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IMPLICATIONS ON SEISMIC HAZARD AND RISK ASSESSMENT OF TWO CITIES OF COLOMBIA AS RESULT OF A LITHOSPHERIC TEAR PROPOSAL IN THE NW SOUTH AMERICA

M.A. Salgado[1], D. Zuloaga[2], G.A. Bernal[3], C.A. Vargas[4] and O.D. Cardona[5]

ABSTRACT

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[1] Ph.D.Student. CIMNE, Universitat Politècnica de Catalunya, Barcelona, Spain
[2] M.Sc. Student, Illinois Institute of Technology, Chicago, USA.
[3] Ph.D.Student. CIMNE, Universitat Politècnica de Catalunya, Barcelona, Spain
[4] Associate Professor, Universidad Nacional de Colombia, Bogotá, Colombia
[5] Associate Professor, Universidad Nacional de Colombia, Manizales, Colombia

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Implications on Seismic Hazard and Risk Assessment of Two Cities of Colombia as Result of a Lithospheric Tear Proposal in the NW South America

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ABSTRACT

The new tectonic interpretation proposing the existence of a lithospheric fault system called "Caldas Tear" has led to a new assessment of the seismic hazard model for Colombia using the same methodology and information of the seismic hazard study updated for the national earthquake resistant building code NSR-10. Both models are used for a probabilistic seismic risk assessment of the cities of Bogotá and Manizales, resulting in the loss exceedance curve, probable maximum losses and the average annual loss. For the estimation of the future losses on the buildings of both cities, seismic microzonations have been taken into account. The comparison presents a relative decrease and increase of seismic risk in Bogotá and Manizales.

Introduction

In January 2011 during the American Geological Society's Penrose Meeting held in Manizales, Colombia, the existence of a lithospheric tear structure with an E-W direction crossing the Colombian Andean Region called "*Caldas Tear*" was proposed [1]. Given the fact that this lithospheric tear was not included in the current national probabilistic seismic hazard analysis (PSHA) and considering that it could potentially have influence in the seismic hazard calculations, it was considered relevant to conduct a new national PSHA using the same base information and methodology as the one employed for the Colombian National Seismic Hazard Assessment General Study [2], [3], [4].

As a result of said analysis a set of stochastic earthquake scenarios was obtained, which allowed for a fully probabilistic seismic risk analysis for the building portfolio of two cities, Bogotá and Manizales, resulting in the loss exceedance curve (LEC), from where probable maximum losses (PML) and the average annual loss (AAL) were derived. It is important to note that the cities are located on medium and high seismic hazard areas respectively, and they both have seismic microzonation studies which are fundamental for the seismic risk calculation. Since numerous different building types exist in both cities, a set of general building typologies were identified and individual vulnerability functions were assigned to each of these; the vulnerability curves represent the expected structural response (damage) of

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[1] Ph.D.Student. CIMNE, Universitat Politècnica de Catalunya, Barcelona, Spain
[2] M.Sc. Student, Illinois Institute of Technology, Chicago, USA.
[3] Ph.D.Student. CIMNE, Universitat Politècnica de Catalunya, Barcelona, Spain
[4] Associate Professor, Universidad Nacional de Colombia, Bogotá, Colombia
[5] Associate Professor, Universidad Nacional de Colombia, Manizales, Colombia

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a given typology for different ground motion intensity levels.

A probabilistic risk analysis constitutes a major contribution to the seismic risk management framework both at national and local levels since the obtained results do not only allow for a quantification of the potential future losses, but it also provides a way to assess the macroeconomic impact of future earthquakes and to design financial protection strategies. Financial protection strategies may include retention and transfer schemes (traditional insurance and reinsurance), as well as risk reduction through vulnerability mitigation strategies in the medium and long term.

The lithospheric Caldas tear structure

Vargas and Mann [1] have suggested the presence of a subduction zone beneath the surface of Colombia which presents two distinct trends, one with an eastward dipping direction and another one with a southeastward dipping direction. Cross-sectional interpretations based on relocated earthquake hypocentral solutions, models supported on gravity and magnetic regional data, and attenuation tomography reveal the presence of a ~240 km long east–west-striking slab tear, coined as the Caldas tear, around ~5.5°N. The proposed Caldas tear separates a zone of shallow, 20°–30°-dipping, southeastward subduction in the area adjacent to Panama and the Caribbean Sea (which is not associated with subduction-related volcanism), from an area of steeper, 30°–40°-dipping, eastward subduction in the area adjacent to the eastern Pacific Ocean (associated with an active north–south chain of active arc volcanoes).

Vargas and Mann [1] suggest that the Caldas tear separating these two distinct subducting slabs, originally formed the southern boundary of the Panama indenter, an extinct island arc that began subducting beneath northwestern South America about 12 Ma. The area south of the Panama indenter is Miocene oceanic crust of the Nazca plate, which subducts eastward beneath northwestern South America at normal angles and melts to form a north–south-trending active volcanic arc. Additionally, Vargas and Mann [1] propose that impedance of the thicker crustal area of the Panama arc-indenter over the past 12 Ma may have led to a down-dip break-off of the previously subducted oceanic crust, which is marked by an extremely concentrated and active earthquake swarm of intermediate-depth earthquakes beneath east-central Colombia as shown in Fig. 1.

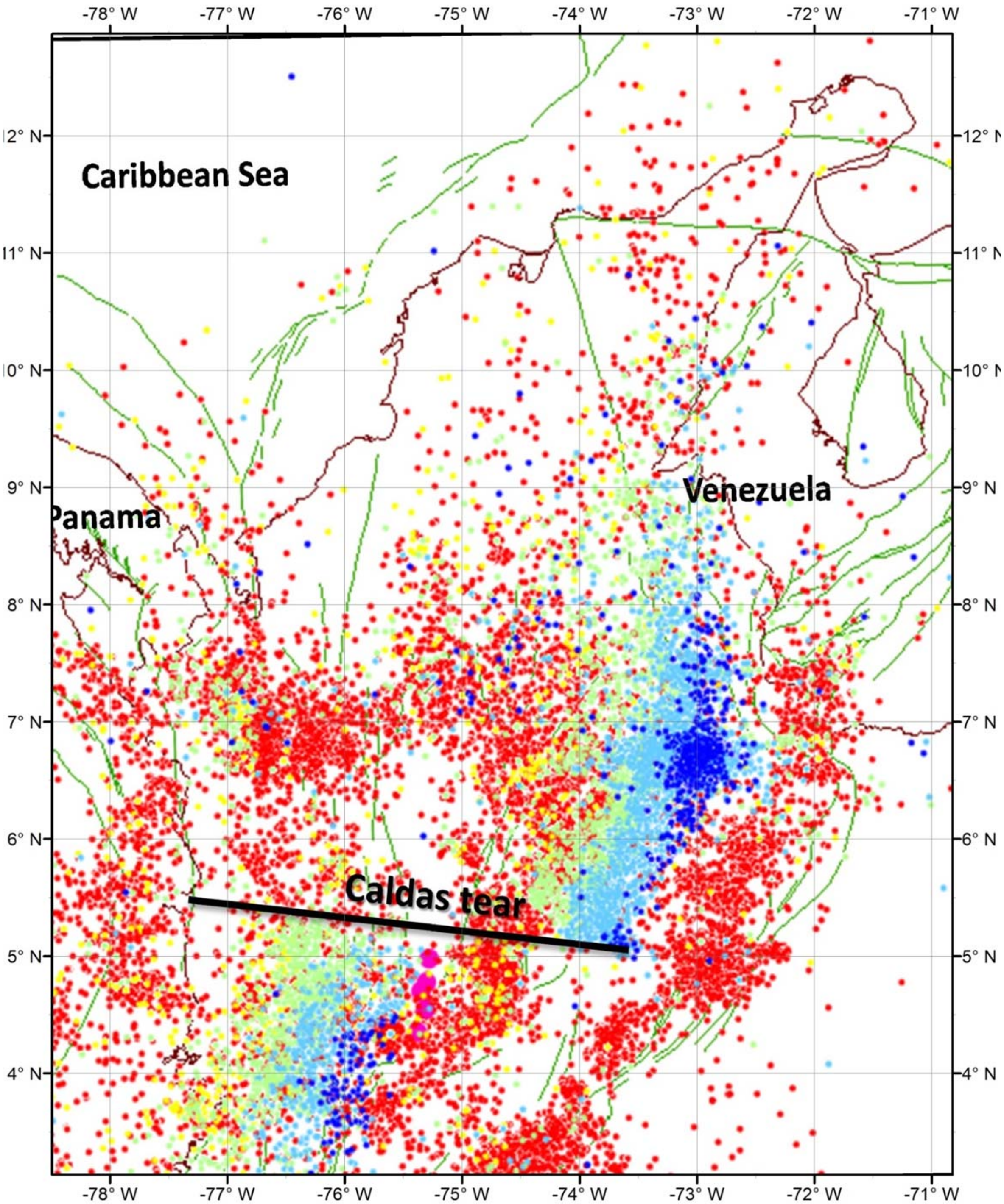

Figure 1. Seismological expression of the lithospheric Caldas tear, a deep faulting system that generates an offset in the hypocentral solutions as well as in the volcanic active belt. Colored points represent earthquakes ($1.0 < M_L \leq 6.5$) from shallow (red) to 200 km depth (dark blue). Other superficial active faults are represented with green lines. The active volcanic belt is insinuated with larger purple points.

Methodology

A fully probabilistic risk assessment was conducted using the different modules that make up the CAPRA[2] Platform. The software CRISIS2007 V7.6 [5] was used for the seismic hazard assessment, whereas the CAPRA methodology and formats [6] were used for the seismic physical vulnerability, and the CAPRA-GIS [7] module was used for the physical risk calculations. For the estimation of the direct physical losses associated to each element in the exposed assets database, an identification and characterization process was first performed to assign structural systems to each element (considering characteristics such as main construction material, number or stories, age and replacement value). Fig. 2 presents the probabilistic risk analysis flowchart employed for the analysis.

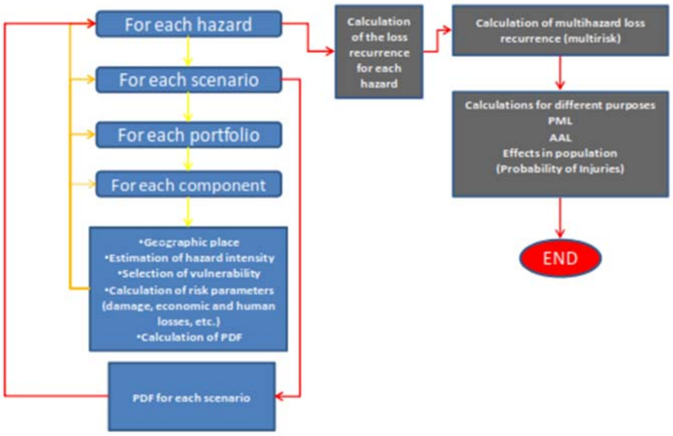

Figure 2. Probabilistic seismic risk assessment flowchart

Seismic hazard assessment

A probabilistic and spectral seismic hazard assessment was performed at bedrock level using the same information available for the Colombian National Seismic Hazard Assessment Study (denoted in this paper as AIS-2009) in addition to the Caldas tear. The exact same catalog was used in both studies given that no major earthquakes have been recorded in Colombia since the AIS-2009 study, and also to facilitate the comparison between models. However, the inclusion of the new lithospheric tear led to a re-assignment of the events included in the catalog.

A local Poisson's seismicity model [8] was used to characterize the seismogenetic sources, where a geometrical area-model was selected for all of them. The Ground Motion Prediction Equations (GMPE's) selected for the analysis are the same as the ones considered in the national study [9], allowing the calculations to be evaluated for different intensities (spectral accelerations, 5% damping) which is required for an exhaustive probabilistic risk analysis. Fig. 3 presents the seismic hazard results in terms of peak ground acceleration (PGA) and a 475 year return period at country level for both models.

As seen from the maps in Fig. 3, there are important differences in terms of the geographical distribution of the seismic hazard in the center of the country. With the obtained results it is possible to calculate the difference in hazard intensity from both models at each point in the calculation grid. Fig. 4 presents the subtraction of the AIS-2009 results from the Caldas

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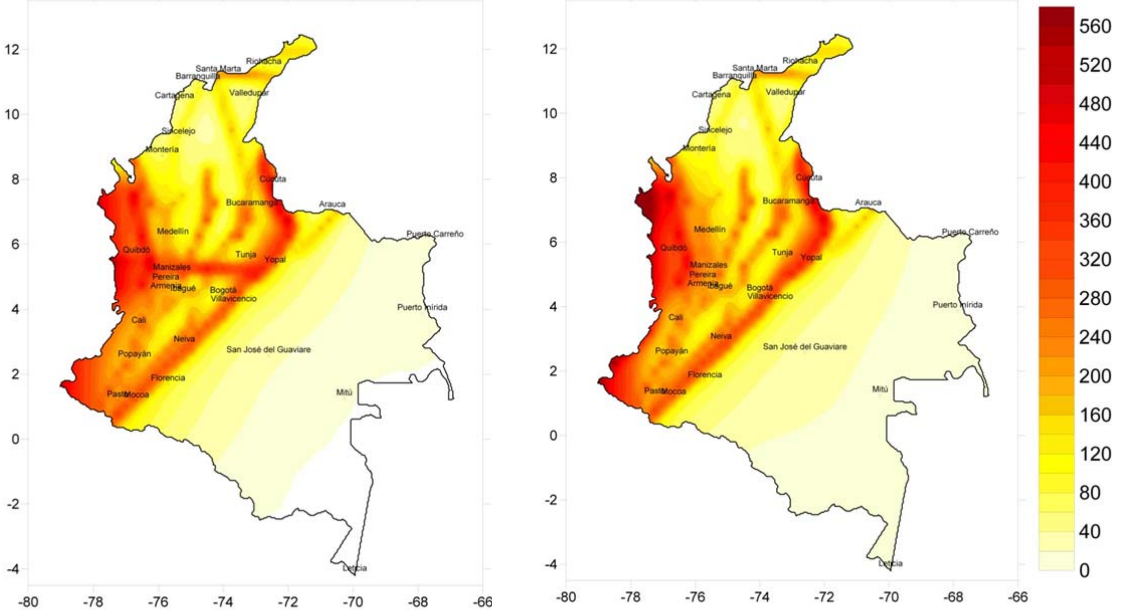
[2] Comprehensive Approach to Probabilistic Risk Assessment (www.ecapra.org)

Tear's results in the area of influence, where the positive difference (red) indicates higher seismic hazard levels with the new model and the negative difference (green) indicates a decrease. Note that there are variations on the seismic hazard results specifically for Bogotá and Manizales, and that is why it was considered relevant to conduct a seismic risk analysis for both cities.

As was mentioned above, sets of stochastic scenarios for each seismic hazard model were generated in order to properly represent the seismic hazard and the associated uncertainties when conducting the risk analysis. All events in the sets are considered to be mutually exclusive, collectively exhaustive and have the intensities' first two statistical moments, the mean and standard deviation.



With Caldas Tear **AIS-2009**

Figure 3. PGA for 475 years return period (cm/s^2) with and without Caldas Tear

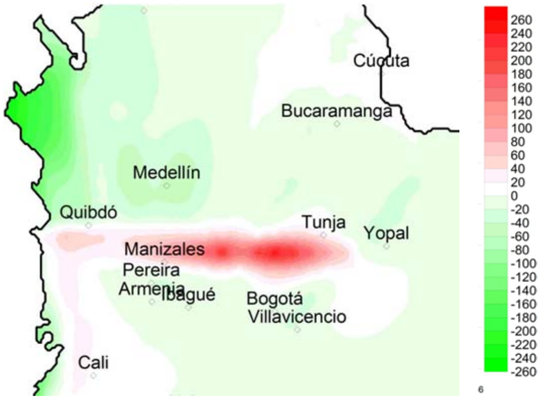


Figure 4. Comparison between the two models for PGA and 475 years return period (cm/s^2)

Site effects

Moreover, when soft soil deposits exist, amplification as well as frequency content and length modifications of ground motion may be of concern and thus should be included when calculating the intensities at ground level. Using the available information from the seismic microzonation studies for both cities, spectral transfer functions were determined and assigned to each of the homogeneous soil zones (45 for Bogotá and 24 for Manizales); these transfer functions were then included in the seismic risk analysis.

Exposed assets database

Bogotá and Manizales are cities that have very good cadastral information, and this allows for a construction of an exposed asset database using a building-by-building resolution. The cadastral information was complemented with a series of characteristics and parameters needed for a seismic risk assessment such as the structural typology, number of stories, age and replacement value. The latter parameter was adjusted by using indexes that take into account the main usage and socio-economic category of each asset. In total, Bogotá's exposed assets database is comprised by 866,915 elements whereas the database for Manizales is comprised by 85,816.

In terms of structural typologies for both cities, systems made of masonry (unreinforced, reinforced and confined), reinforced concrete frames, dual systems, pre-cast concrete and braced steel frames constitute the majority of the distribution. Moreover, earthen structures made of adobe have a considerable number of assets specifically on the cities' centers.

Vulnerability of the exposed assets

Vulnerability functions provide a continuous representation of the expected damages for different intensities of the exposed assets. These functions are assigned to each of the identified building classes based on functions that have been previously developed for both cities [10], [11]. For earthen systems in Manizales, which as mentioned before mainly exist in the historic city center, special vulnerability functions were developed considering different types of roofing systems (light and heavy), as well as the good structural behavior of these structures during previous earthquakes. Fig. 5 presents the employed vulnerability functions; from this figure it is possible to identify significant differences in the expected behavior and damages for different structural systems.

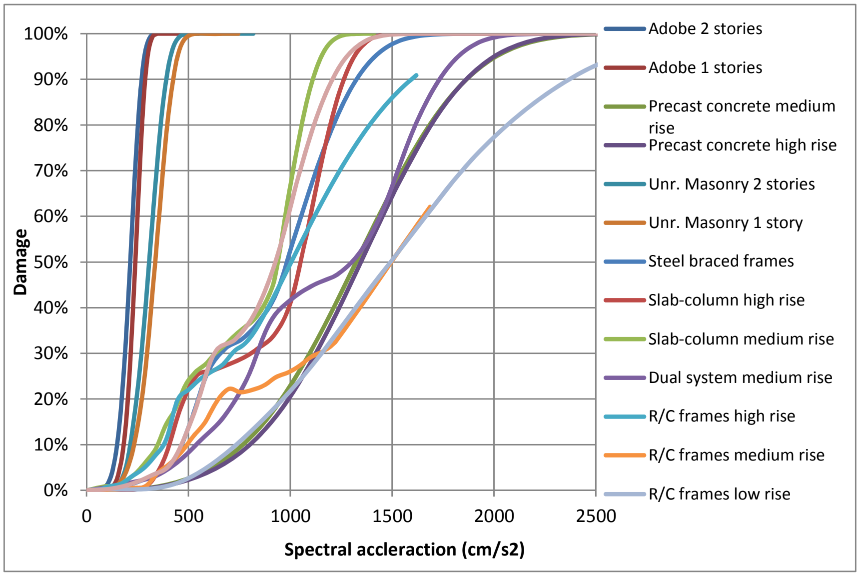


Figure 5. Vulnerability functions used in the study

Seismic risk analysis results

For each event that is included in the stochastic set of earthquake scenarios, the loss probability distribution is calculated by chaining the conditional probability distributions presented in Eq. 1 [12].

$$f(\mathrm{p}|Event\ i) = \int_0^\infty f(\mathrm{p}|Sa)f(Sa|Event\ i)dSa \tag{1}$$

Where $f(p|Event\ i)$ is the loss probability distribution function conditioned to the occurrence of an event, $f(p|Sa)$ is the damage probability distribution function conditioned to the intensity Sa, and $\mathrm{f(Sa|Event\ i)}$ is the intensity probability distribution function conditioned to the occurrence of the event i. Using this information, the loss exceedance rates are obtained for different levels of loss using Eq. 2 [12], where $v(p)$ is the loss exceedance rate, $Pr(P>p|Event\ i)$ is the loss exceedance probability conditioned to the occurrence of Event i, and $F_A(Event\ i)$ is the event's annual occurrence frequency. Using these results it is possible to calculate the loss exceedance curve (LEC) from which other risk metrics such as the probable maximum loss (PML) or average annual loss (AAL) can be derived.

$$v(\mathrm{p}) = \sum_{i=1}^{Events} \Pr(P > p|Event\ i)\, F_A(Event\ i) \tag{2}$$

Results for Bogotá

Fig. 6 presents the seismic risk results[3] for the building portfolio of Bogotá [13], [14] considering both seismic hazard models in terms of the LEC and PML plots. Table 1 compares the AAL for both models, as well as the PML associated to different return periods. Risk results for Bogotá are always lower when the lithospheric Caldas Tear interpretation is included, with a 23% decrease in the AAL and a 10% decrease in the PML for 1,000 years.

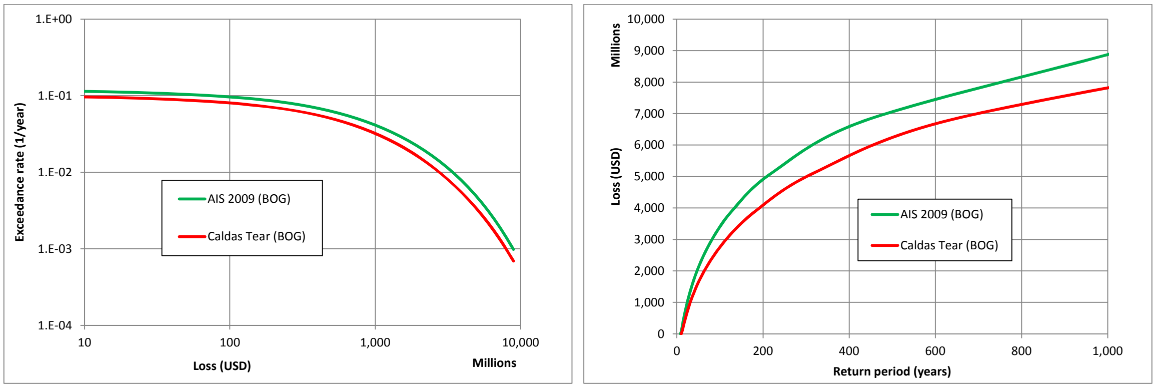


Figure 6. LEC and PML plots for Bogotá

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[3] A Exchange rate of 1USD=1,800 COP was used

Table 1. Risk results comparisons for Bogotá with both seismic hazard models

Model	**AIS-2009**		**Caldas Tear**	
Exposed value	**$\text{COP\$ x}10^6$**	55,731	**$\text{COP\$ x}10^6$**	55,731
AAL	**$\text{COP\$ x}10^6$**	140.19	**$\text{COP\$ x}10^6$**	107.78
	‰	2.516	**‰**	1.934
PML				
Return period	**Loss**		**Loss**	
years	**$\text{USD\$ x}10^6$**	**%**	**$\text{USD\$ x}10^6$**	**%**
100	$3,356.2	6.02	$2,734.2	4.91
250	$5,343.2	9.59	$4,501.3	8.08
500	$7,013.2	12.58	$6,088.0	10.92
1000	$8,872.4	15.92	$7,762.9	13.93

Table 2 presents the risk results classified by structural typologies. From these results it can be concluded that seismic risk in Bogotá is concentrated mainly in earthen and beam-slab reinforced concrete structures. Masonry and R/C frames concentrate the highest risk results in absolute monetary terms, but they also constitute more than 90% of the total number of the dwellings at city level.

Table 2. Risk results by structural systems in Bogotá

Structural type	Distribution		Replacement value		AAL (AIS-2009)			AAL (Caldas Tear)		
	#	%	USD Million	%	USD Million	‰	Participation	USD Million	‰	Participation
Masonry	761,486	87.8%	$ 23,584	42.3%	$ 51.01	2.16	36.4%	$ 41.33	1.75	38.4%
R/C frames	32,442	3.7%	$ 23,796	42.7%	$ 68.65	2.88	49.0%	$ 51.00	2.14	47.3%
Dual systems	1,044	0.1%	$ 2,057	3.7%	$ 4.43	2.15	3.2%	$ 3.32	1.61	3.1%
Beam-column systems	5,463	0.6%	$ 2,384	4.3%	$ 7.17	3.01	5.1%	$ 5.33	2.24	4.9%
Precast concrete	12,604	1.5%	$ 221	0.4%	$ 0.14	0.65	0.1%	$ 0.11	0.48	0.1%
Braced steel frames	27,469	3.2%	$ 3,403	6.1%	$ 5.26	1.54	3.7%	$ 3.83	1.13	3.6%
Adobe	26,407	3.0%	$ 286	0.5%	$ 3.53	12.34	2.5%	$ 2.83	9.91	2.6%
TOTAL	**866,915**	**100.0%**	**$ 55,731**	**100.0%**	**$ 140.19**	**2.52**	**100.0%**	**$ 107.76**	**1.93**	**100.0%**

Results for Manizales

Fig. 7 presents the seismic risk results for the building portfolio of Manizales [13] considering both seismic hazard models in terms of the LEC and PML plots. Table 3 compares the AAL for both models, as well as the PML associated to different return periods. Risk results for Manizales are always higher when the Caldas Tear lithospheric fault interpretation is included, with an 18% increase in the AAL and a 5% increase in the PML for 1,000 years.

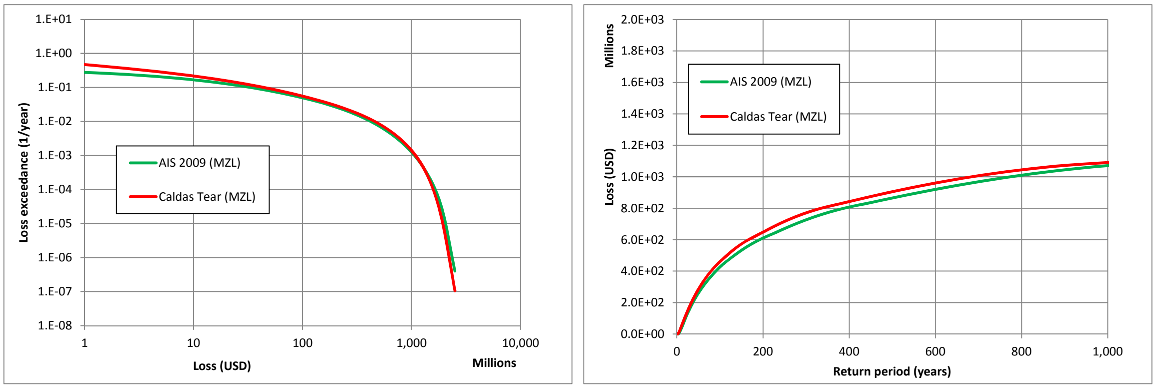

Figure 7. LEC and PML plots for Manizales

Table 3. Risk results comparisons for Manizales with both seismic hazard models

Model	**AIS-2009**		**Caldas Tear**	
Exposed value	**USD$ x10^6**	3,127	**USD$ x10^6**	3,127
AAL	**USD$ x10^6**	19.89	**USD$ x10^6**	23.60
	‰	6.360	**‰**	7.546
PML				
Return period	**Loss**		**Loss**	
years	**USD$ x10^6**	**%**	**USD$ x10^6**	**%**
100	$419.1	13.40	$457.2	14.62
250	$659.3	21.08	$695.1	22.23
500	$852.1	27.25	$878.5	28.09
1000	$1,052.6	33.66	$1,089.8	34.85

Table 4 presents the risk results classified by structural typologies. From these results it can be concluded that seismic risk in Manizales is concentrated both in relative and absolute monetary terms in masonry dwellings, which also constitute the vast majority of the building inventory of the city.

Table 4. Risk results by structural systems in Manizales

Structural type	Distribution		Replacement value		AAL (AIS-2009)			AAL (Caldas Tear)		
	#	%	USD Million	%	USD Million	‰	Participation	USD Million	‰	Participation
Adobe	3,063	3.6%	$ 174,804	3.1%	$ 1,893	10.83	5.3%	$ 1,698	9.71	4.0%
Bahareque	15,222	17.7%	$ 1,184,753	21.0%	$ 6,651	5.61	18.6%	$ 5,515	4.66	13.0%
Precast concrete	349	0.4%	$ 7,771	0.1%	$ 3	0.45	0.0%	$ 4	0.50	0.0%
Masonry	49,838	58.1%	$ 3,035,532	53.9%	$ 23,945	7.89	66.9%	$ 32,273	10.63	76.0%
Beam-column systems	7,716	9.0%	$ 638,033	11.3%	$ 1,871	2.93	5.2%	$ 1,590	2.49	3.7%
R/C frames	9,628	11.2%	$ 587,621	10.4%	$ 1,433	2.44	4.0%	$ 1,394	2.37	3.3%
TOTAL	**85,816**	**100.0%**	**$ 5,628,515**	**100.0%**	**$ 35,798**	**6.36**	**100.0%**	**$ 42,473**	**7.55**	**100.0%**

Conclusions

With the results of the present study it can be concluded that the interpretation of the lithospheric Caldas Tear creates variation on both the seismic hazard and risk in Colombia. In terms of hazard, a 10% increase can be seen for Manizales if compared to the values determined in the national earthquake resistant building code, whereas a 5% decrease in the hazard level can be observed for Bogotá. However, it is worth noting that these variations do not have significant implications in the earthquake resistance design requirements.

Furthermore, and despite the fact that these changes may appear small in terms of hazard, when computing seismic risk they translate into a 23% increase and an 18% decrease on the AAL in Manizales and Bogotá respectively. This effect in risk is important and hence it is suggested that the Caldas Tear be included in risk models focused on risk transfer schemes and instruments.

The LEC of Manizales shows that the increase on the low exceedance rates is around 5%, representing the influence of the moderate and close events that occur with higher frequency; consequently, these more frequent events have a strong influence on the AAL and short return period PML's. Additionally, the results can be disaggregated by categories such as main usage, number of stories, age and socio-economic level [14]. For both cities it was found that buildings constructed before 1984 and in unreinforced masonry concentrate most of the risk. Risk maps can also be generated to present the geographical distribution of expected losses; however, it is important to note that risk is preferably expressed through loss exceedance rates and not only through maps. The obtained results have relevance for the design of risk transfer schemes, such as the collective insurance system that currently exists in Manizales and can be implemented in Bogotá, as well as vulnerability reduction strategies and emergency plans.

Finally, it is important to update these analyses whenever additional or updated information related to any of the topics concerning hazard, exposure or vulnerability becomes available.

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