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APPLICATION AND ROBUSTNESS OF THE HOLISTIC APPROACH FOR THE SEISMIC RISK EVALUATION OF MEGACITIES

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ABSTRACT :

Risk has been defined, for management purposes, as the potential economic, social and environmental consequences of hazardous events that may occur in a specified period of time. From the perspective of this paper, risk requires a multidisciplinary evaluation that takes into account not only the expected physical damage, the number and type of casualties or economic losses, but also the conditions related to social fragility and lack of resilience conditions, which favour the second order effects when a hazard event strike an urban centre. The proposed general method of urban risk evaluation is multi hazard and holistic, that is, an integrated and comprehensive approach to guide decision-making. The first step of the method is the evaluation of the potential physical damage (hard approach) as a result of the convolution of the seismic hazard with the physical vulnerability of buildings and infrastructure. Subsequently, a set of social context conditions that aggravate the physical effects are also considered (soft approach). According to this procedure, the physical risk index is evaluated for each unit of analysis from existing loss scenarios, whereas the total risk index is obtained by multiplying the former index by an impact factor using an aggravating coefficient, based on variables associated with the socio-economic conditions of each unit of analysis. Sensitivity analysis has been performed using Monte Carlo simulations to validate the robustness of this risk evaluation method based on composite indicators. Results are shown for Barcelona (Spain), Bogota (Colombia) and Metro-Manila (The Philippines).

KEYWORDS: Holistic approach, urban risk evaluation, seismic risk, socio-economic vulnerability.

1. INTRODUCTION

In the past, the concept of disaster risk has been defined in many cases in a fragmentary way, according to each scientific discipline involved in its appraisal; however, disaster risk requires an interdisciplinary evaluation for disaster risk management effectiveness. From an integrated perspective, risk evaluation should takes into account not only the expected physical damage, as the number of casualties or economic losses (direct impact), but also the conditions related to social fragility and coping capacity of the society, because they favour the second order effects (indirect impact) when a hazard event strikes an urban centre. Using a multi-criteria approach, it is possible to evaluate the disaster risk of exposed areas using indices and indicators (Cardona 2001, 2004, 2006). This type of approach is based on a constructive rationality and it allows taking into account uncertain, incommensurable, multidimensional aspects and effects. It is a promising estimation framework for making integrated evaluations and for decision making in multiple variable environments (Munda 2000). This process commences with the identification of imaginable variables that may “reflect” the state of a socio-technical system (as a country, region or megacity). These variables may not have a strong comparability or commensurability. The next step is the hierarchical or structural analysis of the variables (indicators). It consists of determining the influence of each variable on all of the rest with the purpose of determining its “weight” or importance using matrices of relationships. This activity may be done by using the Delphi Method (consensus and feedback process with anonymity of the participants) and taking into account the opinion of different experts or stakeholders. This multi-criteria evaluation is a decision-making technique that allows the involvement of different perspectives, for example the seismic risk estimation from a physical, economic, social, political or institutional point of view.

2. METHODOLOGY OF EVALUATION

This article describes an alternative method for urban risk evaluation based on Cardona's model (2001). In this method, the urban risk is evaluated using composite indicators and the expected building damage and losses in the infrastructure obtained from simulated loss scenarios are the basic information for evaluating a physical risk index in each unit of analysis (Carreño 2006). The proposed model improves conceptual and methodological aspects of Cardona's model, refining the applied numerical techniques and turning it into a more versatile tool. It conserves the approach based on indicators, but it improves the procedure of normalization and calculates the final indices in an absolute (non relative) manner. This feature facilitates the comparison of risk among urban centers.

The proposed method is developed for a multi-hazard evaluation and therefore it is necessary to dispose of physical damage estimations for all the significant hazards. Often, when historical information is available, the principal hazard can be usually identified and thus the most potential critical situation. The holistic evaluation of risk by means of indices is achieved affecting the physical risk with an aggravating coefficient, obtained from contextual conditions, such as the socio-economic fragility and the lack of resilience, that aggravate initial physical loss scenario. Available data about these conditions at urban level are necessary to apply the method. A brief explanation of the model and some examples of application for the cities is made forward. Figure 1 shows the theoretical framework of the alternative model.

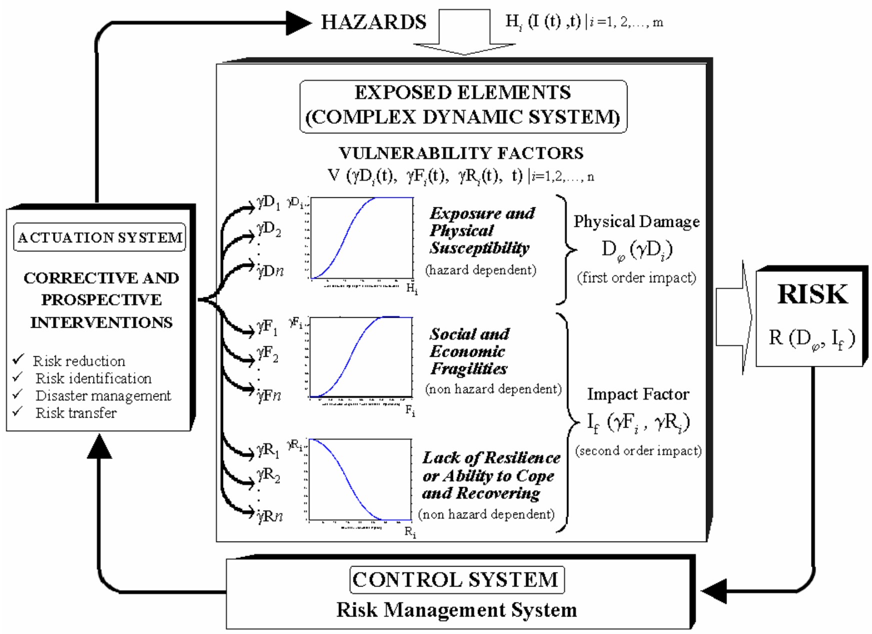


Figure 1 Theoretical framework for holistic approach of disaster risk (adapted from Cardona and Barbat 2000)

From a holistic perspective risk, *R*, is a function of the potential physical damage, D_j, and an impact factor, I_f. That is obtained from the susceptibility of the exposed elements, γD_i, to hazards, H_i, regarding their potential intensities, *I*, of events in a period of time *t*, and the latter depends on the social fragilities, γF_i, and the issues related to lack of resilience, γR_i, of the disaster prone socio-technical system or context. Using the meta-concepts of the theory of control and complex system dynamics to reduce risk, it is necessary to intervene in corrective and prospective way the vulnerability factors and, when it is possible, the hazards directly. Then risk management requires a system of control, institutional structure, and an actuation system, public policies and actions, to implement the changes needed on the exposed elements or complex system where risk is a social process. In this paper the proposed holistic evaluation of risk is performed using a set of input variables, herein denominated descriptors. They reflect the physical risk and the aggravating conditions that contribute to the potential impact. Those descriptors, which will be discussed later, are obtained from the loss scenarios and from socio-economic and coping capacity information of the exposed context (Carreño et al. 2005).

The socio-economic fragility and the lack of resilience are a set of factors that aggravate the physical risk. Thus, the total risk depends on the direct effect, or physical risk, and the indirect effects,

$$R_T = R_F\left(1 + F\right) \tag{2.1}$$

expression known as the Moncho's Equation in the field of disaster risk indicators, where R_T is the total risk index, R_F is the physical risk index and F is the aggravating coefficient. The coefficient, F, depends on the weighted sum of a set of aggravating factors related to the socio-economic fragility, F_{FSi}, and the lack of resilience of the exposed context, F_{FRj}

$$F = \sum_{i=1}^{m} w_{FSi} \times F_{FSi} + \sum_{j=1}^{m} w_{FRj} \times F_{FRj} \tag{2.2}$$

where w_{FSi} and w_{FRj} are the weights or influences of each i and j factors and m and n are the total number of descriptors for social fragility and lack of resilience respectively. The aggravating factors F_{FSi} and F_{FRj} are calculated using transformation functions, examples of these functions are shown in the Figure 2. These functions standardize the gross values of the descriptors transforming them in commensurable factors. The weights w_{FSi} and w_{FRj} represent the relative importance of each factor and are calculated by means of the Analytic Hierarchy Process (AHP), which is used to derive ratio scales from both discrete and continuous paired comparisons (Saaty 1980).

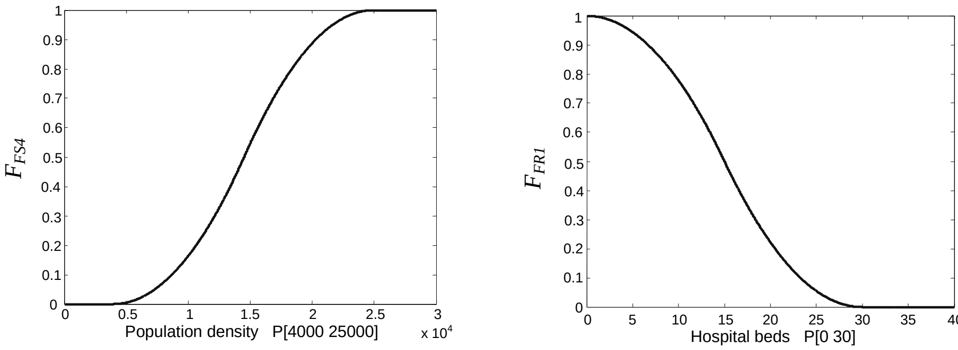


Figure 2 Examples of transformation functions used to standardize social fragility and lack of resilience factors

The physical risk, R_F, is evaluated in the same way,

$$R_F = \sum_{i=1}^{p} w_{RFi} \times F_{RFi} \tag{2.3}$$

where p is the total number of descriptors of physical risk index, F_{RFi} are the component factors and w_{RFi} are their weights respectively. The factors of physical risk, F_{RFi}, are calculated using the gross values of physical risk descriptors such as the number of deaths, injured or the destroyed area, and so on. It has to be mentioned that the calculation of physical risk scenarios is not the objective of the methodology developed in this paper, but the physical risk index is obtained starting from existing loss evaluations. Examples of the corresponding transformation functions for the physical risk index evaluation are shown in the Figure 3.

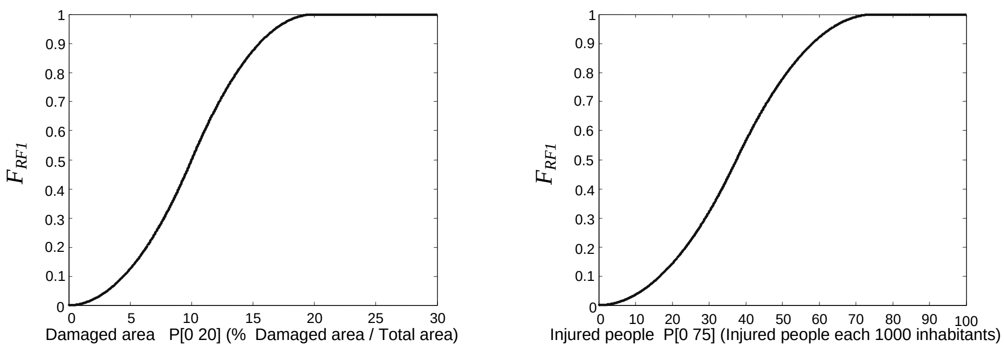


Figure 3 Examples of transformation functions used to standardize the physical risk factors

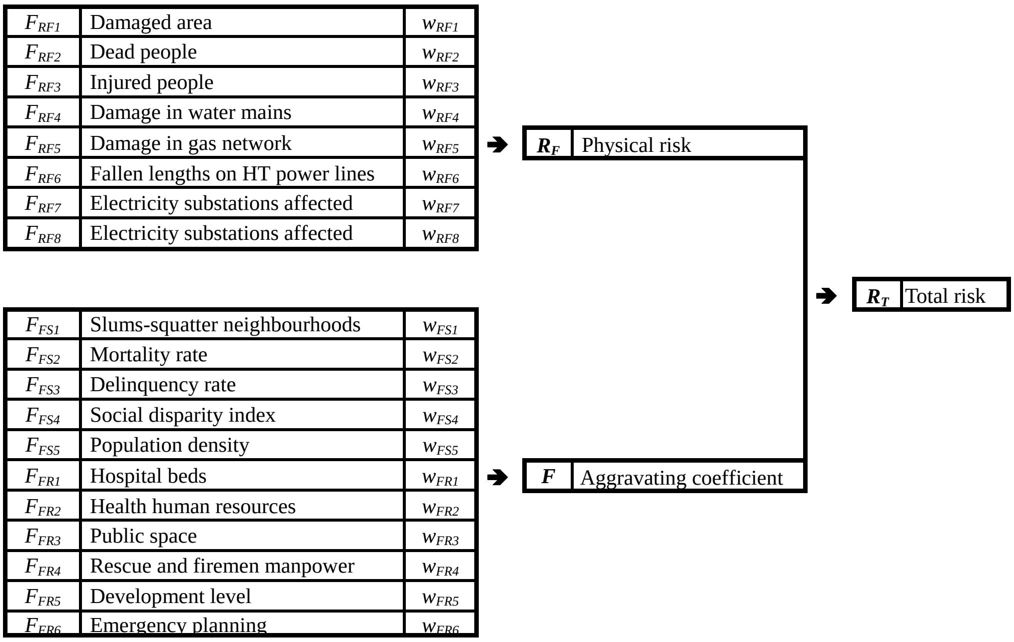


Figure 4 Factors of physical risk, social fragility and lack of resilience and their weights

It is estimated that the indirect effects of hazard events, sized by the factor F in Eqn 2.1, can be of the same order than the direct effects. According to the Economic Commission for Latin America and the Caribbean (Zapata 2004), it is estimated that the indirect economic effects of a natural disaster depend on the type of phenomenon. The order of magnitude of the indirect economic effects for a 'wet' disaster (as one caused by a flood) could be of 0.50 to 0.75 of the direct effects. In the case of a 'dry' disaster (caused by an earthquake, for example), the indirect effects could be about the 0.75 to 1.00 of the direct effects, due to the kind of damage. This means that the total risk, R_T, could be between 1.5 and 2 times R_F. In this method, the maximum value selected was the latter. For this reason, the aggravating coefficient, F, takes values between 0 and 1 in Eqn 2.1.

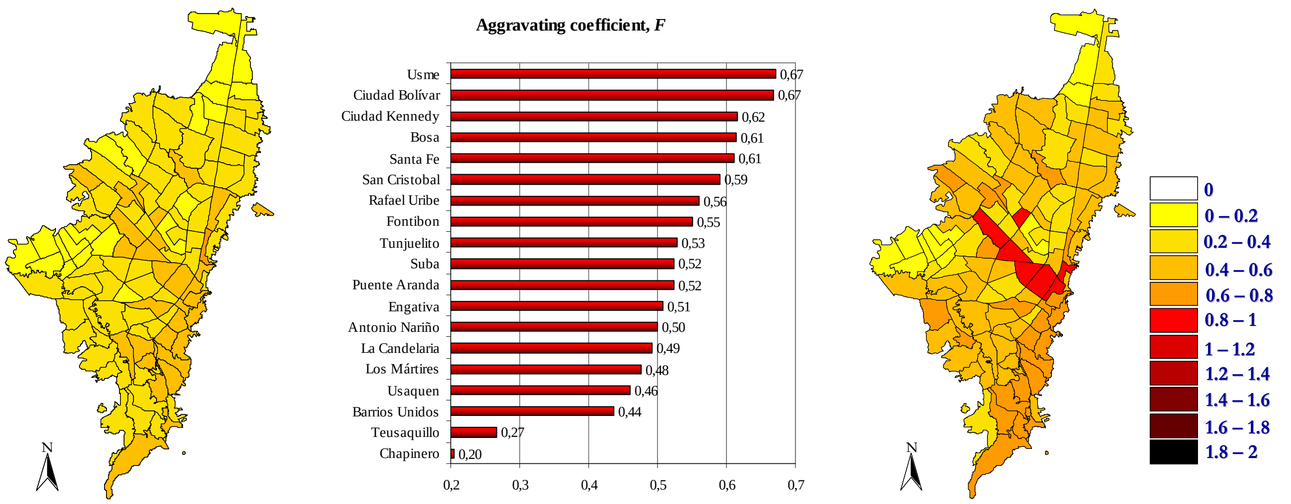
The maximum and minimum values of the transformation functions were fixed using existing information about past disasters as well as the opinion of experts. The transformation functions describe the intensity of the risk for each descriptor. For example, the transformation function for the mortality rate, defined as the number of deaths by natural causes for each 10 000 inhabitants, suggest that the aggravation for this factor is minimal if it takes a value smaller than 50 deaths for each 10 000 inhabitants, and the aggravation is maximal if the value is bigger than 4000 deaths for each 10 000 inhabitants. Another example is the case of the damaged built area; the corresponding transformation function defines a minimum risk (0) when this descriptor is zero and, the maximum risk (1) was established for a potential damaged area of 20% of the constructed one according to the opinion of experts. Figures 2 and 3 show the values of the descriptors in the *x-axis* of the transformation functions. The corresponding factors, or scaled values, are given in the *y-axis*. The factors for a city are obtained in each case using the transformation functions of the aforesaid figures and the variables with the units of tables above-mentioned. Figure 4 shows the process of calculation of the total risk index for the units of analysis, and the variables used to describe the social fragility and the lack of resilience in the estimation of the aggravating coefficient F, and the descriptors of the physical risk, R_F, respectively. Carreño et al. (2007, 2008) give more detailed explanations about this method.

3. EXAMPLES OF APPLICATION

3.1. Seismic risk of Bogota

In Bogota, Colombia, the localities or mayorships are political-administrative subdivisions of the urban territory, with clear competences in financing and application of resources. They were created with the objective of attending in an effective way the needs of the population of each territory. Since 1992, Bogota has 20 localities: Usaquén, Chapinero, Santafé, San Cristóbal, Usme, Tunjuelito, Bosa, Ciudad Kennedy, Fontibón, Engativa, Suba, Barrios Unidos, Teusaquillo, Mártires, Antonio Nariño, Puente Aranda, Candelaria, Rafael Uribe, Ciudad Bolívar and Sumapaz. In this study, only 19 of these localities are considered, because the locality of Sumapaz corresponds to the rural area. These localities are subdivided in 117 territorial units (UPZ). The starting point for the application of the model is a scenario of seismic physical risk developed by Universidad de Los Andes (2005), which corresponds to an earthquake with a magnitude Ms of 7.4 and a return period of 500 years occurs in the frontal fault of the Western Mountains. The seismic risk scenario was calculated by means of building by building simulations and, thus, the descriptors of the physical risk can be obtained for each UPZ. Nevertheless, the aggravating factors have been calculated for each locality.

Figure 5 shows the obtained results for the physical risk index, the aggravating coefficient, and the total risk. The average value of the physical risk and total risk by locality were calculated using the population density. The locality of Candelaria has the most critical situation from the point of view of the physical and total seismic risk, because its aggravating coefficient is significant, although it is not the highest of the city. The localities with greater aggravating coefficient are Usme, Ciudad Bolivar, Ciudad Kennedy and Bosa, whereas the lowest values are those of Barrios Unidos, Teusaquillo and Chapinero. High values of the physical risk index, in addition to Candelaria, are the localities of Santa Fe, Chapinero and Los Martires, whereas the physical risk index is less in Ciudad Kennedy and Bosa. The greater values of total risk index appear in the localities of Candelaria, Santafé and Los Martires, and the smaller are those of Ciudad Kennedy, Barrios Unidos and Bosa.



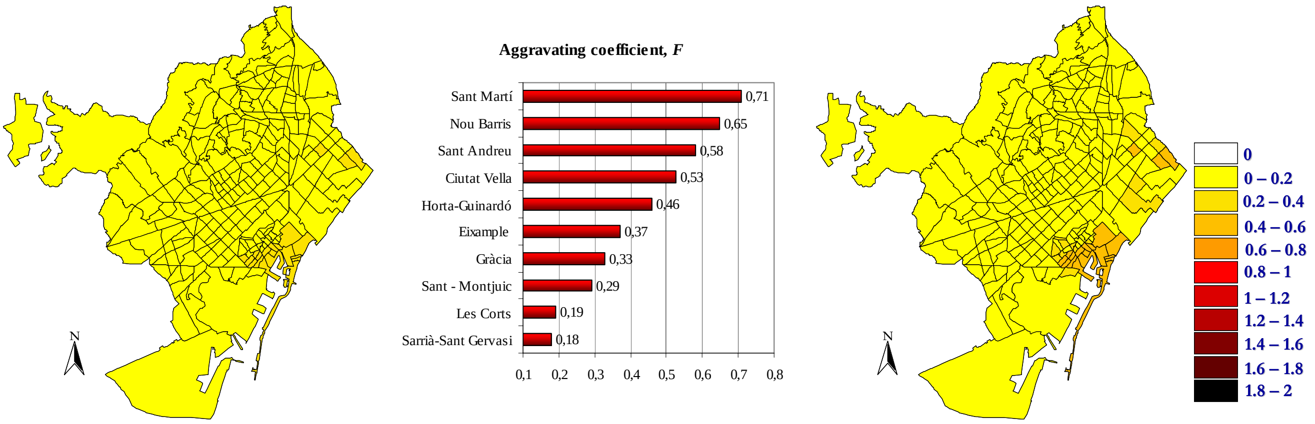
a)Physical risk *b) Aggravating coefficient* *c) Total risk*

Figure 5 Results for the city of Bogota: *a)* Physical risk; *b)* Aggravating coefficient; and *c)* Total risk

3.2. Seismic risk of Barcelona

The city of Barcelona, Spain, is subdivided in ten districts, which are directed by a Mayor. The districts have management competences in subjects like urbanism, public space, infrastructure maintenance, etc. They are: Ciutat Vella, Eixample, Sants-Montjuïc, Les Corts, Sarrià-Sant Gervasi, Gràcia, Horta-Guinardó, Nou Barris, Sant Andreu and Sant Martí. The districts are subdivided in 38 neighbourhoods or large statistical zones. Barcelona is also subdivided in 248 small statistical zones (ZRP). The physical risk index was calculated from a probabilistic risk scenario developed in the framework of the Risk-UE project (ICC/CIMNE 2004).

The physical risk scenario was calculated considering the 248 small ZRP zones. The aggravating coefficient was calculated by district, due to the availability of data at this level only. Figure 6 shows the obtained results for the physical risk index, the aggravating coefficient and the total risk index for Barcelona.

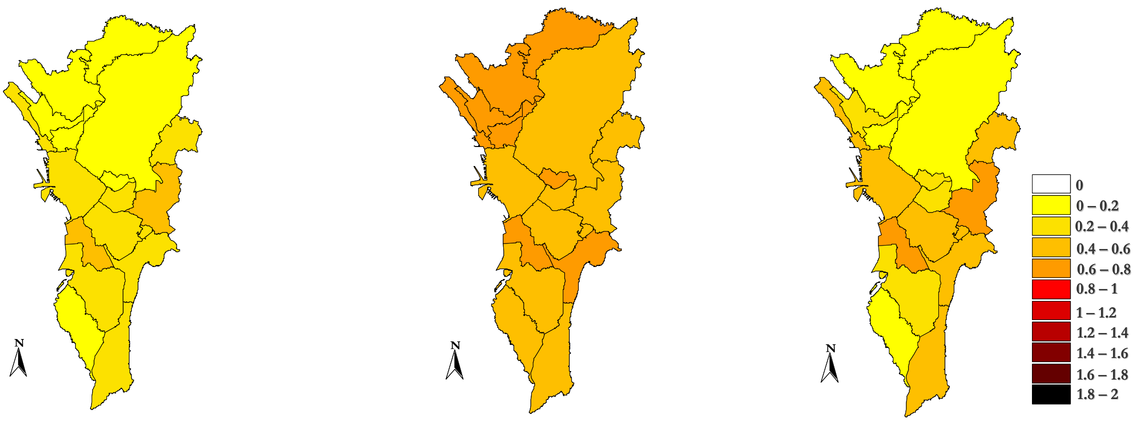


a) Physical risk *b) Aggravating coefficient* *c)Total risk*

Figure 6 Results for the city of Barcelona: a) Physical risk; b) Aggravating coefficient; and c) Total risk

3.3. Seismic risk of Metro-Manila

Metropolitan Manila, the capital city the Philippines is officially called the National Capital Region (NCR). Although it is the smallest region, it is the most densely populated region of the country. Metro Manila is composed by 4 municipalities and 13 cities thereof into an integrated unit with the manager or commission form of government. They are the cities of: Quezon, Kaloocan, Valenzuela, Muntinlupa, Las Piñas, Marikina, Manila, Parañaque, Makati, Mandaluyong, Malabon, Pasay, Pasig. And the municipalities of: Taguig, Pateros, San Juan and Navotas. In order to evaluate the total risk for each city, the physical risk index was calculated using physical risk descriptors based on the earthquake damage MMEIRS-08 (EMI 2006), obtained from the Earthquake Impact Reduction Study of Metro Manila (MMEIRS). This scenario corresponds to an earthquake of magnitude Ms 7.2, in the West Valley Fault, with 2 km of depth. Figure 7 shows the results for the physical risk index, the aggravating coefficient and the total risk index for Manila.



a) Physical risk *b) Aggravating coefficient* *c) Total risk*

Figure 7 Results for the city of Metro-Manila: a) Physical risk; b) Aggravating coefficient; and c) Total risk

3.4. Comparison of results

The average values of the physical risk and total risk by city were calculated using the population density. Table 3.1 shows the average risk values for the three cities. Metro Manila and Bogota are located in zones with intermediate seismic hazard, whereas Barcelona is located in a zone with low to moderate seismic hazard. The average values obtained for the physical risk index, R_F, reflect not only the seismic hazard but also the level of physical vulnerability in each city. It is interesting to remark that the results obtained for the aggravating coefficient, F, are not so different for the three cities. The highest value of physical risk is for Bogota, but the worst situation, taking into account the aggravating coefficient, is for Metro Manila.

Table 3.1 Comparison of results

Index	Barcelona	Bogota	Metro Manila
Physical risk, R_F	0.08	0.32	0.24
Aggravating coeff. F	0.42	0.55	0.59
USRi* = Total risk, R_T	0.11	0.50	0.38

*Urban Seismic Risk Index has been used as the indicator of total seismic risk of the cities.

4. SENSITIVITY ANALYSIS

Sensitivity and uncertainty analyses of the model have been performed to know its robustness through estimating how the variation in the values the Urban Seismic Risk Index, USRi, (or Total Risk, R_T) can be apportioned, qualitatively or quantitatively, to different sources of variation, and how this given index or composite indicator depends upon the information fed into it. In other words, once the proposed model (composite indicator) is determined, it is important to analyze how much the results are influenced by uncertainty in the source data or uncertainty in the model itself (e.g. weights and transformation functions), due to the stakeholders' subjectivity or plurality of perspectives. For this purpose a Monte Carlo-based simulation was performed. By this way, thousands of stochastic results were created with random inputs of each parameter (input data, transformation functions, weights and all simultaneously) for each territorial urban unit of analysis. The obtained results through the simulation are very similar to the obtained results using deterministic or crisp values. The overall results of Table 4.1 show that the territorial units of Metro Manila vary slightly in their rankings and figures. Some units fluctuate at the most by one position.

Table 4.1 Comparison between stochastic results and deterministic results of USRi, positions and classification of Metro Manila cities by risk levels

Level of risk	Deterministic values		Data		Weights		Functions		Data-Weight-TF	
	City	USRi	City	USRi	City	USRi	City	USRi	City	USRi
Very High	Pasay	0.72	Pasay	0.70	Pasay	0.71	Pasay	0.70	Pasig	0,70
	Pasig	0.71	Pasig	0.70	Pasig	0.70	Pasig	0.70	Pasay	0,70
High	Navotas	0.49	Manila	0.52	Manila	0.53	Manila	0.53	Manila	0,52
	Manila	0.48	Navotas	0.49	Navotas	0.49	Navotas	0.49	Navotas	0,49
	Pateros	0.47	Pateros	0.49	Pateros	0.49	Pateros	0.49	Pateros	0,49
	Marikina	0.45	Marikina	0.47	Marikina	0.46	Marikina	0.47	Marikina	0,47
	Taguig	0.45	Taguig	0.46	Taguig	0.46	Taguig	0.46	Taguig	0,45
Médium-High	Muntinlupa	0.43	Makati	0.43	Makati	0.43	Makati	0.43	Makati	0,43
	Makati	0.42	Muntinlupa	0.43	Muntinlupa	0.42	Muntinlupa	0.43	Muntinlupa	0,43
	Mandaluyong	0.39	Mandaluyong	0.40	Mandaluyong	0.40	Mandaluyong	0.40	Mandaluyong	0,40
	Paranaque	0.31	Paranaque	0.33	Paranaque	0.33	Paranaque	0.33	Paranaque	0,33
Médium-Low	San Juan	0.29	San juan	0.31	San juan	0.31	San juan	0.32	San Juan	0,31
	Malabon	0.26	Malabon	0.27	Malabon	0.27	Malabon	0.27	Malabon	0,27
	Quezon	0.19	Quezon	0.21	Quezon	0.21	Quezon	0.22	Quezon	0,22
	Las pinas	0.17	Las pinas	0.19	Las pinas	0.19	Las pinas	0.19	Las pinas	0,20
Low	Kalookan	0.05	Kalookan	0.09	Kalookan	0.09	Kalookan	0.09	Kalookan	0,10
	Valenzuela	0.03	Valenzuela	0.07	Valenzuela	0.06	Valenzuela	0.06	Valenzuela	0,07

In other urban centres as Barcelona, where the method has been applied and where a similar sensitivity analysis has been made, the results are similar than in Metro Manila. In the case of Bogota some territorial units have been more volatile with position changes of two and three ranks; however it is not very relevant for decision-making measures. According to the comparison of the results of sensitivity analysis, and the results obtained by the holistic seismic risk evaluation here described, it is possible to conclude that the methodology is not excessively sensitive to slight variations in the input data and to small changes in the modelling parameters, such as weights and transformation functions. The results do not present important or extreme changes. If the range of variation of data and parameters is reasonable, as it is in the case of seismic risk, in general the results of the model will be stable, reliable and robust. Classification by ranges of risk has special interest, because it is more relevant to take into account the level of risk where a territorial unit is located than its final numerical value for risk management implications.

5. CONCLUSIONS

Risk estimation requires a multidisciplinary approach that takes into account not only the expected physical damage, but also other social, organizational and institutional issues related to the development of communities that contribute to the creation of risk. This paper proposes a model for the multidisciplinary representation of urban seismic risk, based on a parametric approach. This model facilitates the integrated risk management by the different stakeholders involved in risk reduction decision-making. This method allows to compare risk among different cities around the world and to perform a multi-hazard risk analysis. This was applied to the holistic evaluation of the seismic risk for the cities of Barcelona, Spain; Bogota, Colombia; and Metro-Manila, the Philippines. The model was submitted to a sensitivity analysis by means of a Monte-Carlo based simulation which proved the model robustness.

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