Implications on seismic risk assessment for Bogotá as a result of the consideration of a new seismic-tectonic source interpretation for Colombia.

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SUMMARY:

The official seismic hazard map in Colombia was updated in 2010; however, a recent tectonic interpretation, which includes an additional seismic source called Caldas Tear has been taken into account to identify the potential change in the seismic risk results for Bogotá, the capital of Colombia. This paper presents the city's risk results obtained from the consideration of the current and alternative seismic-tectonic models, using a probabilistic approach, considering the local site effects, the inventory of exposed assets and their associated vulnerability functions. The hazard, vulnerability and risk analysis were conducted using the CAPRA platform modules. Results are expressed in terms of probable maximum losses (PML) and average annual losses (AAL) obtained from the loss exceedance probability curve (LEC); these metrics are considered state of the art metrics for probabilistic risk assessment.

Keywords: risk assessment, seismic risk, Bogotá

2. INTRODUCTION

In recent times increased attention has been given to natural disasters and the effects these have on populated areas, including physical effects on infrastructure, economical or financial effects and human affectation. Particularly in the case of developing countries such as Colombia, research related to hazard and assessment and mitigation strategies are all key elements needed to build a much needed disaster risk management culture. The study presented herein is a probabilistic seismic risk assessment that was conducted for the city of Bogotá D.C, Colombia, from which physical losses were estimated. Two different seismic hazard models were used as input, and a probabilistic risk assessment was conducted for the entire exposed assets portfolio considering the local site effects and using vulnerability functions in order to characterize the expected damage for different structural classes. Since a probabilistic approach was followed for the risk assessment, the results are expressed in terms of average annual losses and probable maximum losses for different return periods. With the results for both hazard models it was possible to calculate global losses as well as grouped losses according to structural classes, usage and age.

3. METHODOLOGY

The hazard, vulnerability and risk calculations were performed using the CAPRA platform which allows multi-hazard analysis. This platform uses three modules that result in the associated risk results: the hazard (in this case the seismic hazard), the exposed assets, and their corresponding vulnerability functions (ERN-AL, 2009a; 2009b; 2009c). CAPRA-GIS, the risk calculator, calculates economic losses associated to the expected damage in the exposed assets based on the valuation of these and the vulnerability functions which relate the intensity of the seismic hazard with the mean damage rate. Following this methodology (CAPRA, 2012), the first step was the construction of a database to describe the exposed assets using a building by building level of resolution. The information gathered about each exposed asset includes the structural system, the usage and date of construction. Once the exposure model was defined, vulnerability functions were assigned to each construction class in order to describe the expected damage of each type. Next, a general review and comparison of two available seismic models for Colombia was performed, considering the local site effects through the use of spectral transfer functions from the most recent seismic microzonation study available. Finally, the risk calculations were performed for both seismic hazard models. Figure 1 presents a general flowchart to summarize the process.

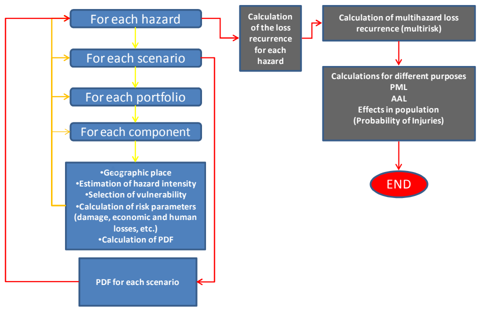

Figure 1. General probabilistic risk assessment process (CAPRA, 2012)

4. SEISMIC HAZARD

4.1. Seismic hazard

The purpose of this study is to compare the seismic risk results according to two different seismic hazard models available for Colombia. One of the models used corresponds to the model included in Colombia's national building code, called the NSR-10 (AIS, 2010; Salgado et.al, 2010) and a second model corresponding to a new tectonic interpretation. This new interpretation corresponds to the inclusion of a new seismic source called Caldas Tear (Salgado et.al, 2011). This source has an east-west direction and the inclusion of this additional source into the National seismic hazard model creates some differences which in some cases result in a lowering of the hazard; this difference for Bogotá can be seen in Figure 2, which shows the uniform hazard spectrum for 475 year return period.

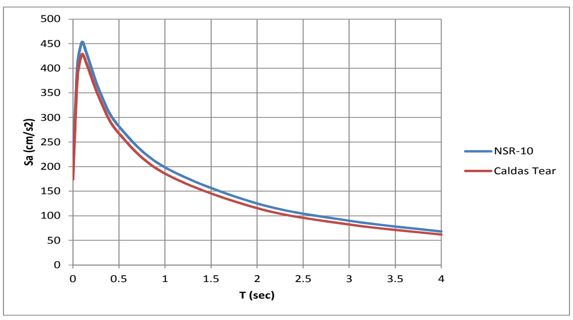

Figure 2. Uniform hazard spectrum for 475 year return period for Bogotá (Salgado et.al, 2011).

4.2. Local site effects

In addition to the national hazard model, the local site effects of the city were included. The site effects study for Bogotá comprises 45 distinct zones, each one having a corresponding spectral transfer function which considers four intensity levels at the base rock to take into account the non-linear behavior of the soil. The consideration of local site effects represents an important aspect for

Bogotá given that there is a significant presence of soft soils which can lead to considerable amplification effects (CEDERI-Universidad de los Andes, 2006). Figure 3 shows an example of three zones which correspond to different types of soil.

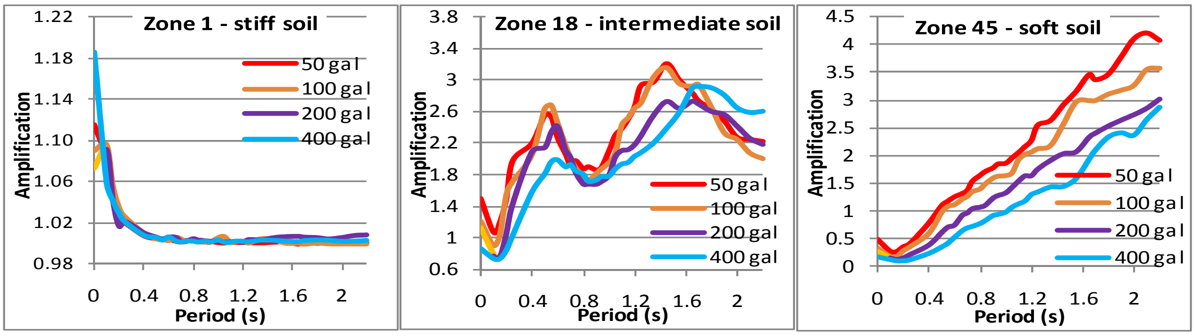

Figure 3. Transfer functions for three types of soil: stiff, intermediate and soft

5. EXPOSED ASSETS PORTFOLIO

The level of resolution available for the exposed assets is a building by building inventory. It is necessary that a minimum amount of information concerning the exposed assets portfolio is gathered so that the city is properly characterized. This is crucial in the sense that the subsequent risk results will describe only the information which was inputted as part of the database, and the objective is that the results provide pertinent information. There are two fields of information that must be known for the exposed elements: the replacement value and the construction type. In this case, information regarding the geographical location, the structural system, age and usage was able to be collected.

5.1 Building stock valuation

The economic replacement value of the entire building stock of Bogotá is presented in Figure 4 by grouping the different assets in District resolution level and block resolution level.

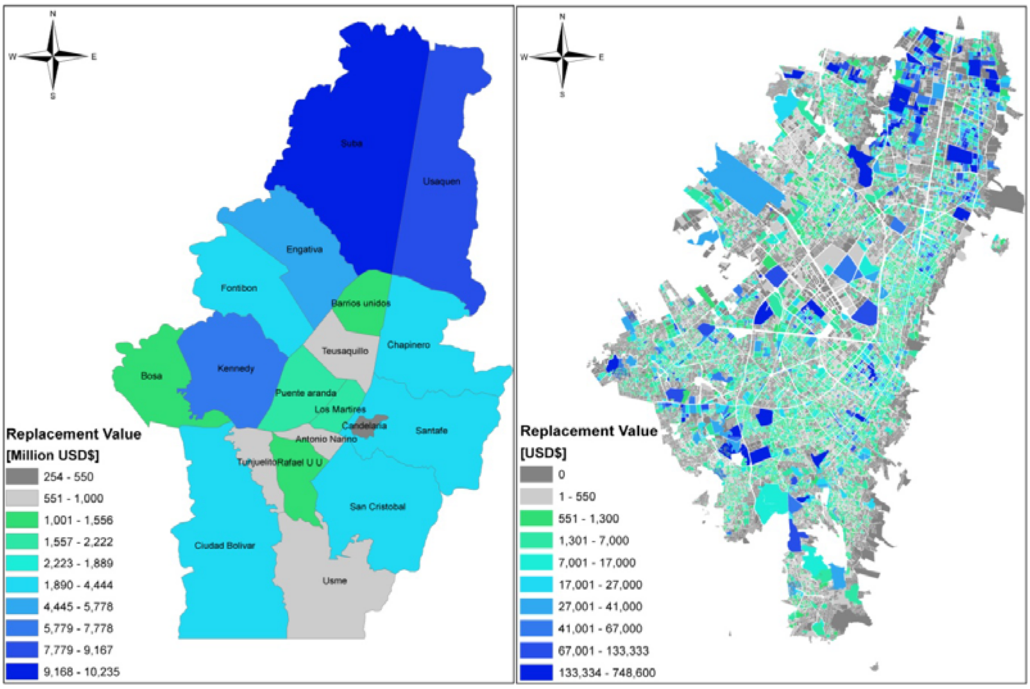

Figure 4. Left: replacement values per District. Right: replacement values per block

5.2 Characterization by structural system

The city's exposed assets were grouped into seven main structural systems: masonry, moment-resisting concrete frames, concrete dual system, slab-column concrete frame, precast concrete, steel frames with light roof and adobe. Table 1 shows the distribution in number and economic value for each of these structural systems.

Table 1. Characterization by construction types

Structural System	Distribution		Exposed Value	
	#	%	US$	%
Masonry (MS)	761,486	88%	23,584,127,263	42%
MR concrete frames (MRC)	32,442	4%	23,796,417,129	43%
Dual systems	1,044	0%	2,056,786,946	4%
Slab-column concrete frames (SCC)	5,463	1%	2,383,661,800	4%
Precast concrete (PC)	12,604	1%	221,230,135	0%
Steel frames (SF)	27,469	3%	3,403,135,532	6%
Adobe (A)	26,407	3%	285,818,845	1%
Total	866,915	100%	55,731,177,650	100%

Figure 5 shows the spatial distribution of the exposure according to this categorization. The masonry constructions are evenly distributed throughout the city, which correlates to the distribution of the residential sector. On the other hand, the adobe constructions are mostly concentrated towards the center/south part of the city, which correspond to the historical sector and the poorest sectors of the city. The opposite occurs with the MR concrete frames which are mostly concentrated on the north-eastern part of the city, belonging to the higher socio-economical area. As far as the steel frames, these correspond to the warehouse type of construction corresponding to industrial constructions.

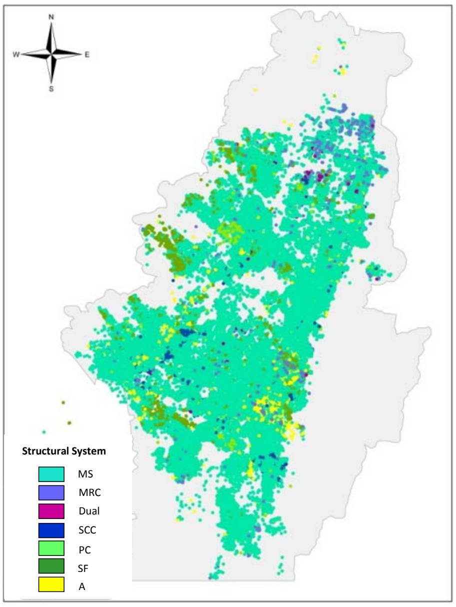

Figure 5. Distribution of buildings by structural system

6. VULNERABILITY OF THE EXPOSED ASSETS

As was discussed in the methodology section, the vulnerability functions relate the hazard (in terms of the intensity, which in this case is spectral acceleration) to the exposed assets though the individually assigned functions according to the structural class. For this study 14 different vulnerability functions were used, which respond to the 7 different structural systems and the different number of stories, as shown in Table 2.

Table 2. Vulnerability functions

Structural System	# Stories	Vul. Function
Masonry	1	S_MS-SLSB-1
	2+	S_MS-RLSB-2
Moment-resisting concrete frames	1	S_PCR-SLSB-1
	2-4	S_PCR-RLSB-2
	3-5	S_PCR-SLSB-B
	5+	S_PCR-RCSB-5
Dual	5+	S_PCM-RCSB-5
Slab-column concrete frame	1-4	S_PCL-RCSB-2
	5+	S_PCL-RCSB-5
Precast concrete	1	S_CP-SLSB-1
	2+	S_CP-FLSB-2
Steel frame	B	S_PAA-SLSB-B
Adobe	1	S_A-SLSB-1
	2	S_A-FPSB-2

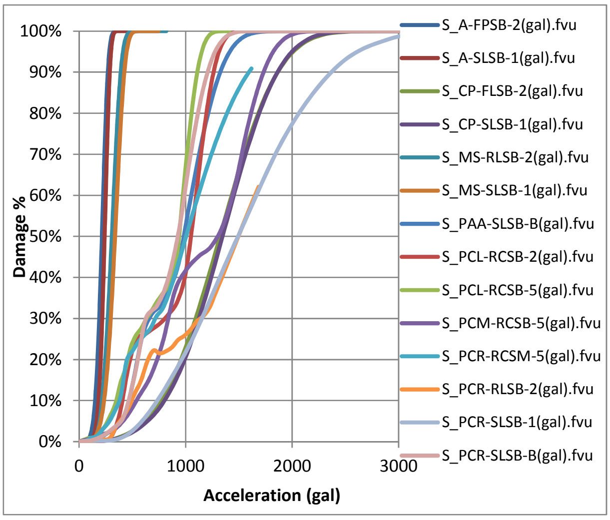

Figure 6. Vulnerability functions used

As can be seen from Figure 6 there is an evident difference between the concrete based structural systems and the masonry and adobe systems, the latter being considerably more susceptible to suffer damages. For an acceleration of approximately 500 cm/s^2 the masonry and adobe systems reach 100% damage, while the concrete systems reach only 25% damage in the worst case.

7. RISK ANALYSIS RESULTS

The results of the probabilistic seismic risk assessment are presented next; these consider the result of the complete set of stochastic scenarios generated as the input for the seismic hazard, the local site effects grid and the characterized assets. The results are presented in terms of expected losses and for different levels of resolution. The comparison is presented for both seismic hazard models; the one developed for the update of the national building code (NSR-10) and the one considering the new geological interpretation (Caldas Tear).

7.2 Risk results with the NSR-10 model

Table 3 and Figure 7 show the general results obtained; these includes the annual average loss (AAL) both in absolute and relative terms, and the values of the expected losses for different return periods (PML) also expressed in both absolute and relative terms. The AAL is approximately $140 million US dollars that corresponds to 2.5‰ of the city's total exposed value. Additionally, if this AAL is compared to Bogotá's 2010 GDP it represents 0.18% (DANE, 2011).

Table 3. General results for the NSR-10 model

Results		
Exposed Value	USD$ x10^6	55,731.11
Annual Average Loss	USD$ x10^6	140.19
	‰	2.516
PML		
Return Period	Loss	
years	USD$ x10^6	%
100	$3,356.15	6.02
250	$5,343.24	9.59
500	$7,013.22	12.58
1000	$8,872.43	15.92

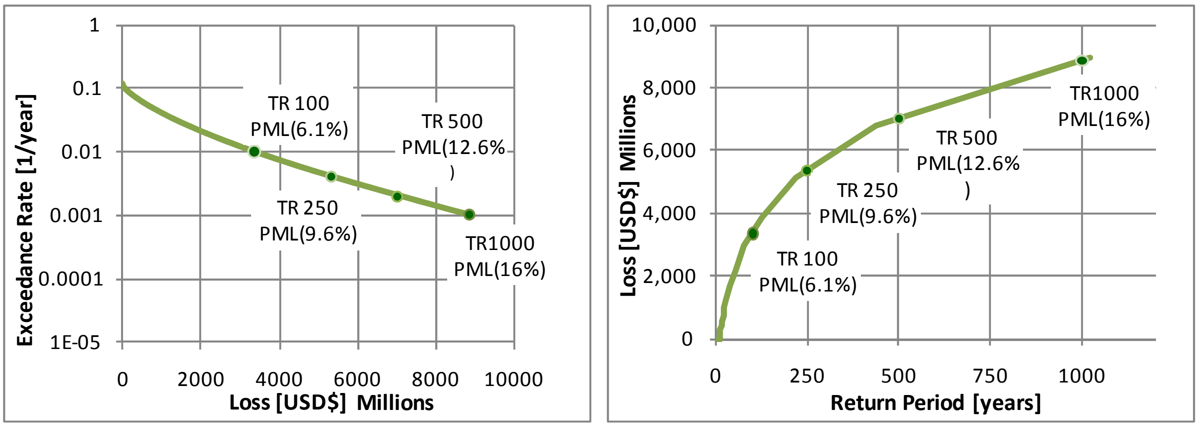

Figure 7. Left: Loss Exceedance Curve (LEC). Right: PML curve for the NSR-10 model

In order to visualize the results spatially throughout the city, the economic losses were grouped by blocks and a map of the city was constructed. Figure 8 presents the expected losses by blocks, expressed first in absolute terms (US dollars) and also in relative terms (percentage of loss with respect to the exposed value). In the map showing absolute value, the higher losses (in red) appear mainly towards the north of the city, which coincides with the wealthier sectors in Bogotá. However, in order to better identify the critical areas, the relative loss was computed with respect to the assets' own exposed value. In this case, the loss distribution changes significantly, indicating that the higher relative losses occur towards the south of the city, where the poorest sectors are located and where the construction is more vulnerable. These figures illustrate the fact that even though the northern area is expected to experience the biggest losses, these are due mainly to the elevated exposed values of the assets, and thus the losses are not so large when calculated relatively. The opposite occurs with the southern area; although the absolute losses are the lowest in the city, the assets have a low economic value, and hence the losses represent a larger part of the exposed value. This analysis allows for a clearer view of the situation: the truly vulnerable areas are the sectors which present high ratios of expected loss to exposed value, and these are more common towards the south.

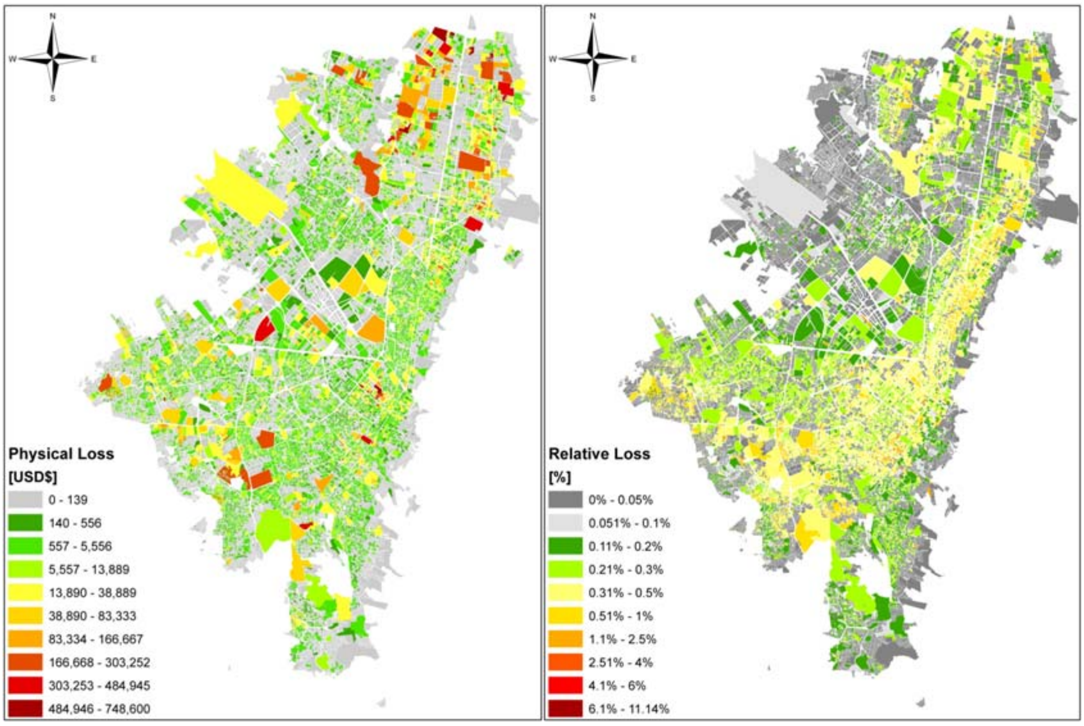

Figure 8. Physical losses by blocks for the NSR-10 model. Left: in US dollars. Right: in relative terms

7.2.1 Results by general usage

The results for the entire building stock were grouped according to the different structural systems in order to identify the different behaviours. They indicate that the residential usage has the largest exposed value, absolute and relative loss. As for the commercial sector, it has the second largest exposed value and absolute loss, but it presents one of the lowest relative losses. The sectors with the lowest relative losses are the institutional and health sectors. These numbers are shown in Table 4.

Table 4. Results by general usage

Usage	Distribution		Exposed Value		Expected Loss		
	#	[%]	US$	%	US$	[‰]	%
Commercial	22,229	2.6%	6,464,644,431	11.6%	13,479,967	2.09	9.6%
Education	3,427	0.4%	925,924,201	1.7%	2,169,707	2.34	1.5%
Industrial	19,617	2.3%	2,239,658,731	4.0%	3,767,469	1.68	2.7%
Institutional	10,629	1.2%	3,669,818,183	6.6%	8,753,924	2.39	6.2%
Health	190	0.0%	244,356,771	0.4%	412,506	1.69	0.3%
Residential	746,124	86.1%	38,951,265,417	69.9%	104,114,656	2.67	74.3%
Others	64,699	7.5%	3,235,509,914	5.8%	7,496,399	2.32	5.3%
Total	866,915	100%	55,731,177,650	100%	140,194,629	2.52	100%

7.2.2 Results by structural system

The results show that the MR concrete frames concentrate the largest exposed value and absolute loss, even though they represent a small percentage of the total exposure, and the relative loss is relatively low. On the other side, masonry buildings represent 88% of the total assets and thus have the second largest value and absolute loss. As for the relative losses, masonry, MR concrete frames, dual systems and slab-column frames all have similar values. The lowest relative losses correspond to precast concrete and steel frames. On the contrary, the largest relative loss corresponds to adobe with a significantly larger value than the rest of the construction types. Table 5 shows these results.

Table 5. Results by structural system

Structural System	Distribution		Exposed Value		Expected Loss		
	#	%	US$	%	US$	[‰]	%
Masonry (MS)	761,486	88%	23,584,127,263	42%	51,014,584	2.2	36%
MR concrete frames (MRC)	32,442	4%	23,796,417,129	43%	68,651,922	2.9	49%
Dual systems	1,044	0%	2,056,786,946	4%	4,425,356	2.2	3%
Slab-column concrete frames (SCC)	5,463	1%	2,383,661,800	4%	7,174,551	3.0	5%
Precast concrete (PC)	12,604	1%	221,230,135	0%	144,497	0.7	0%
Steel frames (SF)	27,469	3%	3,403,135,532	6%	5,256,594	1.5	4%
Adobe (A)	26,407	3%	285,818,845	1%	3,527,126	12.3	3%
Total	866,915	100%	55,731,177,650	100%	140,194,629	2.5	100%

7.3 Caldas Tear hazard model

The results are expressed in the same way as they were on section 7.2. For this model, the overall expected losses are lower than the ones obtained with the NSR-10 model. In this case, the AAL is approximately US$108 million or 1.9‰. If the AAL is compared to Bogotá's 2010 GDP it represents 0.14% (DANE, 2011). Furthermore, a loss of 4.9% is expected to occur an average of 0.01 times per year, a loss of 8.1% approximately 0.004 times per year, a loss of 10.9% approximately 0.002 times per year and a loss of 13.9% approximately 0.001 times per year. These values help illustrate the frequencies with which different losses are expected to occur, and they are shown in Figure 9.

Table 6. General results for the NSR-10 model

Results		
Exposed Value	US$ $x10^6$	55,731.11
Average Annual Loss	US$ $x10^6$	107.78
	‰	1.934
PML		
Return Period	Loss	
years	US$ $x10^6$	%
100	$2,734.22	4.91
250	$4,501.35	8.08
500	$6,087.98	10.92
1000	$7,762.86	13.93

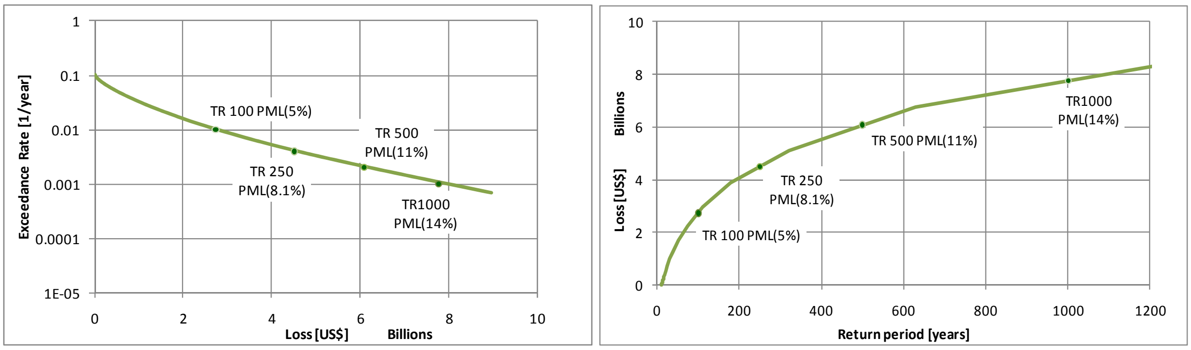

Figure 9. Left: Loss Exceedance Curve (LEC). Right: PML curve for the Caldas Tear model

Figure 10 presents the expected losses by blocks, expressed first in absolute terms and also in relative terms. The maps show the same spatial distribution of losses as was seen in the results with the NSR-10 model; however, both maps have lower loss values in general (the scale is the same as in Figure 8).

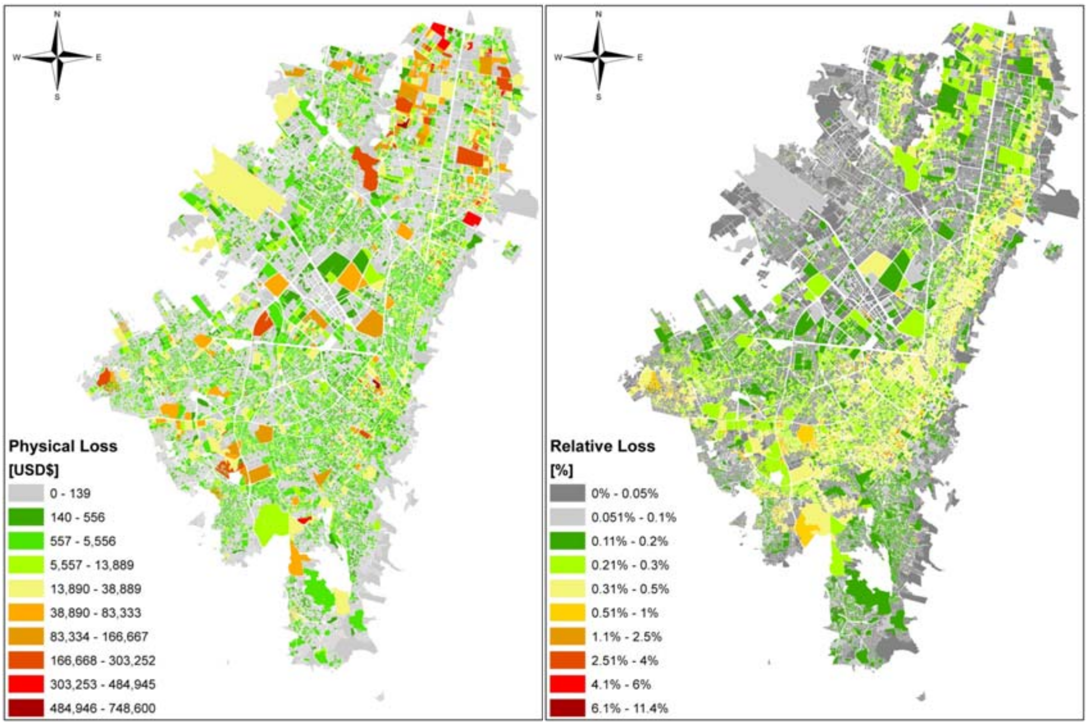

Figure 10. Physical losses by blocks for the Caldas Tear model. Left: in US dollars. Right: in relative terms

7.3.1 Grouped results

In this section the tables for the different grouping categories are presented.

Table 7. Results by general usage

Usage	Distribution		Exposed Value		Expected Loss		
	#	[%]	US$	%	US$	[‰]	%
Commercial	22,229	2.6%	6,464,644,431	11.6%	13,479,967	2.09	9.6%
Education	3,427	0.4%	925,924,201	1.7%	2,169,707	2.34	1.5%
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Others	64,699	7.5%	3,235,509,914	5.8%	7,496,399	2.32	5.3%
Total	866,915	100%	55,731,177,650	100%	140,194,629	2.52	100%

Table 8. Results by structural system

Structural System	Distribution		Exposed Value		Expected Loss		
	#	%	US$	%	US$	[‰]	%
Masonry (MS)	761,486	88%	23,584,127,263	42%	51,014,584	2.2	36%
MR concrete frames (MRC)	32,442	4%	23,796,417,129	43%	68,651,922	2.9	49%
Dual system	1,044	0%	2,056,786,946	4%	4,425,356	2.2	3%
Slab-column concrete frames	5,463	1%	2,383,661,800	4%	7,174,551	3.0	5%
Precast concrete	12,604	1%	221,230,135	0%	144,497	0.7	0%
Steel frames	27,469	3%	3,403,135,532	6%	5,256,594	1.5	4%
Adobe	26,407	3%	285,818,845	1%	3,527,126	12.3	3%
Total	866,915	100%	55,731,177,650	100%	140,194,629	2.5	100%

8. Conclusions

This study estimated the seismic risk in probabilistic terms for the city of Bogotá, Colombia, considering two alternative models for the seismic hazard at country level. As a result, the obtained risk was expressed in terms of expected economic losses, and the metrics commonly used in probabilistic analysis such as the average annual loss (AAL) and the probable maximum loss (PML) for different return periods.

After analyzing the two hazard models, the hazard levels for the city presented by the model with the additional Caldas Tear source were found to be lower than the ones given by the NSR-10 model. Accordingly, the risk analysis produced results in terms of generalized lower losses corresponding to the analysis performed with the Caldas Tear model. This fact was reflected by the decrease in the risk metrics used: AAL of 1.93‰ versus 2.52‰, a PML for a return period of 475 years of 11% versus 12%, and a PML for a return period of 1000 years of 13.9% versus 15.9%.

With respect to the results obtained by grouping the exposed assets by general usage, structural system and construction date, the following conclusions can be stated. Among the six different sectors, the residential sector represents the largest exposed value and relative expected loss. Of the seven construction types, the constructions with adobe concentrate the highest relative loss, even though it represents a minority of the exposed assets in the city (slab-column frames and masonry follow in relative losses). Finally, of the three time periods analyzed, the period prior to 1984 has the lowest exposed value but the highest expected relative loss.

By analyzing the results from the perspective of spatial distribution throughout the city, a few patterns were observed. The eastern-central and south areas of Bogotá concentrate the largest risk of the city due to a combination of factors including structural systems and dates of construction which together create very vulnerable conditions: the adobe construction type is more common in the center and in the south, and also it is in those same areas that most of the buildings built prior to 1984 are located. On the other side, on the northern sector of the city the buildings have more recent construction dates because it is precisely towards the north that Bogotá has been expanding for the past years, which leads to having better construction practices and a reduced associated risk.

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