2643

HOLISTIC SEISMIC RISK ESTIMATION OF A METROPOLITAN CENTER

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SUMMARY

Bogotá, the Capitol City of Colombia, is a 7 million people urban center placed in a moderate seismic hazard prone area of South America. The city has 19 districts with significant physical, economical, and social differences. As a whole, the seismic risk of Bogota is high, but the comparative risk results of its districts are very different depending on social, economic, and resilience differences. Although the city has evaluated detailed seismic microzonation and earthquake loss scenarios, it was necessary to analyze other important variables at district level to estimate the real seismic risk of each one. A comparative and holistic study was developed to include social, economical issues besides the seismological and engineering variables obtained of the detailed microzoning study. This paper presents the multidisciplinary approach used, the methodology, the results, and how the city administration might use them, from the sectoral planning perspective, to promote mitigation measures according to the risk estimation of each district.

INTRODUCTION

In the last years, from the outlook of the natural disasters, it has been attempted to measure the risk, for purposes of management, as the possible economic, social and environmental consequences that might occur in a defined place and time. However, the conceptualization of the risk has not been integral but fragmentary, according to the approach in each discipline involved in its evaluation. To estimate the risk in agreement with its definition, it is necessary to consider, from the multidisciplinary point of view, not only the expected physical damage, the victims or the equivalent economic losses, but also social, organizational and institutional factors, related to the development of the communities. At the urban scale, for example, the vulnerability as internal factor of risk, should be related not only with the exposure of the material context or its physical susceptibility to be affected, but also with the social fragilities and the lack of resilience of the exposed community. The lack of institutional and community organization, the weaknesses in preparing for the emergencies attention, the political instability and the lack of economic health of a geographical area contribute to have a major risk. Therefore, the potential consequences are not only related to the impact of the event, but also to the capacity to sustain the impact and the implications of the impact in the considered geographical area.

The risk evaluation can be carried out by means of the following general formulation, equation 1: once known the hazard or threat Hi, understood as the probability that an event may occur with an intensity larger or equal to i during an exposition period t, and known the vulnerability V_e, understood as the intrinsic predisposition of the exposed elements e to be affected or of being susceptible to suffer a loss as a result of the occurrence of an event with intensity i, the risk R_{ie} can be understood as the probability that a loss can occur over the element e, as consequence of the occurrence of an event with an intensity larger or equal to i, that is, the probability to exceed some social and economic consequences during the given period of time t [Cardona, 1986].

$$R_{ie}\,|_t = (H_i \,.\, V_e)\,|_t \tag{1}$$

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Here a conceptualization of risk is proposed from the perspective of considering not only seismic and structural variables, but also economic, social variables, of response capacity or post-earthquake recovery, or resilience, that allow to guide in an effective manner the decisions of risk mitigation. An estimation of this type could be considered holistic, that is to say integral or complete from the risk. By the way, it is necessary to have the estimation of losses or urban scenarios of earthquake damages, because they are the result of the convolution of the seismic hazard, or microzoning of the city, and the physical vulnerability of the buildings and of the infrastructure; aspects from which a physical risk index or “hard” risk is defined. Also, a context risk index or “soft” risk is valuated, resulting from the estimation of relative seismic hazard descriptor and its convolution with the vulnerability of the context descriptor, which is based on indicators of exposure, social fragility and relative resilience of the analysis units conforming the urban center. Said analysis units could be districts or areas with administrative autonomy that allow the administrative authority of the city to carry out the risk management by using the results of the holistic and multidisciplinary estimation of the urban seismic risk.

METHODOLOGY

The proposed procedure for the holistic and relative estimation of the urban seismic risk starts from the identification of some analysis units, *k*, that are the areas by which the index of total seismic risk is determined, IR_{T_k}. It is expressed by de equations 2 to 7:

$$IR_{T_k} = IR_{H_k} \,.\, \delta_{IRH_k} + IR_{S_k} \,.\, \delta_{IRS_k} \qquad (2)$$

where IR_{H_k}, is the hard seismic risk index of physical seismic risk, which is based on descriptor obtained from the estimation of the urban potential losses caused by future earthquakes; IR_{S_k} , is the soft seismic risk index or context seismic risk, obtained from the scaled product of seismic hazard and of context vulnerability descriptors, and δ_{IRH_k}, δ_{IRS_k} are the participation factors of each index for each analysis area *k*; for its part

$$IR_{H_k} = \sum_i X_{IR_i} \,.\, \delta_{IR_i} \qquad (3)$$

where X_{IR_i} is the value of each indicator *i* obtained from the information of the scenarios of losses and δ_{IR_i} the participation factor of each indicator *i,* for each analysis area *k*; and

$$IR_{S_k} = \alpha\,((H_{S_k} - \beta)(V_{S_k} - \beta) + \beta) \qquad (4)$$

being H_{S_k} the descriptor of seismic hazard of the context, V_{S_k}, the descriptor of vulnerability of the context, and α y β constants of visualization related to the average and the standard deviation of the values that are mentioned farther on in the scaling technique. In turn

$$H_{S_k} = \sum_i X_{H_i} \,.\, \delta_{H_i} \qquad (5)$$

being X_{H_i} the value of the indicators *i* obtained from the study of urban seismic microzoning and δ_{H_i} the participation factor of each indicator *i*, for each analysis area *k*;

$$V_{S_k} = E_{V_k} \,.\, \delta_{E_k} + F_{V_k} \,.\, \delta_{F_k} + R_{V_k} \,.\, \delta_{R_k} \qquad (6)$$

where, E_{V_k} , F_{V_k} , R_{V_k} are indicators of exposure, social fragility and lack of resilience, and δ_{E_k} , δ_{F_k} , δ_{R_k} are their participation factors for each analysis area *k*, what is equivalent to

$$V_{S_k} = \left(\sum_i X_{E_i} \,.\, \delta_{E_i}\right) \delta_{E_k} + \left(\sum_i X_{F_i} \,.\, \delta_{F_i}\right) \delta_{F_k} + \left(\sum_i X_{R_i} \,.\, \delta_{R_i}\right) \delta_{R_k} \qquad (7)$$

being X_{E_i}, X_{F_i}, X_{R_i}, the values of the indicators *i* which compose the exposure, social fragility and lack of resilience and δ_{E_i}, δ_{F_i}, δ_{R_i}, the participation of each indicator *i*, for each analysis area *k*, respectively. These indexes, descriptors, factors and indicators should be defined based on available information for all the analysis units. Conceptually they should reflect, in the most possible direct manner, what is wanted to value and it should be avoided the simultaneous use of variables or indicators that express the same aspect approximately. Figure 1 indicates the composition of the risk indexes in agreement with the mentioned nomenclature.

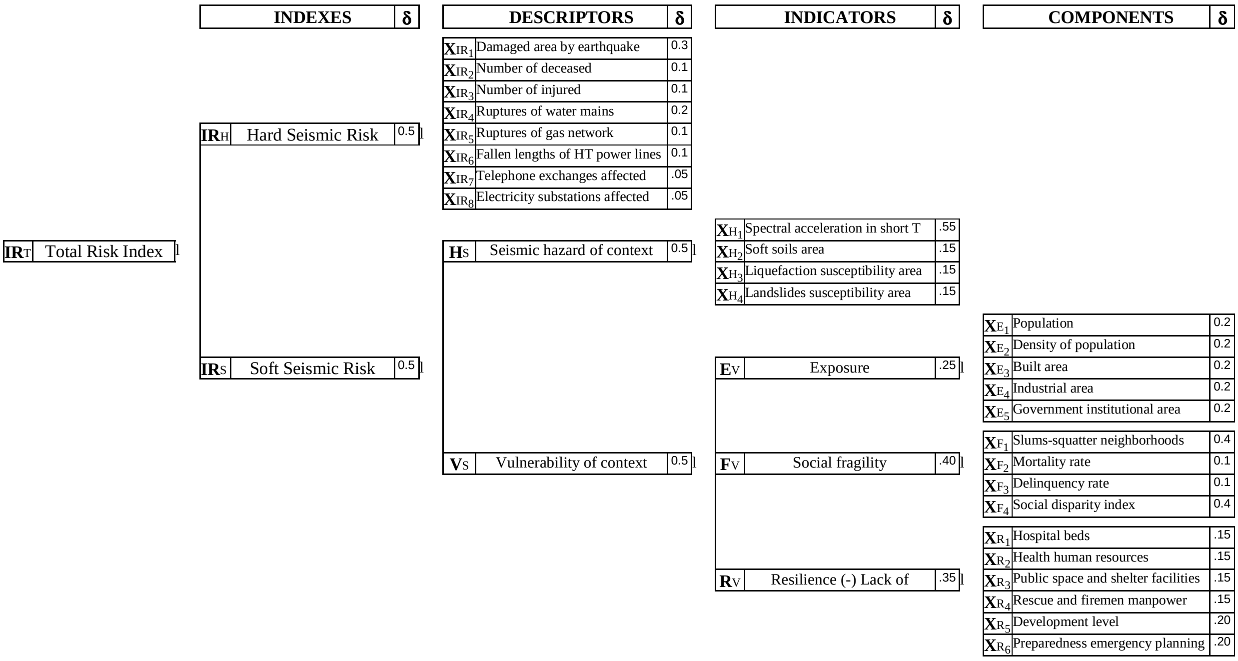


Figure 1. Relative seismic risk indexes defined for the different districts of Bogotá with the participation factors used.

Scaling

Before integrating through a linear combination the indicators in descriptor and in turn the descriptors in factors and indexes, these should be scaled in compatible units that allow to make commensurable relative analyses. The area of public space for the massive attention of people and rescue personnel, for example, cannot be related directly, because square mater is used for the first one, and people for the second. The technique adopted for this case is to scale with regard to the average $\bar{X}_i$ and the standard deviation S_i, thus:

$$X'_{ik} = \frac{X_{ik} - (\bar{X}_i - \beta S_i)}{\alpha S_i} \qquad \text{ó} \qquad X'_{ik} = \frac{-X_{ik} + (\bar{X}_i + \beta S_i)}{\alpha S_i} \tag{8}$$

where the X'_{ik} and X_{ik} are the scaled and the crude value, for the district k and the indicator i, and α and β are constant of visualization related with the average and the standard deviation; in this way if α is 0.8 and β is 4.0 the values of the indicators are scaled with regard to the average (0.0) plus 5.0 (β/α) and the standard deviation (1.0) is expanded 1.25 ($1/\alpha$). These constants should be maintained during the whole scaling procedure. The equation changes sign when the indicator is inverse to the factor which is valued, as it is the case of the resilience indicators, which are inverse to the vulnerability of the context. To express the result as a linear combination implies that interaction does not exist among the indicators or among the indicators and the participation factors used for the weighting. Nevertheless, almost all the indexes of this type, developed so far, use an approach based on a linear combination and the search of other approaches has allowed to conclude that the linear combination is acceptable, if the uncertainties and inaccuracies inherent to the data are considered. On the other hand, to make a non linear function from a risk index could become more appropriate, but it is not clear what type of function could be and its associate complexity makes that the approach ends up for being unsubstantial with the objective of looking for a simple methodology to obtain an index easy to evaluate and easy to understand.

Weighting

Once the indicators are commensurable, their weighting should be accomplished. The participation factor of each indicator illustrates how important is the indicator with regard to the others in determining a component factor or with the same index of seismic risk. An index of this nature should try to capture the collective knowledge of all experts to define its value, conceived by a group like a whole. The weighting is correct provided that it meets that goal. A great variety of weighting techniques has been used for the construction of other composite indexes, however all those proposed based on statistical techniques require, or that the dependent variables can be measured directly -for example, regression- or that the indicators are well correlated (for example, analysis of main components). Since the risk cannot be measured directly and the indicators are not well correlated, any of the techniques with those pre-requirements is not more effective. The only option remaining for the weighting is the subjective evaluation on the part of experts. Although this technique seems to be undesirable for some, for lack of a base explicitly replicable, is the only feasible and reasonable option to capture the criteria, the experience and the judgment of experts [Davidson, 1997]. The participation factors can be obtained by means of neural networks that carry out the *defuzzificatión* of the variables formulated through fuzzy sets. This type of technique facilitates, by means of membership functions, the handling of experts' qualitative assessments and linguistic variables of valuation.

RELATIVE ESTIMATION OF THE SEISMIC RISK

Through the methodology formerly described, for an urban center conformed by a group of suburban areas, such as minor mayor'offices, districts, or communes, the determination of the relative seismic risk for each one of the analysis units is obtained from estimating of physical seismic risk index and the context seismic risk index. The addition of these two indexes allows to arrive to a holistic or integral valuation of the risk. Indicators or evaluations of seismic, demographic, and statistical order exist in each city that can be used to determine aspects that represent or reflect the variables to be valued. The estimation of indexes, descriptors, indicators and components for the 19 districts in Bogotá is presented here using information of the city.

Seismic Risk Scenarios

The determination of the vulnerability matrices of a portfolio of building models representing an urban area must be conducted in a probabilistic framework, due to the uncertainties and randomness inherent to the energy and frequency contents of the ground motion, the duration of the strong phase, the nonstationary evolution of the signals, etc.; the structural types and systems; and the mechanical parameters of the structural models. The evaluation of vulnerability functions or matrices has usually being performed upon the basis of the historical information on damages caused by past earthquakes [Whitman, 1976]; [ATC, 1985]. Important as it is, however, the information conveyed by these matrices or functions depends heavily on the construction types and technology level of the surveyed area, so that it can hardly be extrapolated to other parts of the world. In addition, in some places the design of vulnerability matrices on the basis of the local historical information is hindered by several factors, among which one can count the frequency of earthquake occurrence in the region under study, which can be low or very low, thus implying that the historical information on damaged dwellings is scarce; the age of the urbanization process, which can be so recent that no substantial information concerning observed seismic damage is available in the studied area; and the lack of archivistic and observational culture of the population, which makes difficult the assessment of the intensity of past events. If some or all of these conditions are met there is no alternative than having resort to simulation techniques which allow the synthetic generation of a sample of damage states in the building models adopted as representative of the structural types followed in the different building epochs of an urban zone. This is noting else than an application of the so-called Monte Carlo simulation. This path has been followed by some researchers in the recent times [Barbat *et al.*, 1996]; [Singhal & Kiremidjian, 1996]; [Abrams & Shinozuka, 1998] and was also adopted in the present case due to its clear advantages, as it is able of exploiting the consolidated knowledge of different earthquake engineering disciplines to produce synthetic vulnerability functions to different urban zones. The method comprises the following steps:

1. Definition of representative building models of different urbanization periods of the zone under consideration and determination of their geographical location and distribution.
2. Stochastic definition of the building model. In other words, selection of the random variables that most affect its behavior and, consequently, the assignation of their probability density functions. This task is facilitated by the availability of statistical information about common building materials, such as concrete, steel, timber and others [Sundararajan, 1995].
3. Generation of random samples of each variable [Rubinstein, 1981] and combination of them using efficient techniques, such as Latin Hypercube, Descriptive Sampling, etc. [Hurtado & Barbat, 1998].
4. Stochastic definition of the seismic ground motion, which ideally should be modeled as a evolutionary random process after a prescribed stationary power spectrum or a target response spectra [Vanmarcke, 1976]. The last alternative was followed in the present case in order to preserve the coherency with the seismic zonation. The calculation of the seismic accelerograms associated to each row of the e.g. Latin Hypercube matrix of random variates can be performed by well-known techniques [Shinozuka, 1987]. In the present case use was made of the evolutive spectrum proposed by Wen and Yeh [1989].
5. Nonlinear structural analysis of the various random models in order to determine the structural damage. In the present case the damage index proposed by Park and Ang (1986) was adopted for the case RC buildings.

6. Statistical analysis of the results. It is important to build up well defined probability distribution functions of the overall building damage index corresponding to each hazard level and to each building model.
7. Mapping the structural damage index to a building damage index, which measures the degree of losses on the building including its structural and nonstructural elements [Singhal and Kiremidjian, 1996]

From a computational viewpoint the Monte Carlo method is highly expensive, so that it is usually used in probabilistic analysis of structures mostly as a brute force technique to test the accuracy of other, less costly approaches. In the present case, however, these alternative approaches are not available as stated before. Nevertheless, the implementation of Monte Carlo techniques has been facilitated by the advent of parallel computation. This is due to the fact that the Monte Carlo method is intrisically parallel in that the different random models can be calculated by individual machines independently on each other (the so-called *coarse-grain* parallelism) under the control of a master node, which performs the generation of random variables and processes and the final statistical evaluation. This philosophy has been implemented in the computer code PROMENVIR [CASA, 1997] which has been employed for this task. Figure 2 shows urban damage scenarios.

Hard Seismic Risk Index

To determine the hard seismic risk index, in the case of Bogotá the following descriptors were defined, which were normalized in agreement with the area of each district. [Cardona and Yamín, 1997]:

1. *Damaged area,* X_{IR_1}: Defined as the probable area of destruction of the built zones in square kilometer, estimated according to the methodology described above in the frame of hypothetical seismic scenarios.
2. *Number of deceased,* X_{IR_2}*; Number of injured,* X_{IR_3}*:* Defined as the probable number of dead and injured, using similar estimates to those proposed by Whitman *et al* [1973] in the frame of hypothetical seismic scenarios for the city.
3. *Ruptures in the water mains,* X_{IR_4}*; Ruptures in the gas network* X_{IR_5}*; Fallen lengths of HT power lines* X_{IR_6}: Defined as the probable number of breaks presented in the water and gas lifelines and the fallen lengths of the high-tension power lines, estimated according to the methodology ATC-13 [1985], in the frame of hypothetical seismic scenarios.
4. *Number of telephone exchanges affected,* X_{IR_7}*; Number of electricity substations affected,* X_{IR_8}*:* Defined as the number of the telephone exchanges and electricity substations with a high seismic vulnerability in agreement with the simplified evaluation developed with base in the ATC-21 [1988] and other parameters.

The descriptors composing the index of physical risk are estimated from the convolution of the seismic hazard, obtained from the microzoning of the city and from the physical vulnerability of the buildings and the infrastructure of the public services.

Soft Seismic Risk Index

The soft seismic risk index of Bogotá was defined as the result of the scaled product of the seismic hazard factor and the context vulnerability factor for each district. This product is due to the fact that the hazard and the vulnerability are mutually determining and concomitant for the risk to exist; that is equivalent to the convolution of the component descriptors. Next they are defined these descriptors and they are related their components:

1. *Seismic hazard of the context,* H_{S_k}*:* Defined as an addition of values expressing the level of seismic threat that is presented in the area that covers the district, characterized by relative particularities to the seismic action. For its determination, in this case, the following indicators were defined:

1.1 *Spectral acceleration,* X_{H_1}*:* Defined as the weighted average of the spectral value of seismic acceleration for periods T between 0.2 sec. and 0.5 sec. of the areas of seismic microzoning that have influence in the area of the district considered.

1.2 *Soft soils area,* X_{H_2}: Defined as the percentage of area of the district that is susceptible to the seismic amplification due to the soil dynamic characteristics.

1.3 *Liquefaction susceptibility area,* X_{H_3}: Defined as the percentage of area of the district presenting non consolidated and saturated sandy soils with high liquefaction potential in the event of a strong earthquake.

1.4 *Landslides susceptibility area,* X_{H_4}: Defined as the percentage of area of the district presenting zones with potential instability of slopes in the event of a strong earthquake.

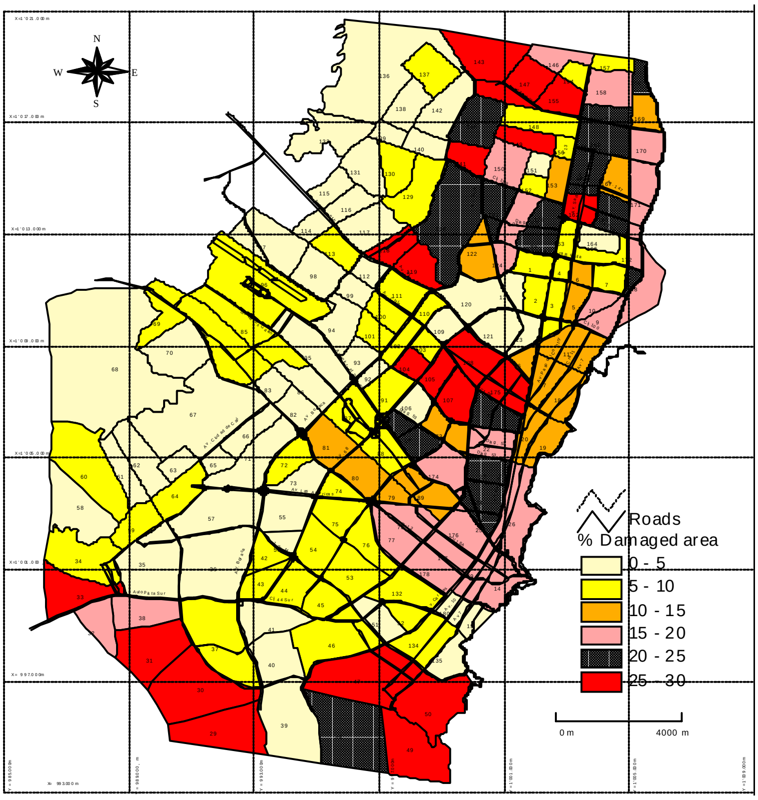


Figure 2: Example of earthquake loss scenario of Bogotá [Universidad de los Andes, 1996]

2. *Seismic vulnerability of the context, VS_k:* Defined as the addition of values expressing aspects of demographic, economic and strategic exposure, absence of economic and social development, weaknesses to absorb the impact, deficiencies in the institutional management and lack of capacity to respond in emergency cases, reflecting and differentiating the global vulnerability of each district. For its determination, three indicators were defined:

2.1 <u>*Exposure*</u>, EV_k: Defined as the normalized volume of population, buildings and economic and strategic possessions exposed to the seismic action in the area covered by the district. For its determination, in this case, the following components were defined:

2.1.1 *Population*, XE_1: Defined as the average number of inhabitants exposed, in thousands, in the area covered by the jurisdiction of the district.

2.1.*2 Density of population*, XE_2: Defined as the number of inhabitants divided by the built area, what reflects the concentration and congestion degree of people in the area of the district.

2.1.3 *Built area*, XE_3: Defined as the normalized area of construction and urban development in the area covered by the district.

2.1.4 *Industrial area*, XE_4: Defined as the normalized area of industrial zones, factories or companies in the area of the district, reflecting values and economic dependence.

2.1.5 *Government* institutional *area*, XE_5: Defined as the normalized area of zones of institutional or government use in the jurisdiction of the district, reflecting strategic values and political dependence.

2.2 <u>*Social fragility*</u>, FV_k: Defined as the inverse of the economic and social development deficit, characterized by the conditions of poverty and marginality, low health level, delinquency and the population's unsatisfied basic needs within the area covered by the district. For its determination, in this case, the following components were defined:

2.2.1 *Slums-squatter neighborhoods*, XF_1: Defined as the normalized area of illegal or marginal human settlements with insufficient public services and low socioeconomic stratification in the area covered by the jurisdiction of the district.

2.2.2 *Mortality*, XF_2: Defined as the rate or number of people which die annually for natural causes for each ten thousand inhabitants in the jurisdiction of the district.

2.2.3 *Delinquency*, XF_3: Defined as the rate or number of annual crimes for each thousand inhabitants in the area of the district, which represents social deterioration in the zone.

2.2.4 *Social disparity index*, XF_4: Defined as the level of unsatisfied basic needs and of relative human development in the district.

2.3 <u>*Lack of resilience*</u>, RV_k: Defined as the inverse of the economic, social and institutional capacity (resilience), representing weakness to absorb the impact of a crisis, the lack of capacity to respond in case of emergency and the deficiencies in the institutional management in the district. For its determination the following components were defined:

2.3.*1 Hospital beds*, X_{R1}: Defined as the normalized number of beds in hospitals and institutions of health in the area covered by the district.

2.3.2 *Health human resources*, X_{R2}: Defined as the normalized number of physicians and nurses who work in health institutions located in the jurisdiction of the district.

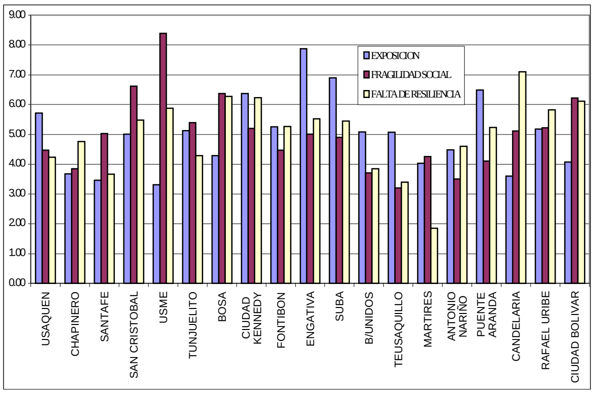
2.3.3 *Public space and shelter facilities*, X_{R3}: Defined as the normalized area of space available for temporary housing or lodging and the massive attention of emergencies in the area covered by the district.

2.3.4 *Rescue and firemen manpower*, X_{R4}: Defined as the normalized number of rescue workers and voluntaries of the Red Cross, Civil Defense and Firemen available in the area of influence of the district.

2.3.5 *Development level*, X_{R5}: Defined as the qualification of the quality of life level, organization and urban planning in the area of the district, valued by the Planning Bureau of the city.

2.3.6 *Preparedness emergency planning*, X_{R6}: Defined as the qualification of the preparation and the capacity of institutional response of the emergency operational committee of the district, valued by the Office of Disaster Prevention and Emergency Response of the city.

Figure 3 presents the values of the exposure indicators, social fragility and lack of resilience that compose the descriptor of vulnerability of the context. Figure 4 presents the values of hazard and vulnerability of the context.



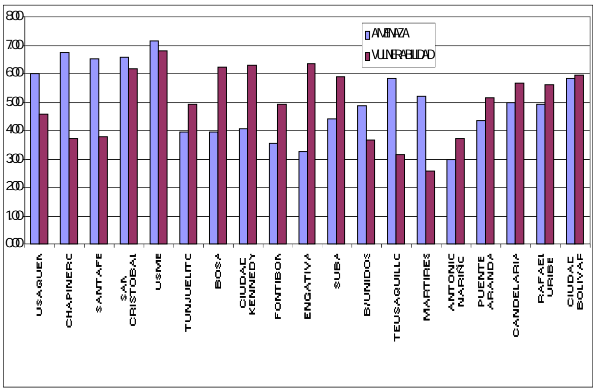
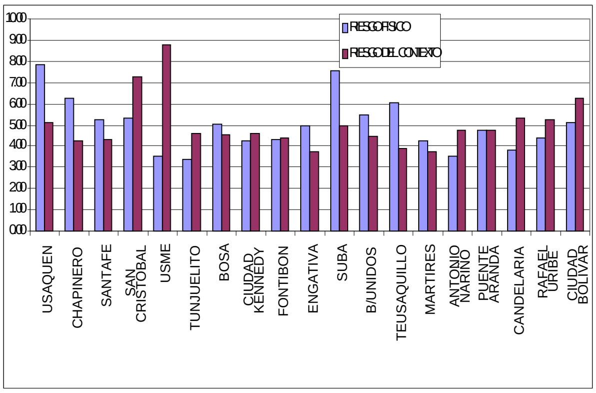


Figure 3:.Vulnerability of context disaggregatede **Figure 4: Hazard and vulnerability of context**

Figure 5 illustrates the values of the hard and soft seismic risk indexes and figure 6 presents the values of the total seismic risk index classified from smaller to larger. This type of graphs allows to categorize and to give priority to the districts presenting the largest comparative values. On the other hand, the disaggregation of the indicators and descriptors allows to identify which indicators have larger comparative incidence and therefore to which of them the mitigation and prevention measures should be addressed.



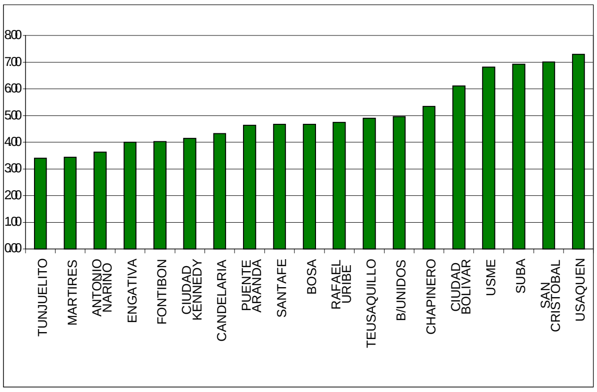


Figure 5: Hard and soft seismic risk indexes **Figure 6: Districts by total seismic risk index**

CONCLUSION

A model for estimating an index of seismic risk has been developed in relation with the districts conforming an urban metropolitan center. This methodology, applied to Bogotá, Colombia, has allowed to classify the hazard, vulnerability and seismic risk of the different districts of the city from a holistic perspective. In this method it is possible to update the value of the variables easily, which favors sensitivity and calibration analyses. In the same way, it can be accomplished the monitoring of the risk scenario and of the effectiveness and efficiency of prevention and mitigation measures. Once the results are shown on graphs, for each one of the towns, it is simple to identify the most relevant aspects of the relative seismic risk, without the need to carrying out bigger analysis efforts and interpretation of results. The main advantage of this technique is the possibility of “returning” by means of the disaggregation of the indexes into descriptors and these, in turn, into indicators, and to identify the reason why a district of the city presents a larger index of risk. This virtue of the method allows to verify the results and to give priority to the prevention and planning actions that should be implemented for intervention and modification of the conditions which have more influence in the seismic risk of the city.

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