069.97	0.13%
500	3,380.29	0.21%
1,000	4,898.39	0.30%
1,500	5,799.44	0.35%

Table 4. Injured people

INJURED PEOPLE		
Exposed value	Inhab.	1,639,880.00
Average Annual Loss	Inhab.	113.55
	‰	0.07‰
PML		
Return period (Years)	Loss	
	Inhab.	%
50	101.41	0.01%
100	654.30	0.04%
250	2,069.97	0.13%
500	3,380.29	0.21%
1,000	4,898.39	0.30%
1,500	5,799.44	0.35%

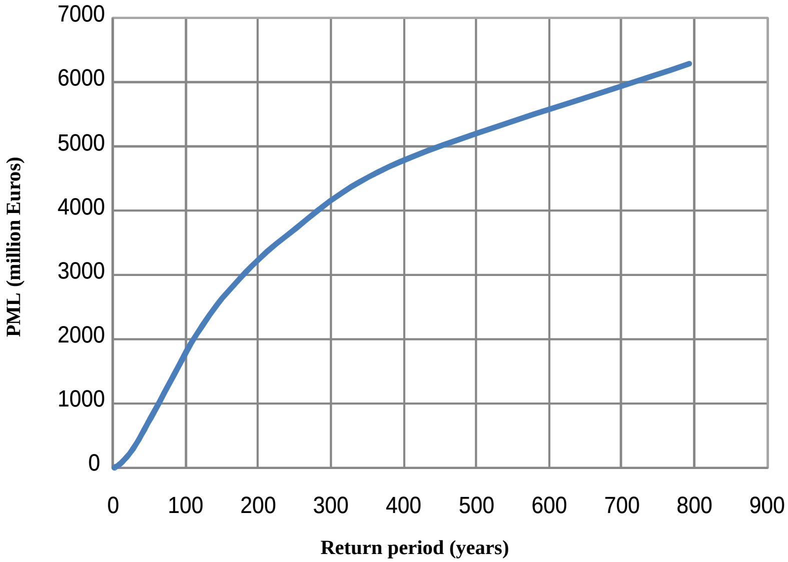


Figure 7. PML curve for Barcelona

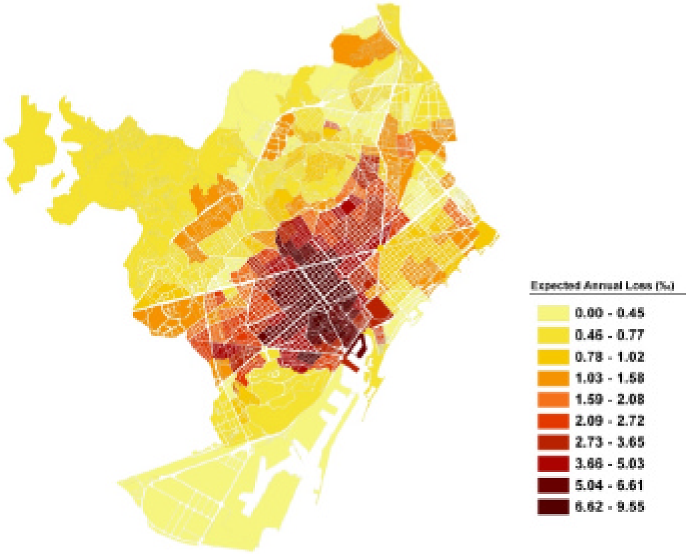


Figure 8. Expected annual loss for the AEBs of Barcelona

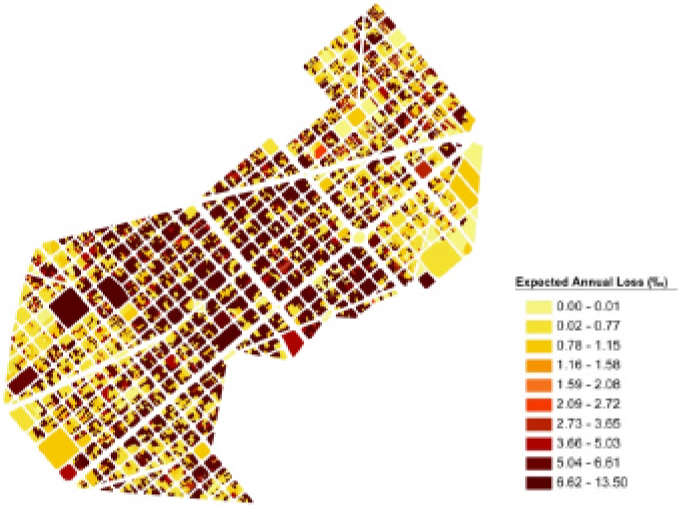


Figure 9. Expected annual loss for each building in the Eixample District of Barcelona

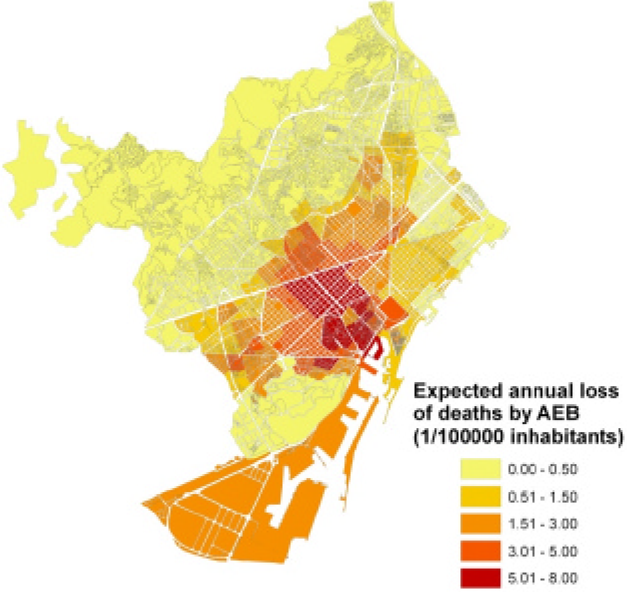


Figure 10. Expected annual loss for deaths by AEB in Barcelona

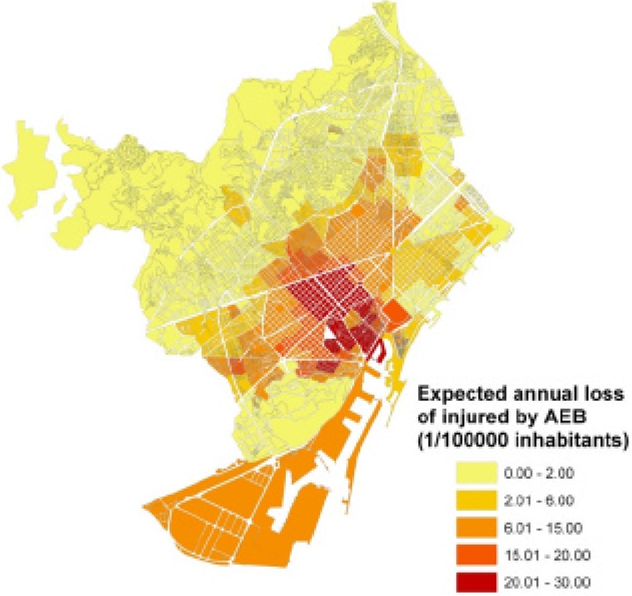


Figure 11. Expected annual loss for injured by AEB in Barcelona

In addition to the probabilistic economic figures, it is also relevant for the emergency response plans of the city to count with critical earthquake loss scenarios. In the case of Barcelona, a critical scenario for a loss with a return period of approximately 1000 years was chosen, to estimate the people that could lose their job or their houses. Assessments of these figures are based on the percentage of damage of each structure (greater than or equal to 20%). Table 6 presents the information of the critical scenario for Barcelona.

Table 6. Information of the critical scenario for Barcelona

Nº	Scenario		Loss	
	Source	Magnitude	€ x10^6	%
600	Zona 4_SF2	6.56	6.78E+03	21

The Figure 12and Figure 13 show the scenarios of homeless and jobless by AEB in Barcelona.

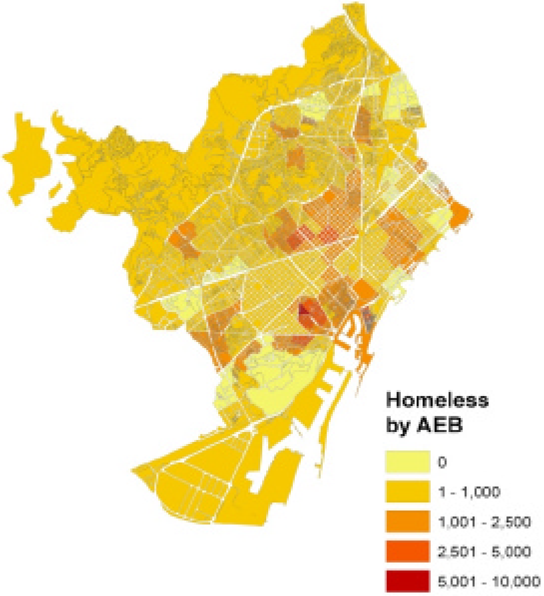


Figure 12. Homeless by AEB in Barcelona.

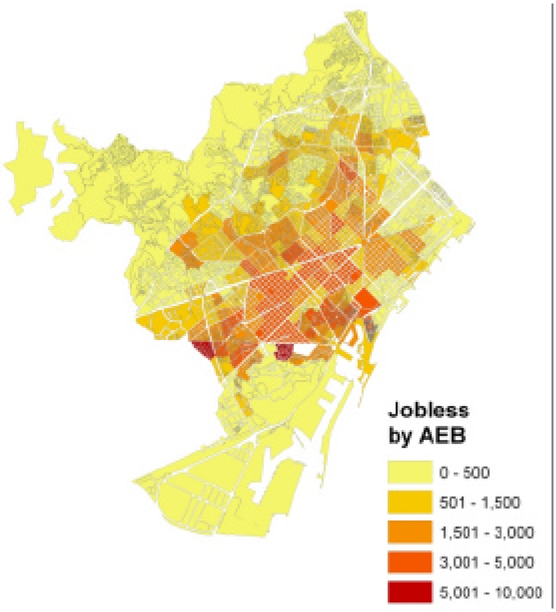


Figure 13. Jobless by AEB in Barcelona.

7. CONCLUSIONS

Catastrophic risks such as earthquake risk impose a dreadful threat not only for private insurers and reinsurers, but also for governments whom, in turn, are risk-takers for most of the uninsured and uninsurable risk. Therefore, seismic risk models become powerful tools for government officials in economic and financial planning institutions. The retention and transfer of risk should be a planned and somewhat controlled process, given that the magnitude of the catastrophic problem could represent a great governmental response and financial liabilities. For management purposes, the risk assessment should improve the decision-making process in order to contribute to the effectiveness of risk management, identifying the weaknesses of the exposed elements and their evolution over time. It is expected that the application in Barcelona will be useful for the risk reduction and emergency preparedness plans in the city.

This study focuses on the risk assessment at urban level (by geographic units) due to the earthquake hazards, using as risk measure the Probable Maximum Loss (PML) for different return periods and the Average Annual Loss (AAL) or technical risk premium. The values of PML and AAL are the main results of this application. These measures are of particular importance for the future design of risk retention (financing) or risk transfer instruments, and therefore they will be a particularly valuable contribution to further studies to define a strategy for financial protection to cover the fiscal liability of the State.

References

1. Ambraseys, N.N., Simpson, K.A. and Bommer, J.J. (1996): "Prediction of horizontal response espectra in Europe". Earthquake Engineering and Structural Dynamics 25: 375-400.
2. Andersen, T. (2002). *Innovative Financial Instruments for Natural Disaster Risk Management*. Inter-American Development Bank. Sustainable Development Department. Technical Papers
3. Barbat, A.H.; Carreño, M.L.; Pujades, L.G.; Lantada, N.; Cardona, O.D. and Marulanda, M.C. (2010).“*Seismic vulnerability and risk evaluation methods for urban areas. A review with application to a pilot area*”. Structure and Infrastructure Engineering. Vol. 6, Nos. 1-2, Taylor & Francis.
4. Cardona O.D., Ordaz, M.G., Reinoso, E., Yamín, L.E., Barbat, A.H. (2010a). *Comprehensive Approach for Probabilistic Risk Assessment (CAPRA): International Initiative for Disaster Risk Management Effectiveness.* in Proceedings of 14th European Conference on Earthquake Engineering, August 2010, Ohrid, Macedonia.
5. Cardona O.D., Marulanda, M.C. (2010b). *Mecanismos Financieros, Seguro y Reaseguro contra Desastres Naturales en América Latina y el Caribe: Experiencias Recientes.* Secretaría Permanente del Sistema Económico Latinoamericano y del Caribe, SELA, SP/SR-IPMFSRCDALC/DT Nº 2-10, Caracas. Available at: http://www.sela.org/attach/258/EDOCS/SRed/2010/11/T023600004489-0-TDR_Estudio_Seguro_contra_Desastres_ALC_2010_REV-ODC.pdf
6. Cardona, O.D., Ordaz, M.G., Marulanda, M.C., & Barbat, A.H. (2008a). Estimation of Probabilistic Seismic Losses and the Public Economic Resilience—An Approach for a Macroeconomic Impact Evaluation, *Journal of Earthquake Engineering*, 12 (S2) 60-70, ISSN: 1363-2469 print / 1559-808X online, DOI: 10.1080/13632460802013511, Taylor & Francis, Philadelphia, PA.
7. Cardona, O.D., Ordaz, M.G., Yamín, L.E., Marulanda, M.C., & Barbat, A.H. (2008b). Earthquake Loss Assessment for Integrated Disaster Risk Management, *Journal of Earthquake Engineering*, 12 (S2) January 48-59, ISSN: 1363-2469 print / 1559-808X online, DOI: 10.1080/13632460802013495, Taylor & Francis, Philadelphia, PA.
8. Cardona, O.D., Ordaz, M.G., Marulanda, M.C., Barbat, A.H. (2008c). Fiscal Impact of future earthquakes and country’s economic resilience evaluation using the disaster deficit index, *Innovation Practice Safety: Proceedings 14th World Conference on Earthquake Engineering, Beijing*, China.
9. Cardona, O.D., Ordaz, M.G., Yamin, L.E., Arámbula, S., Marulanda, M.C., Barbat, A.H. (2008d). Probabilistic seismic risk assessment for comprehensive risk management: modeling for

innovative risk transfer and loss financing mechanisms, *Innovation Practice Safety: Proceedings 14th World Conference on Earthquake Engineering,* Beijing, China.

10. 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.
11. Cid J. (1998). Zonación sísmica de la ciudad de Barcelona basada en métodos de simulación numérica de efectos locales. Tesis doctoral. Dpto. Ingeniería del Terreno, Cartográfica y Geofísica. Universidad Politécnica de Cataluña, Barcelona. 215 pp.
12. Freeman, P., Keen, M and Muthukumara, M. (2003). Dealing with Increased Risk of Natural Disasters: Challenges and Options. IMF – International Monetary Fund. Working Paper 03/197.
13. Grossi P. & Kunreuther H. (2005). Catastrophe modeling: A new approach to managing risk, Springer Science.
14. RISK-UE (2004). An advanced approach to earthquake risk scenarios with applications to different European towns. Project of the European Commission, Contract number: EVK4-CT-2000-00014.
15. Lantada N. (2007): Evaluación del riesgo sísmico mediante métodos avanzados y técnicas gis. Aplicación a la ciudad de Barcelona. Doctoral dissertation. Universidad Politécnica de Cataluña, Barcelona, Spain.
16. Marulanda, M.C., Cardona, O.D., Barbat, A.H. (2010) Revealing the socio-economic impact of small disasters in Colombia using DesInventardatabase, *Disasters*, December 11/2009; 34(2): 552- 570, Overseas Development Institute, Blackwell Publishing, Oxford.
17. Marulanda, M.C., Cardona, O.D., Ordaz, M.G., Barbat, A.H. (2008). La gestión financiera del riesgo desde la perspectiva de los desastres: Evaluación de la exposición fiscal de los Estados y alternativas de instrumentos financieros de retención y transferencia del riesgo. Monografía CIMNE IS-61, Universidad Politécnica de Cataluña, Barcelona.
18. Miranda, E. (1999) Approximate seismic lateral deformation demands on multistory buildings, *Journal of Structural Engineering* 125:4, 417-425.
19. Pollner, J. (2001). Managing Catastrophic Disaster Risks Using Alternative Risk Financing and Pooled Insurance Structures. World Bank Technical Paper, No. 495.
20. 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.
21. Woo, G. (1999): *The Mathematics of Natural Catastrophes*, Imperial College Press.Yamin, L.E., Gallego, M., Cardona, O.D., Phillips, C.A. (2004). “Recent Advances in Seismic Microzonation Studies, The Manizales-Colombia Case”, 13th World Conference on Earthquake Engineering, Vancouver.