16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 905

Registration Code: S-A1461766509

SEISMIC DAMAGE SCENARIOS FOR UNREINFORCED MASONRY STRUCTURES OF BOGOTÁ, MEDELLÍN AND CALI (COLOMBIA)

A. Acevedo[(1)], J. Jaramillo[(2)], C. Yepes-Estrada[(3)], V. Silva[(4)]

[(1)] *Professor, Universidad EAFIT, aaceved14@eafit.edu.co*
[(2)] *Professor, Universidad EAFIT, jjarami@eafit.edu.co*
[(3)] *Seismic risk engineer, GEM Foundation, catalina.yepes@globalquakemodel.org*
[(4)] *Seismic risk coordinator, GEM Foundation, vitor.silva@globalquakemodel.org*

Abstract

This study presents a number of earthquake scenarios for unreinforced masonry structures located in the cities of Bogotá, Medellín and Cali, where 12.9 million of Colombians are settled (26% of Colombia's population). These three cities are characterized by a medium to high seismic hazard. Exposure models for each city were developed in which residential buildings were identified according to their structural system, built-up area, replacement cost and number of inhabitants. Results from the exposure models indicate unreinforced masonry structures as the most common building class, a common trend in developing countries. Fragility curves for unreinforced masonry buildings were generated considering the local characteristics of this type of buildings. Seismic damage scenarios were developed for the three cities by the selection of possible earthquakes that could affect each city considering a return period of 475 years. The resulting damage scenarios indicate that events with moderate magnitude could cause slight to moderate damage to 16%, 3% and 20% of the exposed unreinforced masonry building stock in Bogotá, Medellín and Cali, respectively.

Keywords: earthquake scenario; fragility curves; unreinforced masonry structures

1. Introduction

Colombia is located in an earthquake prone region, with more than 80% of its population placed in zones from medium to high seismic hazard. Experiences from previous earthquakes as the Armenia earthquake of January 25th of 1999 (M_w 6.1) and the Popayan earthquake of March 31st of 1983 (M_w 5.6) have exposed the high vulnerability of the residential building stock. As in many Latin American countries, population at capital cities has been rapidly increasing in the last decades. For example, the three largest cities of Colombia; Bogotá, Medellín and Cali, gather 12.9 million inhabitants (26% of the population). Bogotá and Medellín, with 8.0 million and 2.5 million inhabitants, respectively, are located in zones of medium hazard, while the city of Cali, with 2.4 million inhabitants, is characterized by a high seismic hazard.

Although Colombia has a current seismic code that meets international standards, many structures were built before the seismic code became mandatory in the country (year of 1984). In addition, as the population of the main cities is constantly increasing, newcomers usually settle down at city limits in self-built structures that do not meet code requirements. As a consequence, even though unreinforced masonry structures have been forbidden in all of the Colombian seismic codes, an important percentage of the country building stock consists of this type of buildings.

For a developing country such as Colombia, with the majority of its population exposed to seismic hazard, the quantification of its seismic risk becomes a necessity in order to reduce the socio-economic impact of future earthquakes. This work presents results of seismic damage scenarios of residential unreinforced masonry structures for the three largest cities of Colombia. Exposure models for residential buildings were developed for each city; all of the models indicate unreinforced masonry structures as the most common building type, which is a common trend in developing countries. Fragility functions were developed for unreinforced masonry structures considering the local characteristics and construction practice. The developed fragility functions, as well as the exposure models, were used for the definition of significant damage scenarios in each city.

2. Seismic hazard

Colombia' seismicity is the result of the interaction between the Nazca, South America and Caribbean plates. Main sources of seismicity in the country are the subduction in the Pacific Ocean (between the Nazca and South American plates) and crustal seismicity from active geological faults aligned from South to North in the direction of the Andes Mountains. The majority of the country's population (more than 85%) is settled in the Andean, Pacific and Caribbean regions, exposed to medium and high seismic hazard. The latest seismic hazard assessment of Colombia [1] indicates medium seismic hazard for Bogotá and Medellín, and high seismic hazard for Cali.

Main sources of seismicity have been identified for each city by previous microzonation studies [2, 3, 4]. Bogotá is mainly exposed to events from the Pacific subduction zone and crustal events from the Romeral fault system and the Frontal fault system of the East mountain range [2]. Earthquakes of July 12th of 1785 (M_s 7.0), November 16th of 1827 (M_s 7.7) and August 31st of 1917 (M_s of 7.3) caused partial destruction in the city of Bogotá.

Main sources of seismicity of Medellín are crustal events from seismogenic zones located in the North-West of Colombia, events from the seismogenic zone of the "Eje Cafetero" (Middle-West) and shallow seismicity from the Romeral fault system [3]. Two main events have affected the city in the last decades: the Mistrató earthquake of November 23rd of 1979 (M_w of 7.2) which caused damage in several buildings of Medellín, and the Murindó earthquake of October 18th of 1992 (M_w 7.1) that severely damage more than 240 buildings, despite the low acceleration registered in the city [5].

The city of Cali is exposed to events from the interaction of the Nazca and South American plates (subduction interface and intraslab events), and shallow events from active faults such as the Cali-Patía, Dagua-Calima and Guabas-Pradera (South-West) [4]. Events of January 31st of 1906 (M_s 8.2) –one of the biggest one of the XX century–, February 9th of 1967 (M_w 7.0), November 23rd of 1979 (M_w 7.2), January 25th of 1999 (M_w

6.1) and the Pizarro earthquake of November 15th of 2004 (M_w 7.2) are a clear indicator of the high seismic hazard that affects the city of Cali.

3. Exposure models

Exposure models for the cities of Bogotá, Medellín and Cali were developed for microzonation studies [2, 3, 4]. Nevertheless, datasets used for such studies are not publically available. In this work, exposure models for residential buildings of the aforementioned cities have been developed in terms of built-up area, number of buildings, dwellings and inhabitants, building class and replacement cost. The models were generated based on cadastral information, survey data and expert judgment. All of the models are accessible to the general public through the *OpenQuake-platform* (https://platform.openquake.org) and *SARA wiki* (https://sara.openquake.org/risk:detailed_exposure:risk_colombia). Table 1 summarizes built-up area, number of dwellings, number of buildings and replacement cost given by the developed exposure models. Information in Table 1 is given for all of the considered building classes (total) and for unreinforced masonry structures (MUR) building class.

Table 1 – Summary of exposure models

City	Built-up area (km^2)		Number of buildings		Number of dwellings		Replacement cost (millions of Colombian Pesos)	
	Total	**MUR**	**Total**	**MUR**	**Total**	**MUR**	**Total**	**MUR**
Bogotá	179	72	843,856	400,576	1,925,553	778,799	173,547,417	59,172,127
Medellín	79	41	343,123	248,759	730,586	408,226	76,386,242	31,293,915
Cali	68	36	345,965	212,207	696,743	363,341	44,898,183	21,853,471

The models were developed at the neighborhood resolution. Cadastral information, comprising a map of building footprints, built-up area and number of stories, was available for the cities of Bogotá and Medellín. For the city of Cali, a map of built area at block level was available. Additional data was available regarding the socio-economic characteristics and population distribution in the neighborhoods. In Colombia, major cities have classified their neighborhoods into socio-economic strata (SES), based on a scale from one to six, where one refers to areas with the lowest income and six to areas with the highest income. The methodology for the exposure models development is briefly presented in the next section; additional details can be found in [6] and the *SARA wiki*.

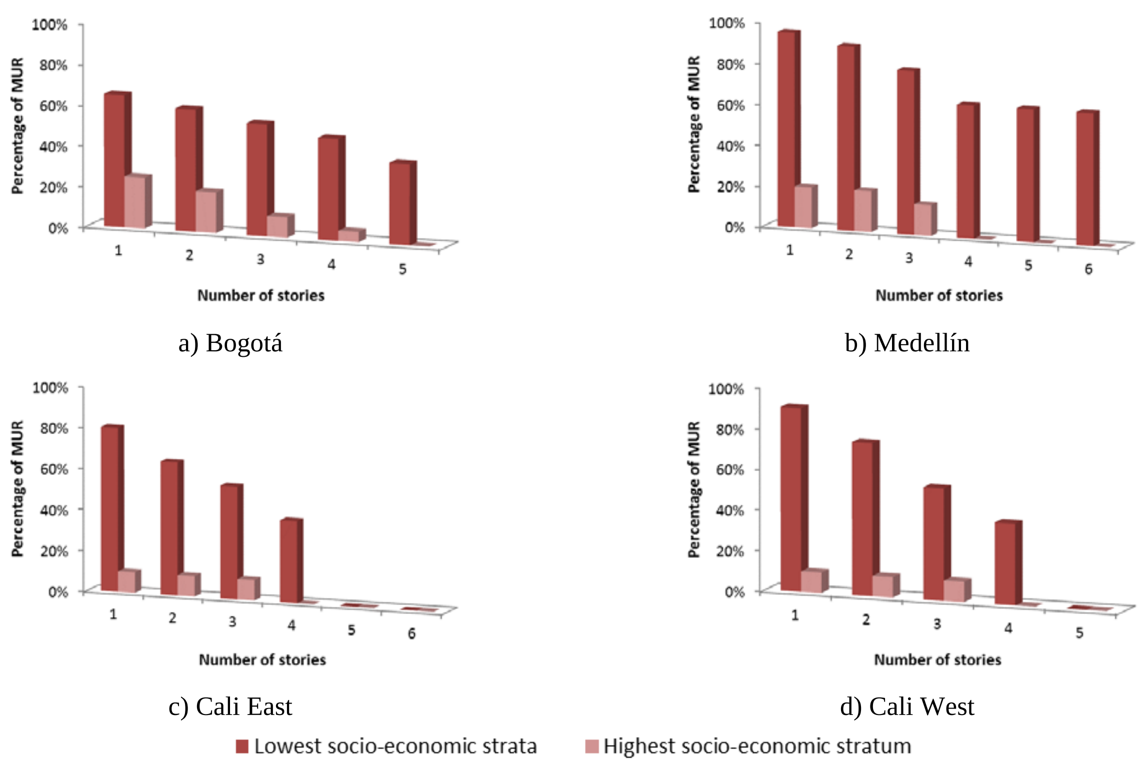
3.1 Structural system distribution

As the cadastral data had no information about structural typology, this parameter was defined as a function of the socio-economic strata (SES) and the number of stories. Information of the number of stories for the cities of Bogotá and Medellín was known from the cadastral data. For the city of Cali, as information on the number of stories was not available, the definition of the structural typology distribution required additional efforts. An initial city overview indicated that difference in topography between the east and west side of the city strongly influences the distribution of the building classes. The city was divided into east and west zones, which were divided once again according to their socio-economic strata. A total of five homogeneous zones were defined and named as strata/zone (1-2-3/East, 1-2-3/West, 4-5/East, 4-5/West and 6/E&W). A total of 3,222 field inspections were carried out in order to define the number of stories distribution shown in Fig. 1. Data from the inspections was also used to define the structural system distribution for each homogeneous zone as a function of the number of stories.

Fig. 1 – Distribution of number of stories for Cali

All of the models included ten main building classes defined by the lateral load resisting system as follows: ductile reinforced concrete infilled frame (CR/LFINF/DUC), non-ductile reinforced concrete infilled frame (CR/LFINF/DNO), reinforced concrete wall system (CR/LWAL), reinforced concrete dual frame-wall system (CR/LDUAL), confined masonry (MCF), reinforced masonry (MR), unreinforced masonry (MUR), reinforced rammed earth (ER+ETR), wood (W) and unknown or other typologies (UNK). Each of these classes was divided according to the number of stories. GEM taxonomy was used for building classification [7]. Building classes were defined based on gathered data from field and virtual visits; the latter were completed by the use of *Google Street View* application.

Fig. 2 shows the distribution of the unreinforced masonry (MUR) building class for the lowest socio-economic strata (1 for Bogotá and Medellín, and 1-2-3 for Cali) and the highest socio-economic stratum (6). It can be observed that unreinforced masonry structures (MUR) are common in the lowest socio-economic strata, mainly for one and two stories buildings. The distributions of the remaining strata levels and building classes are available at the *SARA wiki*.



a) Bogotá

b) Medellín

c) Cali East

d) Cali West

Fig. 2 – Distribution of unreinforced masonry building class for the lowest and highest socio-economic strata

3.2 Replacement cost

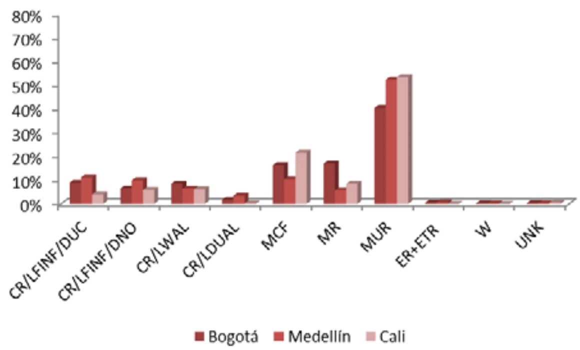
Replacement cost refers to the cost of structural and non-structural components of a building and it is a value associated to building rehabilitation. This value differs from the commercial value, as land price is not included. Construction companies were consulted in order to assume a replacement value per square meter according to socio-economic strata. As the exposure model is given in built-up area, replacement cost can be easily modified in order to update the model. Replacement cost values are given in Colombian Pesos (COP) in Table 2 (1 US = 2.998 Colombian pesos; April 2016).

Table 2 – Replacement cost (Colombian pesos – COP per square meter)

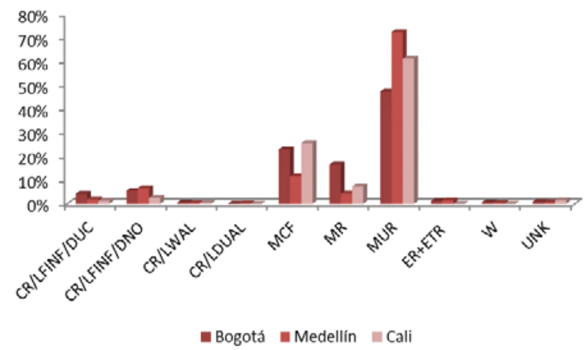
City	Socio-economic strata					
	1	**2**	**3**	**4**	**5**	**6**
Bogotá	625,000	625,000	925,000	1,437,500	1,812,500	2,187,500
Medellín	500,000	500,000	740,000	1,150,000	1,450,000	1,750,000
Cali	400,000	400,000	592,000	920,000	1,160,000	1,400,000

3.3 Number of dwellings and number of buildings

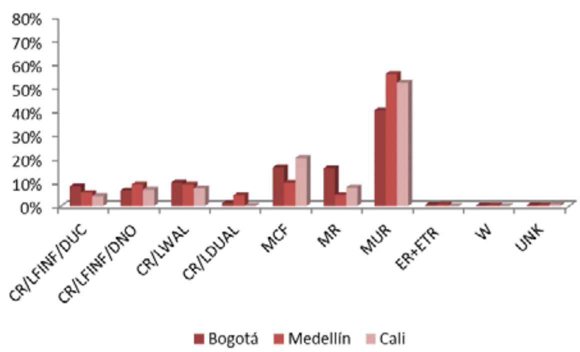
Fig. 3 presents the distribution of the built-up area, number of buildings, number of dwellings and replacement cost according to the building class for the three exposure models.



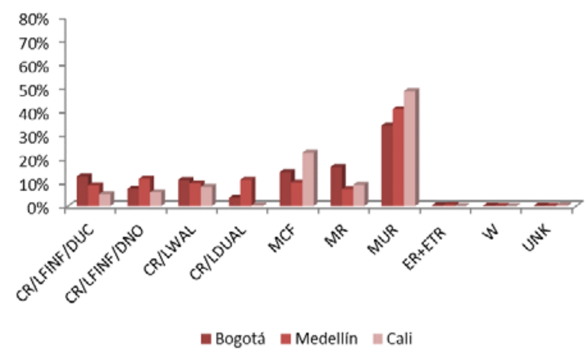
a) Built-up area



b) Number of buildings



c) Number of dwellings



d) Replacement cost

Fig. 3 – Distribution of exposure models parameters as function of building class

Since the exposure model was developed in terms of built-up area, additional information was required in order to define the number of dwellings and buildings. Average dwelling area was defined as function of the building class and socio-economic strata (SES) based on construction statistics and expert judgement. Average dwelling area for unreinforced masonry building class was defined as 69 m^2 (SES: 1), 83 m^2 (SES: 2), 109 m^2 (SES: 3), 130 m^2 (SES: 4), 275 m^2 (SES: 5) and 184 m^2 (SES: 6). Values for the remaining building classes are available at *SARA wiki*.

It can be observed from Fig. 3. that unreinforced masonry structures are the predominant building classes regardless of the considered parameter. The percentage of unreinforced masonry buildings in the exposure model ranges between 45 and 70%, which is not unexpected for a Latin American country. These percentages are in agreement with results from an exposure model recently developed for the residential building stock in South America based on national census data and expert judgement [8], which indicates that approximately 40% of the urban dwellings of Colombia are unreinforced masonry structures.

4. Fragility curves for unreinforced masonry structures

Although unreinforced masonry structures are not permitted by any Colombian seismic code, they still constitute an important percentage of the building stock of Bogotá, Medellín and Cali. The majority of the unreinforced masonry buildings is informal construction at low-income neighborhoods; nevertheless, properly built pre-code unreinforced buildings (built before the year 1984) can be found throughout the three cities. Fig. 4 illustrates some examples of unreinforced masonry buildings in the city of Medellín.

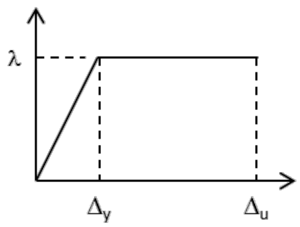
Fig. 4 – Examples of unreinforced masonry structures of Medellín

For a country like Colombia, it becomes a necessity to quantify the seismic vulnerability of unreinforced masonry structures. In this work, analytical fragility functions were computed for six classes of unreinforced masonry structures (from one to six stories). The fragility functions were specifically developed for the characteristics of this type of buildings in Colombia; for that purpose forty unreinforced masonry structures were surveyed in order to capture the variability in geometry and material properties, required for the generation of the capacity curves.

Fragility curves were developed from the results of non-linear time history analyses on single-degree-of-freedom (SDOF) oscillators that represent the capacity curve of each building class. Fig. 5a depicts the calculation of the structural capacity of each building class, as explained in detail in section 4.1. A total of one hundred capacity curves and their respective SDOF oscillator were randomly generated for each building class. Fig. 5a presents the capacity curves for the 3-stories building class (darker line represents the average capacity curve).

4.1 Generation of capacity curves

The structural capacity of each building class was defined by a bilinear curve and computed by a simplified pushover analysis [9]. As can be seen from Fig. 5a, the capacity curve is defined based on the yielding and ultimate displacements (Δ_y and Δ_u), as well as the collapse multiplier (λ). Δ_y and Δ_u are defined based on the total building height (h_T); inter-story height (h_p); inter-story drift corresponding to the drift limit at yield (δ_y) and the collapse drift (δ_u); and parameters k_1 and k_2, which are required to obtain the equivalent single-degree-of-freedom system [10]. The collapse multiplier was computed as proposed by Benedetti and Petrini [11] with two assumptions valid for the majority of the Colombian buildings in which all of the floors have similar weights: i) the lowest floor was assumed as the weakest floor, ii) same wall distribution and shear resistance was assumed throughout the building height. The equation that defines the collapse multiplier (λ) is dependent on the ratio between the area of walls in a floor to the floor area (ρ_{wA}), the ratio of the total building weight to the floor area (ρ_{wt}), the ratio between ρ_{wA} and ρ_{wB} (γ_{AB}), the shear resistance of the masonry (τ_k), the total length of the walls in the direction of the applied seismic loads (L_T) and the total length of the walls without openings in the direction of the applied seismic loads (L_w). ρ_{wB} stands for the maximum wall density between the wall density in the direction of the applied seismic loads and the orthogonal direction. The first term of the equation for λ shown in Fig. 5a corresponds to a correction coefficient for torsional effects [10].

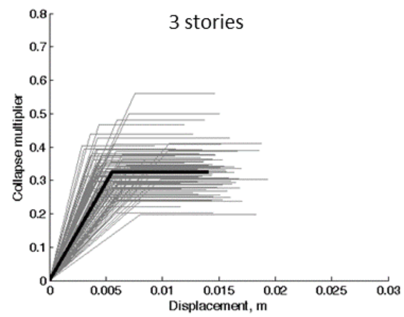


$$\Delta_y = k_1\, h_T\, \delta_y$$

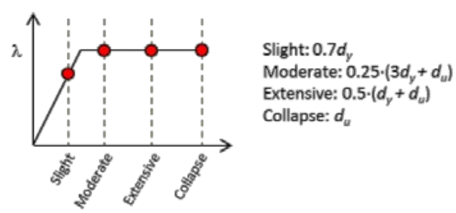
$$\Delta_u = k_1\, h_T\, \delta_y + k_2\,(\delta_u - \delta_y)\, h_p$$

$$\lambda = \frac{1}{5.5\,\frac{\tau_k}{L_w/L_T} + 0.5} \cdot \left\{ \frac{1}{\rho_{wt}}\, \rho_{wA}\tau_k \left[1 + \frac{\rho_{wt}}{1.5\tau_k \rho_{wA}(1+\gamma_{AB})} \right]^{1/2} \right\}$$

Parameter	Mean	Variance	Distribution
ρ_{wx} (m²/m²)	0.05	1.02E-04	Log-normal
ρ_{wy} (m²/m²)	0.0745	1.50E-04	Log-normal
ρ_{slab} (MN/m²)	0.0033	1.45E-07	Log-normal
Dead load (MN/m²)	0.001	---	---
30% of live load (MN/m²)	0.00054	---	---
Inter-story height (m)	2.4	5.55E-02	Log-normal
τ_k (MN/m²)	0.2	0.0025	Log-normal



a) Generation of capacity curves



b) Definition of damage states

Fig. 5 – Generation of capacity curves and damage states definition

Forty unreinforced masonry structures were surveyed in order to gather the information required for the generation of the capacity curves. Fig. 5a indicates the statistical parameters of the gathered data: wall density in the longitudinal and orthogonal direction (ρ_{wx} and ρ_{wy}, respectively), ratio between the slab weight and the floor area (ρ_{slab}) and inter-story height (which was assumed constant for all of the floors of a building). Values of dead and live loads from current Colombian code were used [12] and the masonry shear resistance was taken from experimental results [13] and expert judgement. Additional information required for the capacity curve generation are the yielding and ultimate displacements (δ_y and δ_u, respectively). Values of δ_u and the ratio δ_u/δ_y were established based on experimental results [14] as follows: mean and coefficient of variation of δ_u were set to 0.005 and 11%, respectively; mean and coefficient of variation of δ_u/δ_y were set to 5.0 and 46%, respectively. For both parameters, lower and upper limits were defined as plus/minus one standard deviation.

4.2 Calculation of fragility curves

Non-linear time history analyses of each of the SDOF oscillator of each building class were performed with the oscillator subjected to 300 ground motion records. These records were selected form the PEER (Pacific Earthquake Engineering Research) database, based on the local tectonic environment and seismicity of the studied cities. The dynamic characteristics of the unreinforced masonry buildings were represented by two intensity measure types: peak ground acceleration (PGA) and spectral acceleration (Sa) at 0.4 seconds. A group of 300 ground motion records was selected for each intensity measure type. The estimated maximum displacement of each SDOF due to each record was compared to damage state thresholds defined as shown in Fig. 5b. These damage thresholds were defined based on the yielding and ultimate displacement (d_y and d_u, respectively). The comparison of the oscillator displacement with the damage states thresholds allowed the definition of a damage matrix containing the number of SDOF in each damage state. Data from the damage matrix was used to model the fragility function using a cumulative lognormal distribution. The analyses for the fragility curves derivation were performed using the GEM´s Risk Modeller’s Toolkit [15]. Table 3 presents the statistical parameters of the fragility function of each building class. Additional information can be found in [6].

Table 3 – Parameters of fragility functions for unreinforced masonry building

Building class	**Intensity measure type**	**Slight**		**Moderate**		**Extensive**		**Collapse**	
		Mean	**Std. dev.**	**Mean**	**Std. dev.**	**Mean**	**Std. dev.**	**Mean**	**Std. dev.**
1 story	PGA [g]	1.304	0.654	2.399	1.656	2.982	2.162	5.081	4.738
2 stories	PGA [g]	0.454	0.134	0.736	0.290	1.008	0.413	1.390	0.647
3 stories	PGA [g]	0.324	0.095	0.450	0.150	0.594	0.224	0.778	0.243
4 stories	Sa(0.4s) [g]	0.278	0.081	0.331	0.067	0.418	0.134	0.563	0.141
5 stories	Sa(0.4s) [g]	0.215	0.037	0.286	0.085	0.346	0.105	0.451	0.113
6 stories	Sa(0.4s) [g]	0.204	0.057	0.239	0.067	0.280	0.089	0.359	0.103

5. Seismic damage scenarios

Seismic damage scenarios for the three studied cities were performed in order to explore the seismic risk of their unreinforced masonry building stock. The calculations were performed using the *OpenQuake-engine*, developed by the Global Earthquake Model [16, 17]. A stochastic event based probabilistic seismic risk approach was performed for each city in order to identify the earthquake ruptures capable of generating a number of collapse buildings with a frequency equivalent to a return period of 475 years. To this end, 50,000 years of events were generated based on the probability of occurrence specified in the seismic source model. The rupture that led to a number of collapses that occurred once every 475 years was selected for each city.

The scenarios selected for each city are summarized in Table 4: a magnitude 6.5 (M_w) crustal event with a focal depth of 14 km, corresponding to a right lateral-reverse fault rupture from the *Usme* syncline, located south of Bogotá (epicenter at 4.40 N, 74.09 W); a magnitude 5.5 (M_w) crustal event with a focal depth of 10 km corresponding to a reverse fault rupture located in the Romeral system –the most active fault system of the country–, south of Medellín (epicenter at 6.15 N, 75.65 W); and a magnitude 7.4 (M_w) subduction event with a focal depth of 100 km and epicenter north of Cali at 3.42 N, 77.24 W.

As presented in Table 4, different ground motion prediction equations (GMPEs) were used to account for the epistemic uncertainty in the selection of the ground motion model. In the case of Bogotá and Medellín, three equally weighted GMPEs for active shallow events were considered [18, 19, 20], while for Cali, two equally weighted GMPEs for subduction events were considered [21, 22]. On the other hand, aleatory uncertainty in the ground motion was considered by the generation of one thousand ground motion fields for peak ground acceleration (PGA) and spectral acceleration (Sa) at 0.4 seconds. Site effects were taken into consideration through the shear wave velocity in the 30 meters layer (Vs30). Vs30 values for Medellín correspond to values indicated in the microzonation study of the city [3]; values for Bogotá and Cali were taken from the *Global Vs30 Map Server* from the United States Geological Survey (http://earthquake.usgs.gov/hazards/apps/vs30/).

Table 4 – Selected seismic scenarios in the three cities

City	**Magnitude** (M_w)	**Depth (km)**	**Epicenter**	**Tectonic region**	**Ground motion prediction equations (GMPEs)**
Bogotá	6.5	14.3	4.40 N, 74.09 W	Active shallow	Akkar et al. (2014) [18] Bindi et al. (2014) [19] Boore et al. (2014) [20]
Medellín	5.5	10	6.15 N, 75.65 W	Active shallow	
Cali	7.4	98.7	3.42 N, 77.24 W	Subduction Intraslab	Abrahamson et al. (2016) [21] Montalva et al. (2015) [22]

The present study concentrates on the damage distribution of the unreinforced masonry buildings (MUR), as already described in section 3. Six building classes were considered for Bogotá and Medellín (buildings from one to six stories), while for Cali only five classes were utilized (one to five stories). For each one of the one thousand ground motion realizations, and for each GMPE, mean and standard deviations of number of buildings in each damage state was estimated for each building class presented in the exposure model. Fig. 6 shows the mean collapse map of unreinforced masonry buildings for each city and Fig. 7 shows the damage distribution per building class for each scenario. The mean ground motion field, including all GMPEs, for PGA and Sa(0.4) for the considered scenarios are shown in Fig. 8 and Fig. 9, respectively. It is clear from the results that the expected ground shaking in the city of Medellín is significantly smaller than the expected ground shaking in the cities of Bogotá and Cali.

Results indicate that 16%, 3% and 20% from the total amount of unreinforced masonry buildings would suffer damage (slight to collapse) for the cities of Bogotá, Medellín and Cali, respectively. From the affected buildings 37%, 21% and 33% would suffer extensive damage or collapse in Bogotá, Medellín and Cali, respectively. Buildings with extensive damage and collapse are mainly those with four or more floors, as shown in Fig. 7. Although it would be desirable to validate the results presented in this study, an earthquake with a return period of 475 years has not been recorded in the cities under study. A direct comparison cannot be done with previous studies for Bogotá [23] and Medellín [24] as those studies estimated the losses instead of damage buildings.

Bogotá Medellín Cali

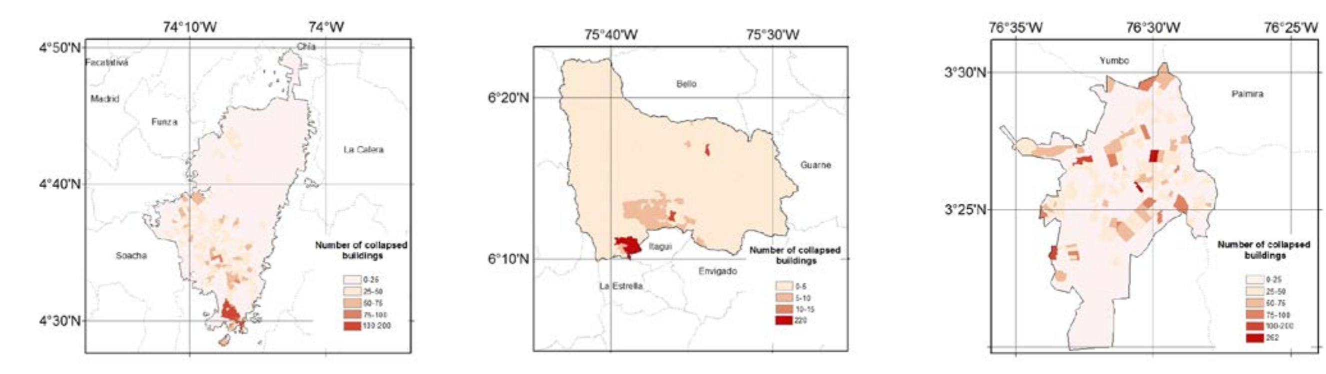
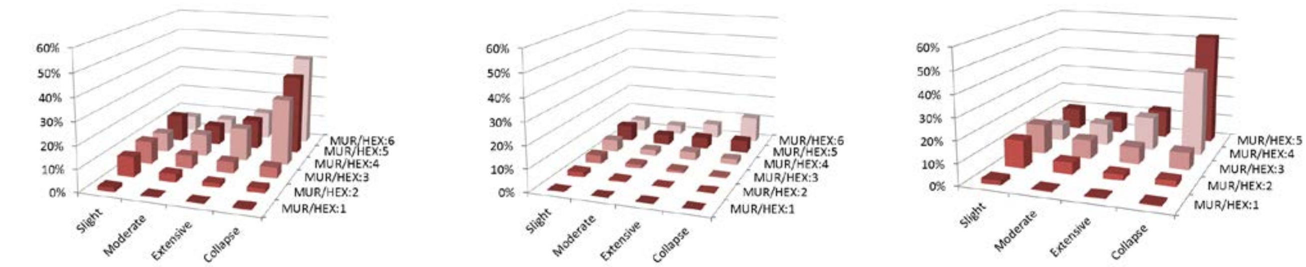
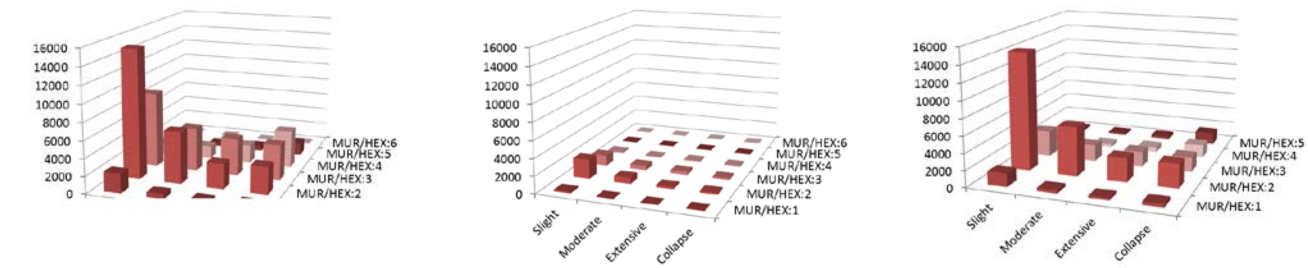


Fig. 6 – Mean collapse map for unreinforced masonry structures

Bogotá Medellín Cali



a) Percentage of buildings in each damage state with respect to total of buildings in a building class



b) Number of building in each damage state

Fig. 7 – Damage distribution per building class

Bogotá Medellín Cali

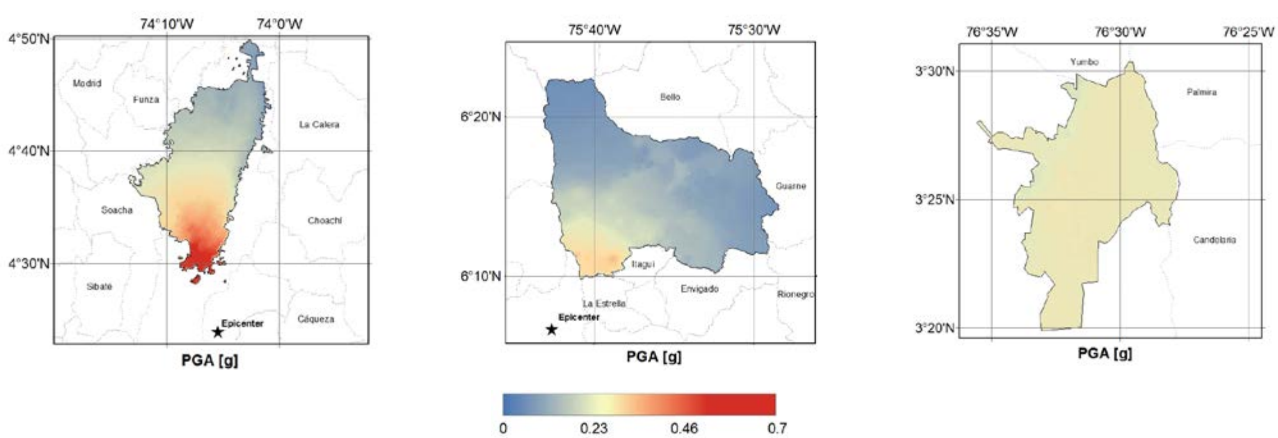


Fig. 8 – Mean ground motion (PGA)

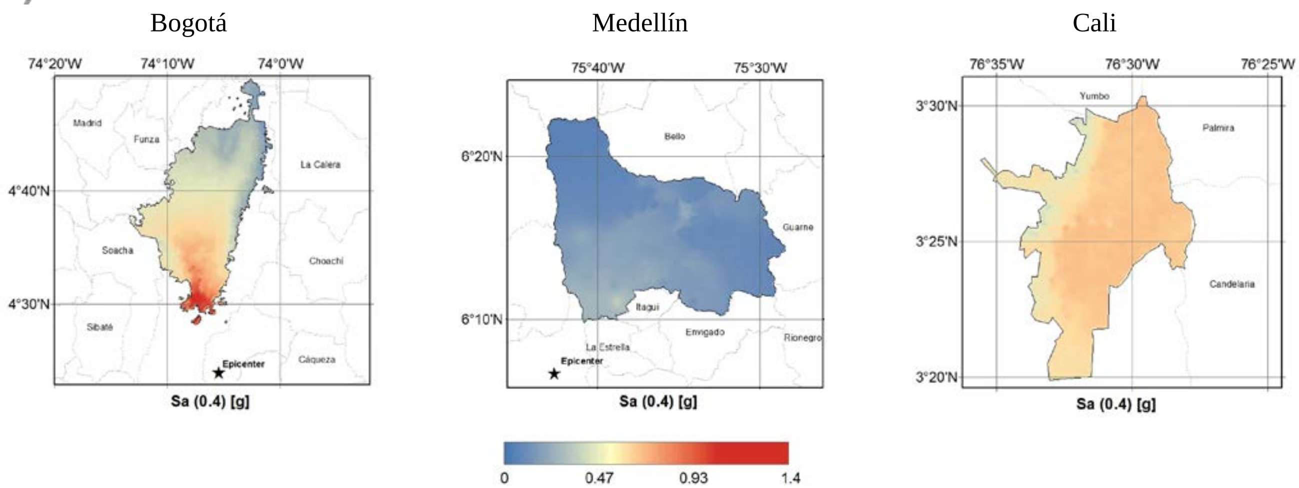


Fig. 9 – Mean spectral acceleration (Sa) at 0.4 seconds

6. Conclusions

Earthquake scenarios for the unreinforced masonry building stock in the cities of Bogotá, Medellín and Cali (Colombia) were presented in this study. Each scenario was represented by a rupture that led to a number of collapses equivalent to the 475 years return period. Results clearly indicate the cities of Cali and Bogotá as the most critical. Comparison of results between the studied cities is reliable as all of the exposure models were developed by the same procedure, same fragility functions and risk assessment methodology.

The high vulnerability of Colombian unreinforced masonry buildings was shown by the scenario results. The large number of unreinforced masonry buildings in the studied cities (around 50% of the total number of buildings) makes of this building class a critical one, which stresses the need to develop appropriate risk mitigation actions for this type of construction. Important attention should be given to unreinforced structures, and retrofitting campaigns should start in order to reduce the risk in each city.

These types of analysis help to improve the understanding of possible earthquake events that can potentially affect the main cities of Colombia. Results could be used for the formulation of disaster risk reduction strategies and the improvement of the cities preparedness.

Acknowledgements

This research was carried out as part of the South America Risk Assessment (SARA) project, supported by the Global Earthquake Model (GEM) Foundation and funded by the SwissRe Foundation. The authors of this work thank both organizations for their support.

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