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ORIGINAL PAPER

Evaluation of the seismic risk of the unreinforced masonry building stock in Antioquia, Colombia

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Abstract This paper presents the development of an exposure model for the residential building stock in Antioquia (the second most populated Department of Colombia), the development of fragility functions for unreinforced masonry buildings, and estimation of building damage for two possible seismic events. Both the exposure and fragility models are publically available and can be used to calculate damage and losses due to single events, or probabilistic seismic hazard. The exposure model includes information regarding the total built-up area, number of buildings and inhabitants, building class, and replacement cost. The methodology used for the creation of the exposure model was based on available cadastral information, survey data, and expert judgment. Fragility functions were derived using nonlinear time history analyses on single-degree-of-freedom oscillators, for unreinforced masonry structures which represent more than 60% of the building stock in the region. Both seismic scenarios indicate that an event corresponding to a return period of 500 years located within the region of interest would cause slight or moderate damage to nearly 95 thousand structures, and about 32 thousand would have severe damage or collapse. This study was developed as part of the South America Risk Assessment project, supported by the Global Earthquake Model and SwissRe Foundation.

Keywords Exposure · Seismic risk · Fragility functions · Masonry buildings

1 Introduction

Over the last four decades, two main seismic events have affected Colombia: the magnitude 6.2 (M_w) Armenia earthquake of 1999 and the magnitude 5.0 (M_b) Popayán earthquake of 1983. Both events caused considerable human losses with 1,185 and 287

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deceased, respectively. The estimated economic losses from these events correspond to 1.88% of the gross domestic product (GDP) in 1999, and 1.5% in 1983 (AIS 2009; Cardona et al. 2004). The experienced damage for relatively small magnitude events is a clear indicator of the high vulnerability of some types of construction in Colombia. In addition, more than 80% of the population is settled in areas of medium to high seismic hazard, thus characterizing Colombia as a country with a high seismic risk.

For a developing country such as Colombia, the reduction in the economic impact of earthquakes and the improvement in public safety are fundamental. As a first step, a reliable seismic risk assessment is required, as this information can be used to support earthquake disaster management and mitigation. An initiative from the Inter-American Development Bank (IDB), among others, has estimated the seismic risk of some Latin-American countries (including Colombia), through the development of Indicators of Disaster Risk and Risk Management (http://idea.unalmzl.edu.co/). Some efforts have been done in the main cities of Colombia such as Bogotá, Medellín, and Armenia, in which the estimation of earthquake loss scenarios has been performed (Cardona et al. 1997; Salgado et al. 2013; Salgado-Gálvez et al. 2014; Consorcio Microzonificación 2007).

Seismic hazard, exposure, and vulnerability information for the region of interest are required in order to assess its seismic risk. The first seismic hazard study for Colombia dates from 1972 (Atuesta 1972), and it has been updated several times. The results from the latest seismic hazard assessment of the Colombian Association of Seismic Engineering (AIS 2009) are featured in the current seismic regulation, the NSR-10 (AIS 2010). For what concerns exposure, several models have been compiled for Bogotá, Medellín, Manizales, Cali, and Bucaramanga, mainly for the purposes of microzonation, in which the main structural characteristics of the building portfolio and soil conditions are described. For what concerns structural vulnerability, a few models have been specifically developed for Colombia, such as the one proposed by Bonnet (2003) for reinforced concrete frames for the city of Manizales. Moreover, fragility/vulnerability curves for building classes such as confined masonry, reinforced masonry, unreinforced masonry, adobe, earth, reinforced concrete frames, pre-cast concrete, and dual frame-wall system have been used in the risk assessments previously mentioned. Although the final results of the aforementioned studies have been released to the public, the majority of the information such as hazard and exposure datasets, and the statistical parameters that represent fragility/vulnerability curves were kept private. The lack of data was one of the greatest challenges, as well as the motivation, in the development of the current study.

The present manuscript describes an exposure model and fragility functions for unreinforced masonry structures for the region of Antioquia. In order to explore the reliability and usefulness of these models, two earthquake scenarios were performed. 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 SwissRe Foundation. The exposure model and fragility functions are accessible to the general public through the OpenQuake platform (https://platform.openquake.org) and SARA wiki (https://sara.openquake.org/risk).

2 Seismic hazard in Antioquia

Colombia is located in the *Ring of Fire*, a zone where approximately a third of the global seismicity takes place. The seismic activity in the country is the result of the interaction of the Nazca, Caribbean and South America tectonic plates. This interaction generates regions of low, medium, and high seismic hazard.

Fig. 1 Geographical organization of the region of interest

Antioquia, the second most populated department of Colombia, is located in the northeast of the country as can be observed in Fig. 1. Antioquia is divided in nine sub-regions with 125 municipalities. The most populated area is the Aburrá Valley (*Valle de Aburrá*), where more than 58% of the population of the Department is concentrated. The Aburrá Valley has approximately 80 km length and constitutes the metropolitan area of Medellín, the capital city. It includes the municipalities of Medellín, Caldas, La Estrella, Sabaneta, Envigado, Itagüí, Bello, Copacabana, Girardota and Barbosa.

In the case of Antioquia, the latest seismic hazard assessment of Colombia (AIS 2009) indicates medium hazard for 62% of the municipalities and high hazard for the remaining 38%. Only two of the municipalities of the Aburrá Valley (Caldas and La Estrella) are classified with high seismic hazard. The main sources of seismicity are crustal events from seismogenic zones located in the North-West of Colombia, depth and shallow events from the seismogenic zone of the "Eje Cafetero" (Middle-West), deep events from the subduction of the Nazca Plate under the South American plate, and shallow seismicity from the Romeral fault system. Romeral is the most active fault system of the country, with an approximately total length of 700 km (Pulido 2003).

Figure 2 presents the distribution of both historical and instrumental seismic events for magnitude larger than 4.0 (M_w) for Antioquia and its surroundings, as well as the active faults near the Department. Instrumental events of Fig. 2a were extracted from the Colombian Geological Survey, SGC (http://seisan.sgc.gov.co/RSNC/index.php/consultas/

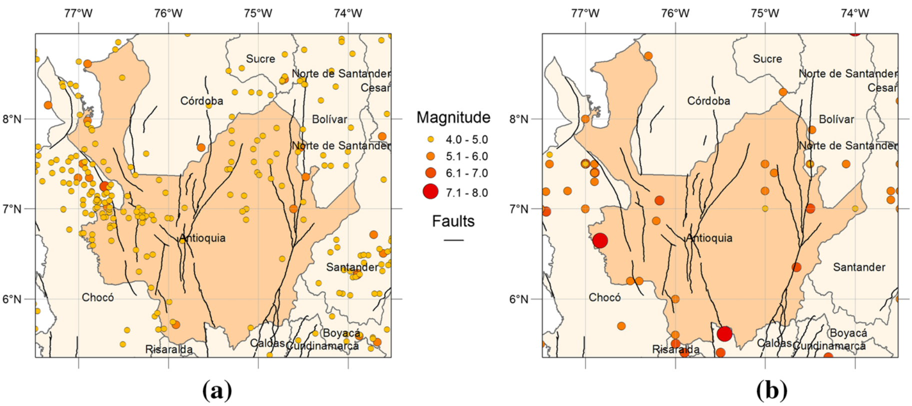


Fig. 2 Seismic events of Antioquia. **a** Instrumental events. **b** Historical events

consulexp). The historical events of Fig. 2b have been taken from the historical catalogue developed by the *SARA project*.

Two main earthquakes have affected the region over the past 50 years: the crustal Mistrató earthquake of 23 November 1979 with a magnitude of 7.9 (M_0), in which several buildings were damaged, and the Murindó earthquake of 18 October 1992 with a magnitude of 7.3 (M_s), generated by the seismogenic zone of the “Eje Cafetero”. In the latter event, more than 240 buildings were heavily damaged (Martínez et al. 1994), despite the low acceleration registered in Medellín (the epicentre was located about 150 km away). Four historic events are reported by Ramírez (1975) with an epicentre around Medellín: the 13 April 1972 event, in which several houses were destroyed; and the events of 15 September 1868, 31 October 1928 and 11 October 1966. As paleoseismic studies are scarce in the region, there is great uncertainty associated with the historical events.

3 Exposure modelling of the building stock

As in many Latin-American countries, the building stock, infrastructure, and population are mainly concentrated in a few regions. In Colombia, 59% of the population is located in only 6 of the 32 departments. The second most populated department is Antioquia, with more than 6 million inhabitants (14% of Colombia’s population) and an area of 63,612 km^2. Antioquia is divided in 9 sub-regions with 125 municipalities. The sub-region of the Aburrá Valley constitutes the metropolitan area of Medellín, the capital city; it gathers ten municipalities and 58% of the Department’s population.

Although a modern seismic code is available for the country, an important number of buildings in Antioquia does not comply with its minimum requirements. Formal construction is usually located in the municipalities of Medellín, Envigado, Itagüí and Bello, and in some developing areas within other municipalities (Consorcio Microzonificación 2007). However, a significant amount of informal construction can still be found in these regions, due to the rapid increase in population in the last decades. In addition, many residential buildings built before the year of 1984 did not include seismic provisions, as the first seismic code was released in that year. Yepes et al. (2016) estimated that 65% of the Colombian building stock has a lateral load resisting system not appropriated to sustain seismic loads, while Mejía (2011) indicates that approximately 60% of the housing stock of Antioquia is non-engineered unreinforced brick masonry buildings.

The exposure model for Antioquia developed in this study indicates a total of 147 km^2 of built-up area, and 834 thousands of buildings. The Aburrá Valley sub-region has a total of 109 km^2 built-up area and 476 thousands of building; the city of Medellín has a total of 79 km^2 of built-up area and 343 thousands of buildings. The total replacement cost for the residential building stock of Antioquia was estimated as 135×10^6 million Colombian Pesos—COP/43,038 million US dollars (values of replacement cost are given in COP as the exchange rate to US dollars fluctuates severely for this currency; the average exchange rate for the first semester of 2016 corresponds to 1 US dollar =3140 COP). For the Aburrá Valley and Medellín, the total replacement cost was estimated as 97×10^6 million COP (30,982 million US) and 76×10^6 million COP (24,327 million US), respectively. Replacement cost refers to the cost of structural and non-structural components, and it is a value associated with building rehabilitation. This value differs from the commercial value, as land price is not included. It must be kept in mind that after a seismic event, a structure must be repaired according to modern seismic regulations, regardless of the structural system.

Building classes included in the exposure model were defined according to the lateral load resisting system, construction materials, and number of storeys. Differentiation between ductile and non-ductile structures was specified only for reinforced concrete structures. For Medellín and the Aburrá Valley, 80% of the reinforced concrete frame buildings between one and five storeys were assumed as non-ductile as they were mainly built before 1984; the remaining reinforced concrete frame buildings were considered as ductile. On the other hand, even though the majority of the reinforced concrete frames outside of the Aburrá Valley have been built in the last few decades when seismic design was already mandatory, informal construction is still common in those municipalities. For that reason, 50% of the reinforced concrete frames outside the Aburrá Valley were assumed as ductile, while the remaining 50% were assumed as non-ductile. The GEM taxonomy was used for the building classification (Brzev et al. 2013). Table 1 presents the list of the resulting building classes. A total of 121 building classes were included in the model. Figure 3 presents the replacement cost, built-up area, and building distribution for Antioquia, the Aburrá Valley, and Medellín.

It can be observed from Fig. 3 that the majority of the built-up area of Antioquia corresponds to unreinforced masonry structures, with a total of 78 km^2, representing 508 thousands of buildings (53% of the total built-up area and 61% of the building stock). This type of structures has been forbidden by all of the Colombian seismic codes, but it is still common in the region. Confined masonry constitutes the second most common building typology in Antioquia with a built-up area of 16 km^2, representing 97 thousands of buildings (11% of the total built-up area and 12% of the building stock).

An innovative methodology is described for the development of the exposure model of Antioquia, which allows the calculations of the built-up area, number of buildings, number of storeys, and structural system. Three exposure models have been developed, for each

Table 1 Building classes of the exposure model

Building class	GEM taxonomy	
	Material and system	Number of storeys
Reinforced concrete infilled frame, ductile	CR/LFINF/DUC	HEX:1 to HEX:24
Reinforced concrete infilled frame, non-ductile	CR/LFINF/DNO	HEX:1 to HEX:6
Reinforced concrete wall system	CR/LWAL	HEX:4 to HEX:39
Reinforced concrete dual frame-wall system	CR/LDUAL	HEX:11 to HEX:39
Confined masonry	MCF	HEX:1 to HEX:7
Reinforced masonry	MR	HEX:1 to HEX:7
Unreinforced masonry	MUR	HEX:1 to HEX:6
Unreinforced stone masonry	MUR + STRUB	HEX:1
Reinforced rammed earth[a]	ER + ETR	HEX:1 or HEX:2
Wood[b]	W	HEX:1 or HEX:2
Unknown or other typologies	UNK	HEX:1

[a] This building class aggregates both rammed earth and wattle and daub buildings

[b] Non-engineered wood

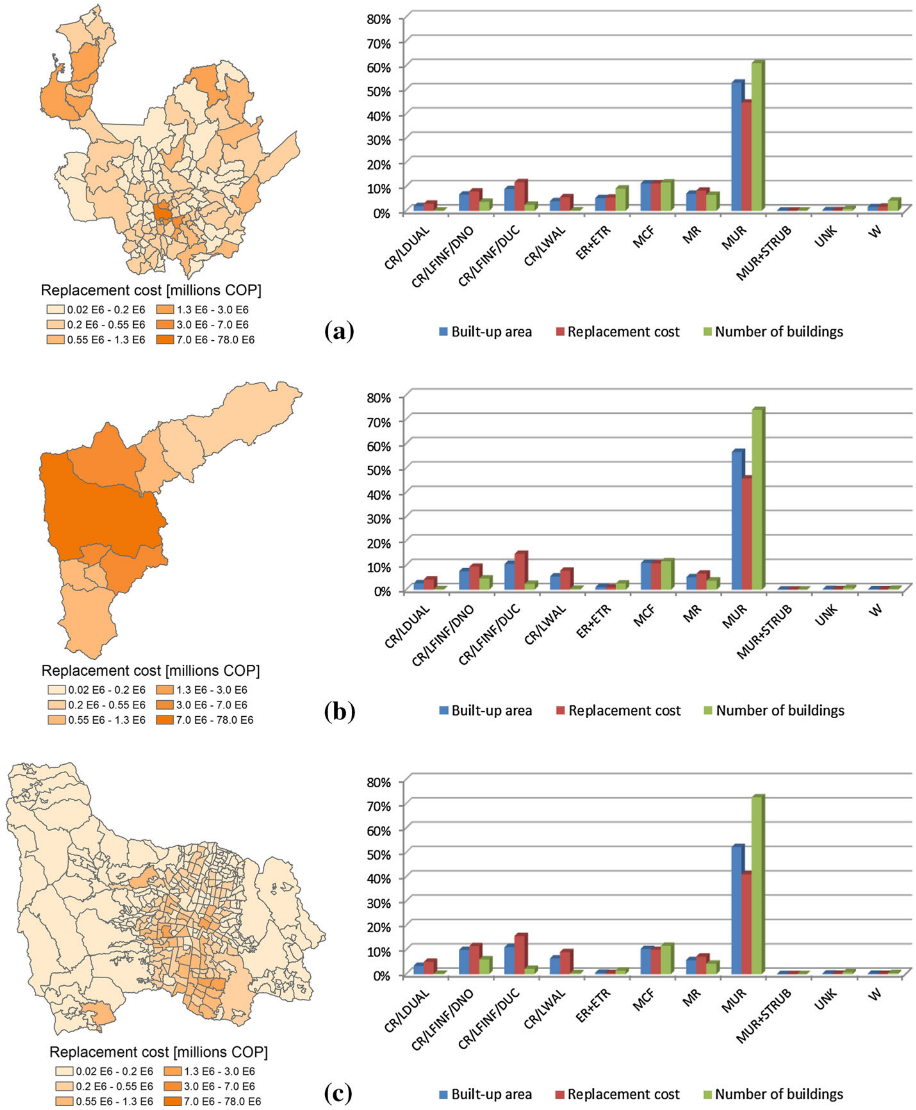


Fig. 3 Replacement cost, built-up area, and building distribution for Antioquia (**a**), the Aburrá Valley (**b**), and Medellín (**c**)

one of the three regions: the city of Medellín, the metropolitan area (Aburrá Valley sub-region without Medellín), and the remaining 115 municipalities. Data availability was the main reason for the development of three different models. Table 2 presents a summary of the available information for each exposure model. A description of the assumptions made in order to generate the missing data referred in Table 2 is presented in the next section. The methodology developed for the exposure model definition can be applied to any location, granted that the minimum information is available.

The exposure models include information about the location (neighbourhoods for the model of Medellín, and municipalities for the other two models), the number of

Table 2 Available and required data for exposure model development

Required data	Available information for each region		
	Medellín	Aburrá valley	Other municipalities
Built-up area	Cadastral map of year 2012 (building resolution)	From homogenous areas defined in the microzonation study of Medellín and the Aburrá Valley	Cadastral map of year 2012 (for some municipalities)
Number of floors	Cadastral map of year 2012 (building resolution)	Distribution from previous studies	Cadastral map of year 2012 (for some municipalities)
Structural system distribution	N/A	N/A	N/A
Socio-economic strata	Information for each neighbourhood	Information for each municipality	N/A
Population	Information for each neighbourhood	Information for each municipality	Information for each municipality
Replacement cost	N/A	N/A	N/A

inhabitants, socio-economic strata, total built-up area, and replacement cost for the different building classes. Socio-economic strata refer to the hierarchical economical difference between dwellings. Colombia' social strata are divided in a scale from one to six, in which strata 1–3 refer to dwellings which are occupied by the lowest income inhabitants, while strata 4–6 correspond to dwellings where the highest income inhabitants live. Strata 1 and 2 can be associated with uncontrolled urban development in marginal areas, which with time is included into the city limits. Although replacement cost was not used in the damage scenario presented in Sect. 6, it is still presented in this study as it might be useful for future studies.

As results in the models are given in terms of built-up area, additional calculations were required to compute the number of buildings and dwellings. The number of buildings for each region was computed by defining an average number of dwellings and average dwelling area for each building class. The average number of dwellings was defined as a function of the number of storeys, while average dwelling area was defined as a function of the socio-economic strata (dwellings in the highest strata have larger area). These parameters were defined based on expert judgement and visual inspections. Furthermore, in order to assess realistic values for the number of dwellings and average dwelling area for unreinforced masonry structures (as this type of construction constitutes more than half of the building stock), 151 real structures from Medellín and surrounding municipalities were surveyed in order to relate the aforementioned parameters. This exercise allowed obtaining information regarding the socio-economic strata, built-up area, number of storeys, number of dwellings per building, and dwelling area.

Results of the number of dwellings of the exposure models were compared with available information. Values of Medellín and the metropolitan area (Aburrá Valley) were compared to values from the "Life quality survey" of the year 2011 (DANE 2011). Data from the 2005 General Census (DANE 2005) were used for the comparison of the number of dwellings of the municipalities outside the Aburrá Valley. The exposure model of

Medellín indicates a total of 713 thousands of dwellings when all of the neighbourhoods are considered, which equals the reference value. If only urban dwellings are considered, the exposure model of Medellín indicates 660 thousands of dwellings, while the reference reports 569 thousand of dwellings (ratio of 0.86). For the remaining municipalities of the Aburrá Valley, the ratio of the number of dwellings of the reference to the number of the dwellings of the exposure model ranges between 0.81 and 0.97. The small variation of the number of dwellings of the exposure model of Medellín and the Aburrá Valley to the reference numbers indicates a reasonable reliability of the model. The ratio of the number of dwellings of the exposure model for the municipalities outside the Aburrá Valley to the reference number ranges between 0.5 and 2.0 for 86% of the municipalities. These results indicate large differences, but it is not clear to the authors of this study what was the criterion used in the 2005 General Census for the definition of the urban area of each municipality. Moreover, a larger number of dwellings than the value reported in the Census is expected as the population have increased significantly in the last decade.

4 Methodology for development of the exposure model

As can be observed from Table 2, an important amount of data required for the development of the exposure model was missing. A brief description of the assumptions made in order to generate the missing data is explained in this section for the three regions: Medellín, Aburrá Valley and municipalities outside the Aburrá Valley.

4.1 Medellín exposure model

The city of Medellín has the most detailed information of all of the municipalities of Antioquia. Cadastral information of the year 2012 (map of plan built areas and number of storeys) was available. Total built-up area was computed by the multiplication of the plan area by the number of storeys. Information regarding the population and socio-economic strata was also available for each of the 350 neighbourhoods of Medellín. The cadastral information did not include information concerning the building class, which is a key aspect for the development of an exposure model for seismic risk analyses.

The structural system was defined as a function of the socio-economic strata and the number of storeys, relying on expert judgment and data collected from surveys compiled for the microzonation study of the Aburrá Valley (Consorcio Microzonificación 2007). Data from the General Census of 2005 were not used as it only differentiates floor and roof materials, and it is not possible to differentiate from this information a structural system such as reinforced concrete, steel, or masonry (reinforced, unreinforced and confine).

Figure 4 presents the structural system distribution defined for Medellín for the lowest income strata (socio-economic strata 1) and the highest income strata (socio-economic strata 6). The distribution for the remaining strata can be found in the *SARA wiki*. From this figure, it can be observed that the building class distribution differs greatly between buildings with one to ten storeys according to the socio-economic strata. Unreinforced masonry structures, which constitute more than half of the built-up area of Antioquia, are more common in socio-economic strata from one to four. Buildings of this type in high-income zones usually correspond to structures built before the endorsement of seismic codes in Colombia. Reinforced concrete buildings have mainly five to ten storeys and low-

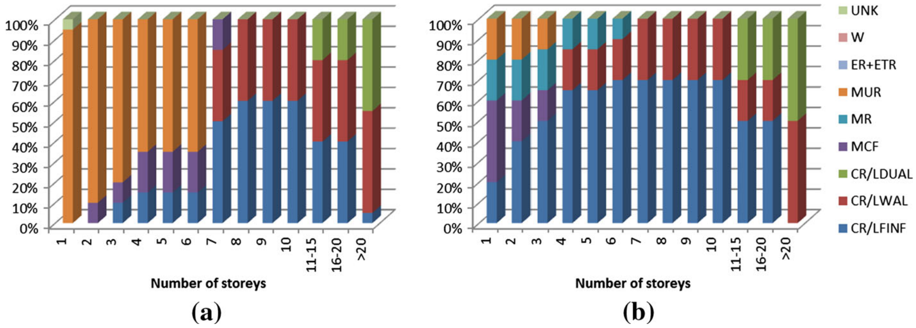


Fig. 4 Structural system distribution for Medellín as a function of the number of storeys and socio-economic strata. **a** Socio-economic strata 1, **b** socio-economic strata 6

rise reinforced concrete structures are commonly found in high-income strata. High-rise buildings of more than ten storeys are reinforced concrete frames, wall systems, or dual frame-wall systems. High-rise buildings have been built mainly over the last decade, for either the lowest income or the highest income zones. Earth structures are not commonly found in the city, as they have been replaced by other structural systems.

The replacement cost was defined as a function of the area and socio-economic strata. Several construction companies were consulted in order to estimate a reasonable cost. Values in Colombian Pesos/US dollars (COP/US) per square meter were defined as 500,000 COP/159 US for strata 1 and 2; 740,000 COP/236 US for strata 3; 1,150,000 COP/366 US for strata 4; 1,450,000 COP/462 US for strata 5; and 1,750,000 COP/557 US for strata 6.

4.2 Aburrá Valley exposure model

The Aburrá Valley sub-region has ten municipalities: Medellín, Caldas, La Estrella, Sabaneta, Envigado, Itagüí, Bello, Copacabana, Girardota, and Barbosa. Cadastral information (map of plan built areas and number of storeys) was only available for Giradota (year of 2007). Homogenous areas defined in the microzonation study of Medellín and the Aburrá Valley (Consorcio Microzonificación 2007) were used in order to obtain built-plan area of the municipalities without cadastral information. Homogenous areas refer to residential areas within each municipality where buildings have similar number of storeys. Five types of residential areas were defined in the microzonation study based on building's most common number of storeys as follows: zone 1 (1 and 2 storeys), zone 2 (3–5 storeys), zone 3A (6–10 storeys), zone 3B (11–15 storeys), and zone 3C (16 and more storeys). Figure 5 shows the number of storeys distribution of the homogeneous areas *zone 1* and *zone 2* of the municipality of Bello. It can be observed from the figure that the most common number of storeys for *zone 1* is one and two; in the case of *zone 2* the most common number of storeys is three to five. As plan areas defined in the microzonation study included green areas, streets, and other open spaces, only a percentage of each area was considered in this study. As building shapes are easy to identify from aerial pictures, a comparison of such pictures with the areas defined in the microzonation study allowed for the percentage definition, leading to values between 35 and 50%.

Survey data specifically collected for the microzonation study were used to define the distribution of number of storeys per building for each homogeneous zone, with the

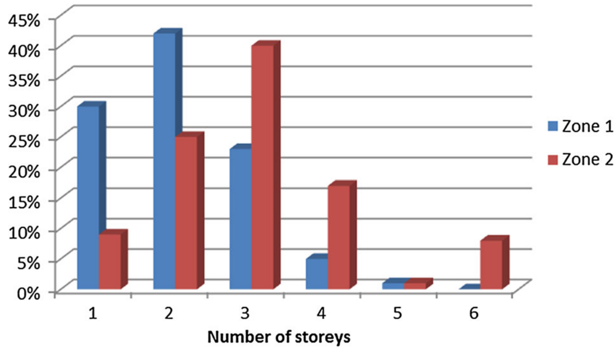


Fig. 5 Number of storeys distribution for homogeneous zones 1 and 2 of Bello

exception of Girardota. For the latter municipality, a map with the number of storeys was already available.

As in the case of Medellín, structural system distribution was defined as a function of the socio-economic strata and the number of storeys. Data collected from the micro-zonation study, as well as judgement of local experts, were used to define the structural system distribution. Three main groups of municipalities were defined according to the expected common building classes and economic development of each municipality: Group 1—Itagüí, Bello and Copacabana; Group 2—La Estrella, Girardota, Caldas and Barbosa; and Group 3—Envigado and Sabaneta. A structural system distribution was used for each group, and the same replacement cost used in Medellín was assumed for the entire Aburrá Valley.

4.3 Exposure model of municipalities outside the Aburrá Valley

The exposure model for the 115 municipalities outside the Aburrá Valley incorporates many uncertainties, due to the several assumptions required to compensate for the lack of data (see Table 2). These municipalities constitute 41.6% of Antioquia's population, and are organized in eight sub-regions (Bajo Cauca, Magdalena Medio, Nordeste, Norte, Occidente, Oriente, Suroeste and Urabá). The 2005 General Census Survey (population, number of dwellings and distribution of wall and floor material) was available for all of the municipalities. Cadastral information of the year 2012 (map of plan built areas and number of built storeys) was available for the urban area of 80 municipalities.

For the municipalities in which cadastral information was not available, the built-plan area was defined from the analysis of aerial imagery. Figure 6 presents an example of the built area definition for the municipality of Apartadó, in which, based on buildings plan shapes, general residential areas were drawn (black polygons). A reduction factor was applied to these areas in order to exclude non-residential areas such streets and parks. The reduction factor was computed by the comparison of several general areas (black polygons) to their real built-plan areas (white rectangles). Inaccuracy in the resultant built area is accepted as the definition from aerial imagery of all of the building shapes in a given municipality is an extremely time-consuming task.

For the municipalities with cadastral information, the distribution of number of storeys was obtained directly from the cadastral map. For the remaining municipalities, the distribution of number of storeys was defined as: (a) distribution of a similar municipality

Fig. 6 Definition of built-plan area for Apartadó

with cadastral information (similar population and/or area), or (b) if there was not a similar municipality with cadastral information, a virtual survey was performed to obtain the typical number of floors. Virtual surveys refer to the collection of information about storey height and structural system from randomly selected buildings, using imagery available in the Google Street View application.

As no information was available about the structural system, virtual surveys were performed. This process was comprised of four steps: (1) the municipality with the greatest population within each sub-region was selected; (2) data from the virtual survey was used for the determination of the building classes; (3) the building class distribution of the selected municipality was applied to all of the municipalities of the same sub-region; and (4) adjustments were done in each municipality as data of the 2005 General Census (DANE 2005) identifies the percentage of earth and wooden dwellings. Figure 7 presents the number of storeys and the structural system distribution for Apartadó.

The structural system distribution was defined only according to the number of storeys, as socio-economic strata information was not available. Regardless of the structural system, a unique replacement cost of 1,000,000 Colombian Pesos (318 US) per meter square was assumed for all of the municipalities. This value was defined based on the judgement of several construction companies from the region, and taking into consideration that the majority of the structures outside the metropolitan area do not comply with code regulation, and therefore the replacement cost will be rather uniform considering that a damaged building must be replaced by a structure that complies with code regulations.

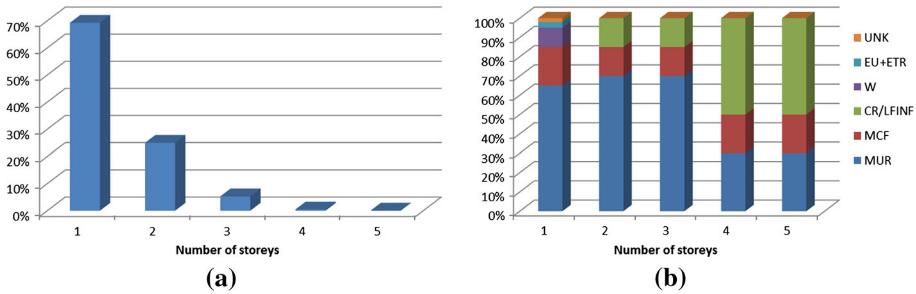


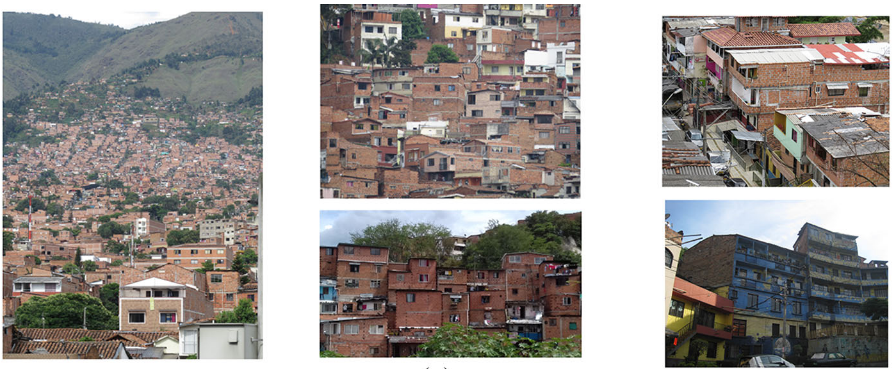
Fig. 7 Number of storeys and structural system distribution for Apartadó. **a** Number of storeys distribution. **b** Structural system distribution

5 Vulnerability of unreinforced masonry structures

As shown in Fig. 3, near 60% of the residential building stock in Antioquia is unreinforced masonry structures (508 thousands of buildings), which unfortunately are highly vulnerable to seismic hazard. Colombian unreinforced masonry structures showed a poor performance during the Armenia earthquake of 1999 (M_w 6.2); nearly 50,000 dwellings were reported as affected by the event, from which 17,551 urban dwellings were reported as destroyed or non-habitable (Cardona et al., 2004). Although data of the building typology of the affected dwellings are not available, it is well known that many of those structures were unreinforced masonry buildings. Figure 8 shows images of typical unreinforced masonry structures in Medellín. The majority of these buildings in Antioquia are characterized by informal construction at low-income neighbourhoods, ignoring seismic provisions, as presented in Fig. 8a. On the other hand, Fig. 8b illustrates pre-code unreinforced masonry structures (before the year 1984) at medium-income neighbourhoods, but with better construction practice.

Figure 9 presents the distribution of unreinforced masonry buildings according to the number of storeys for Medellín, Aburrá Valley, and Antioquia. It can be observed that about 80% of these buildings have one or two storeys and nearly 10% of the buildings have three storeys. A very small percentage of buildings are structures of four or more storeys (2, 4 and 3% for Medellín, the Aburrá Valley and Antioquia, respectively). Six storeys buildings are only found in the Aburrá Valley and Medellín and represent 0.10% of the total number of unreinforced masonry buildings.

In order to perform an earthquake loss scenario, fragility and/or vulnerability functions are required. Fragility functions relate the probability of exceeding a set of damage states



(a)

(b)

Fig. 8 Examples of unreinforced masonry structures. **a** Lower socio-economic strata. **b** Medium socio-economic strata

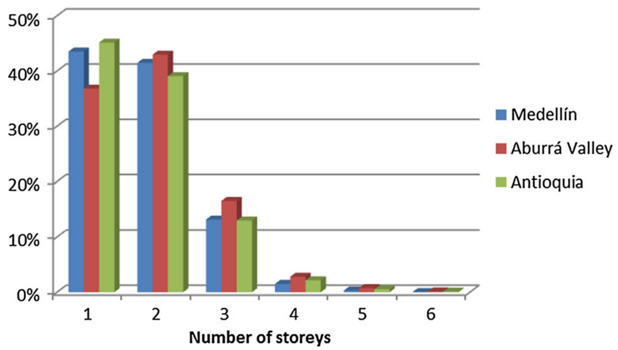


Fig. 9 Number of storeys distribution for unreinforced masonry buildings in Medellín, Aburrá Valley, and Antioquia

conditional on a given ground motion level, while vulnerability functions relate the probability of loss ratio (ratio of repair cost to replacement cost) for a set of ground motion levels. Fragility functions can be converted into vulnerability functions using a damage-to-loss model.

In this study, analytical fragility functions were derived for in-plane response of unreinforced masonry structures based on the simplified pushover-based earthquake loss assessment method, SP-BELA (Borzi et al. 2008). A simplified procedure was selected in order to reduce the computational and modelling effort. The SP-BELA methodology for in-plane failure mechanism is partially based on the MeBaSe procedure (Restrepo-Vélez and Magenes 2004), which has been proven to be suitable for application to Colombian unreinforced masonry structures. Six building classes were considered according to the number of storeys. In order to derive the fragility functions, the structural capacity of each building class was represented by a set of 100 equivalent single-degree-of-freedom (SDOF) oscillators, while the demand was represented by 300 ground motion records, thus allowing the propagation of the building-to-building and the record-to-record variabilities (see Sect. 5.3). In order to obtain the response of each SDOF oscillator under each accelerogram, a nonlinear time history analysis (NLTHA) procedure was used (see Sect. 5.4). The following sections present in detail the steps involved in the fragility curves generation.

5.1 Capacity curves

Capacity curves for in-plane failure mechanism were calculated using a simplified push-over analysis (Borzi et al. 2008). The pushover curve was defined as a bilinear curve (see Fig. 10) using three parameters: yield displacement (Δ_y), ultimate displacement (Δ_u), and collapse multiplier (λ).

The yielding and ultimate displacements can be calculated using the following formulae:

$$\Delta_y = k_1 h_T \delta_y \tag{1}$$

$$\Delta_u = k_1 h_T \delta_y + k_2 \left(\delta_u - \delta_y\right) h_p \tag{2}$$

where h_T and h_p are the total building height and inter-storey height, and δ_y and δ_u are the inter-storey drift corresponding to the drift limit at yield and the collapse drift, respectively.

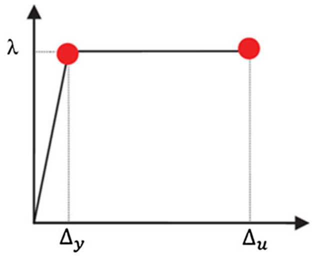


Fig. 10 Capacity curve for elastic perfectly plastic structural behaviour for in-plane mechanism (adapted from Borzi et al. 2008)

Parameters k_1 and k_2 are coefficients required to obtain the equivalent height of the single-degree-of-freedom system, as defined by Restrepo-Vélez and Magenes (2004) for buildings with masses uniformly distributed along the building height and for walls with a mass equal to 30% of the floor mass.

The collapse multiplier, λ, relates to the lateral load required to produce the structure collapse, F, by the structure mass, M, and the gravitational acceleration, g, as follows:

$$F = \lambda Mg \tag{3}$$

The structure collapse multiplier will be the smallest among the collapse multiplier of each floor (λ_i). The collapse multiplier for the ith floor (λ_i), was computed using formula (4), as proposed by Benedetti and Petrini (1984).

$$\lambda_i = \frac{1}{W_T \frac{\sum_{k=i}^{n} h_k W_k}{\sum_{j=1}^{n} h_j W_j}} A_i \tau_{ki} \left[1 + \frac{\sum_{k=i}^{n} W_k}{1.5 \tau_{ki} A_i (1 + \gamma_{AB})} \right]^{1/2} \tag{4}$$

where W_T stands for the total weight of the building (including weight of walls, floor, roof, dead loads and 30% of live loads), W_i refers to the weight of the floor i, τ_{ki} represents the shear resistance of the masonry at the floor i, A_i refers to the total area of the resisting walls at level i in the direction of application of the seismic loads, γ_{AB} represents the ratio between A_i and B_i, with B_i being the maximum area between the area of wall in the loaded direction and the orthogonal direction, and n is the number of storeys. Masonry shear resistance was conservatively taken as 200 kPa based on experimental results (López et al. 2012) and expert judgment. The building collapse multiplier is the smallest among all of the calculated collapse multipliers.

Typically, unreinforced buildings in the metropolitan area of Medellín have similar floor weights. Thus, the weakest floor (smallest collapse multiplier) is usually located in the lower floor. In addition, it was assumed equal values of A_i and B_i, floor weight, storey height, and shear resistance throughout the building height. Equation (4) is rewritten taken into consideration these assumptions and leading to the following formula:

$$\lambda = \frac{1}{\rho_{wt}} \rho_{wA} \tau_k \left[1 + \frac{\rho_{wt}}{1.5 \tau_k \rho_{wA} (1 + \gamma_{AB})} \right]^{1/2} \tag{5}$$

where ρ_{wA} is the ratio between area of walls in a floor to floor area (wall density), ρ_{wt} stands for the ratio of total building weight to floor area (weight density), γ_{AB} is the ratio between ρ_{wA} and ρ_{wB}, with w_B being the maximum wall density between the wall density in the direction of the applied seismic loads and the orthogonal direction.

Torsional effects were taken into account by the incorporation of the correction coefficient ϕ_c suggested by Restrepo-Vélez and Magenes (2004) and expressed in formula (6).

$$\phi_c = 5.5\frac{\tau_k}{\left({L_w}/{L_T}\right)} + 0.5 \tag{6}$$

The correction coefficient is function of the shear resistance of the masonry, τ_k, and the ratio of the total length of the perimeter walls (including openings and non-structural walls), in the direction of the applied seismic loads, L_T, to the sum of the lengths of the resistant perimeter walls in the same direction, L_w. The coefficient was derived by Restrepo-Vélez and Magenes (2004) from the comparison of the structural behaviour of 3D models versus the simplified 2D models of five different buildings with two to five storeys and different shear strength of masonry. Formula (7) presents the final equation used for the calculation of the collapse multiplier.

$$\lambda = \frac{1}{5.5\frac{\tau_{ki}}{{L_w}/{L_T}} + 0.5} \cdot \left\{ \frac{1}{\rho_{wt}} \rho_{wA} \tau_k \left[1 + \frac{\rho_{wt}}{1.5\tau_k \rho_{wA}(1+\gamma_{AB})} \right]^{1/2} \right\} \tag{7}$$

Forty unreinforced masonry buildings were selected from the 151 structures initially surveyed (see Sect. 3) in order to gather data required for the generation of the capacities curves. Plan views of the lower floor of the forty buildings were analysed in order to calculate wall densities in both directions. Figure 11 shows plan views of two of the surveyed buildings; it can be observed that the typical dimensions of this building typology (15 m length, 6 m width, and inter-storey height of 2.5 m) reported by Mejía (2011) are in agreement with the surveyed buildings. Floor weights were estimated from the observed type and thickness of both floor and roof. Values of dead and live loads from current Colombian seismic code (NSR-10) were used (AIS 2010). As stated before, value of masonry shear resistance was based on experimental results. The collected data displayed no significant correlation between the structural parameters and the number of storeys. Therefore, data from the entire sample (regardless the number of storeys) were used to generate the statistics (best-suited distribution, mean and variance) for the wall density, slab weight, floor area and inter-storey height, as describe in Table 3. The values presented in the table were used to generate the capacity curves for buildings between one and six floors.

In addition to the parameters presented in Table 3, yielding and ultimate displacements are required for the calculation of the capacity curves. As previously depicted in Fig. 10, the yielding and ultimate displacements depend on the total height of the building (h_t) and the inter-storey height (h_p). For the purposes of this study, the same inter-storey height was assumed throughout each building, and thus the total height was estimated by multiplying the inter-storey height by the number of storeys.

For the definition of the collapse drift and the ratio between the collapse and yielding drifts, experimental results of unreinforced masonry walls reported by Magenes and Calvi (1997) were used. These results indicated a uniform distribution of the δ_u and a large scatter in the ratio δ_u/δ_y. Lower and upper limits for both δ_u and δ_u/δ_y were defined as plus/minus one standard deviation, as described in Table 4.

One hundred capacity curves were randomly generated for each building class (defined by the number of storeys). Figure 12 shows the capacity curves for one, three and six storeys buildings. Darker lines indicate the mean value of each set of capacity curves.

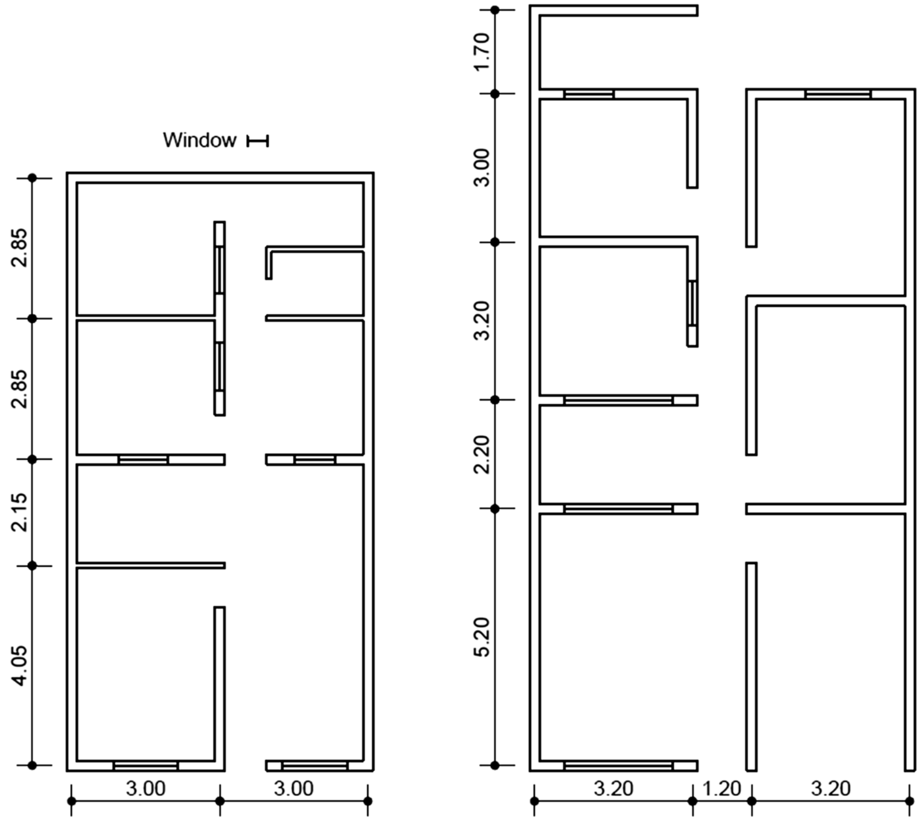


Fig. 11 Examples of plan views of the surveyed unreinforced masonry buildings

Table 3 Statistical parameters from gathered data

Parameter	Mean	Variance	Statistical distribution
Wall density in the longitudinal direction, ρ_{wx} (m^2/m^2)	0.05	1.02E−04	Log-normal
Wall density in the orthogonal direction, ρ_{wy} (m^2/m^2)	0.0745	1.50E−04	Log-normal
Ratio between slab weight and floor area, ρ_{slab} (MN/m^2)	0.0033	1.45E−07	Log-normal
Dead load (MN/m^2)	0.001	–	–
30% of live load (MN/m^2)	0.00054	–	–
Inter-storey height (m)	2.4	5.55E−02	Log-normal
Masonry shear resistance (MN/m^2)	0.2	0.0025	Log-normal

5.2 Damage states

For each SDOF, the observed maximum spectral displacement due to each ground motion record was estimated and compared with the corresponding damage state thresholds in order to allocate the structure within a damage state. Damage limit states were defined as a

Table 4 Results for the collapse drift and ratio between the collapse and yielding drifts

Parameter	Mean	C.O.V. (%)	SD	Lower limit	Upper limit
δ_u	0.005	11	0.00055	0.00445	0.0055
δ_u/δ_y	5.0	46	2.3	2.7	7.3

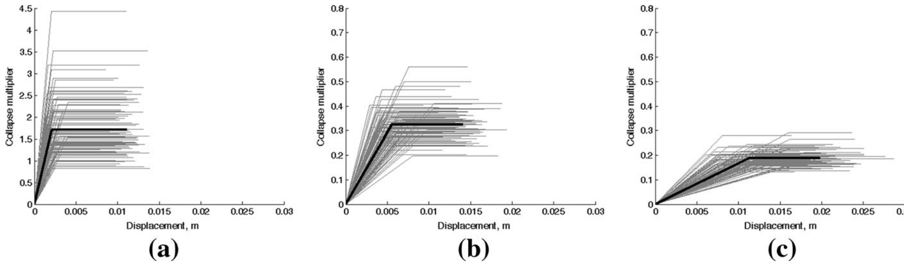


Fig. 12 Capacity curves for in-plane failure mechanism of unreinforced masonry buildings of one, three and six storeys. **a** 1 storey. **b** 3 storeys. **c** 6 storeys

Table 5 Damage state criterion

Limit state	Displacement
Slight	$0.7d_y$
Moderate	$0.25 \cdot (3d_y + d_u)$
Extensive	$0.5 \cdot (d_y + d_u)$
Collapse	d_u

function of the yielding and ultimate displacements (d_y and d_u, respectively), as described in Table 5 and suggested by several studies (Lagomarsino and Giovinazzi 2006; Erberik 2007; Silva et al. 2014). Comparison of the displacements to damage state thresholds allowed building a damage matrix containing the number of SDOF in each damage state per ground motion record.

5.3 Ground motion records selection

The ground motion records used in this study were selected from the PEER (Pacific Earthquake Engineering Research) database, in such a way that they would be compatible with the local tectonic environment and seismicity, as previously described in Sect. 2. The selected set was composed of ground motion records with moment magnitudes between 5 and 9, depending on the distance. For long distances (i.e. over 50 km), only records with a moment magnitude above 7 were considered, while for shorter distances magnitudes between 5 and 7 were selected. A rock soil type was assumed and no near-fault effects were considered. A maximum scaling factor of 2 was considered (Watson-Lamprey and Abrahamson 2006). Two intensity measure types (IMT) were defined as representative of the dynamic characteristics of the building classes: peak ground acceleration (PGA) for the stiff buildings (one to three storeys) and spectral acceleration (Sa) at 0.4 s for buildings with four or more storeys (0.4 s was defined based on the elongated period, in order to account for the effect of structural damage in the dynamic properties of the building stock).

For each IMT, 10 levels of intensity were defined and 30 records were scaled, leading to two sets of 300 ground motion records.

5.4 Fragility functions

To develop the fragility functions equivalent SDOF oscillators were generated based on the capacity curves for each building class. Nonlinear time history analyses (NLTHA) were performed using the GEM's Risk Modeller's Toolkit (Silva et al. 2015). This module uses the open-source software for nonlinear structural analysis OpenSEES (McKenna et al. 2000) to perform the nonlinear dynamic analyses. The hysteretic behaviour of each SDOF was defined based on its capacity curve and following the "Pinching4 Material" model with degradation, as defined by McKenna et al. (2000).

For each SDOF, the maximum spectral displacement due to each record was estimated and compared with the corresponding damage state thresholds (see Sect. 5.2) in order to allocate the structure within a damage state. This process allowed building a damage matrix containing the number of SDOF in each damage state. Finally, each fragility function was modelled using a cumulative lognormal distribution, whose parameters (i.e. logarithmic mean and logarithmic standard deviation) were derived through a statistical regression (least square method).

Figure 13 presents the resulting fragility functions for the six building classes, and Table 6 contains the statistical parameters for each function.

6 Seismic damage scenarios

In order to explore the seismic risk of the unreinforced masonry building stock, a scenario damage assessment was conducted considering the six building classes (from one to six storeys). The calculations were performed using the OpenQuake engine, the open-source software for seismic hazard and risk analysis developed by the Global Earthquake Model (Silva et al. 2013; Pagani et al. 2014).

Two scenarios were selected for the damage assessment corresponding to an active shallow event of magnitude 5.9 at a depth of 10 km in the south-west of the Aburrá Valley (6.21 N, 75.64 W) and a subduction intraslab event with magnitude 7.1 at a depth of 112 km (epicentre at 6.08 N, 75.70 W), as shown in Fig. 14. Both scenarios were selected based on probabilistic seismic risk analysis, in which events that led to a number of collapsed buildings with a return period close to 500 years in the metropolitan area were identified. These calculations were performed using the recently proposed probabilistic seismic hazard model for South America (https://sara.openquake.org/hazard) and considering an investigation time of 100,000 years. Four equally weighted ground motion attenuation equations for active shallow events (Akkar et al. 2014; Bindi et al. 2014; Boore et al. 2014; Sadigh et al. 1997) and two equally weighted ground motion attenuation equations for subduction intraslab events (Abrahamson et al. 2016; Montalva et al. 2016) were used to account for the epistemic uncertainty in the selection of the ground motion model. Site effects were taken into account through the shear wave velocity in the top 30-m layer (Vs30), as indicated in the microzonation study for the region (Consorcio Microzonificación 2007). Figure 14 presents the mean ground motion field for PGA for both scenarios.

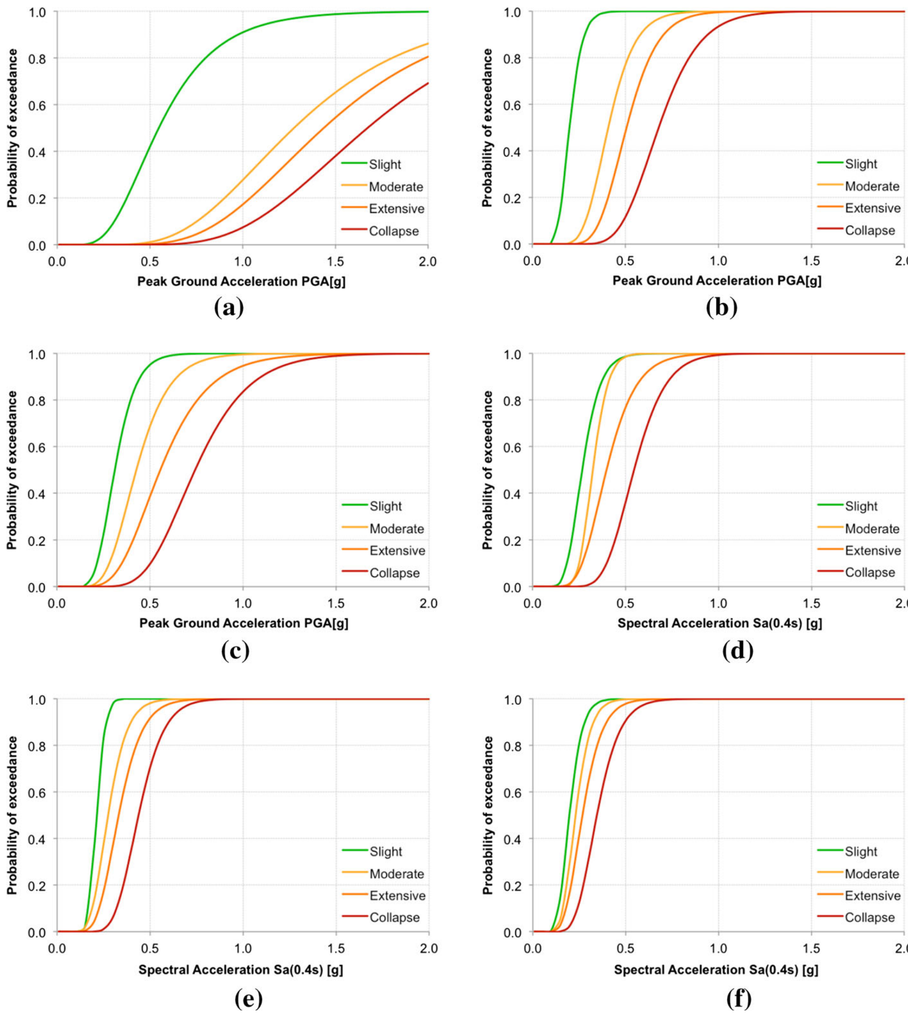


Fig. 13 Fragility curves for in-plane failure mechanism of masonry buildings between one and six floors. **a** 1 storey. **b** 2 storeys. **c** 3 storeys. **d** 4 storeys. **e** 5 storeys. **f** 6 storeys

To assess the damage distribution, one thousand ground motion fields were generated and combined with the exposure and fragility functions to calculate the mean and standard deviation of the number of buildings in each damage state (e.g. Ansal et al. 2009; Fiorini et al. 2012). Figure 15 presents the spatial distribution of the mean number of collapsed MUR buildings in each municipality. A total of 21 thousand and 16 thousand buildings are expected to collapse in the active shallow and subduction scenario, respectively. In both scenarios the majority of collapsed buildings are located in the Aburrá Valley (6% of the exposed assets for the active shallow scenario; 4% for the subduction scenario). Collapsed buildings from the shallow event concentrate in the city of Medellín and its neighbourhood municipalities; on the other hand, collapsed buildings from the subduction event are widespread in the department.

Table 6 Statistical parameters of the fragility functions

Unreinforced masonry	Intensity measure type	Slight		Moderate		Extensive		Collapse	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
1 Storey	PGA [g]	0.606	0.288	1.390	0.599	1.547	0.616	1.783	0.656
2 Storeys	PGA [g]	0.207	0.057	0.424	0.119	0.524	0.139	0.702	0.183
3 Storeys	PGA [g]	0.324	0.095	0.450	0.150	0.594	0.224	0.778	0.243
4 Storeys	Sa (0.4 s) [g]	0.278	0.081	0.331	0.067	0.418	0.134	0.563	0.141
5 Storeys	Sa (0.4 s) [g]	0.215	0.037	0.286	0.085	0.346	0.105	0.451	0.113
6 Storeys	Sa (0.4 s) [g]	0.204	0.057	0.239	0.067	0.280	0.089	0.359	0.103

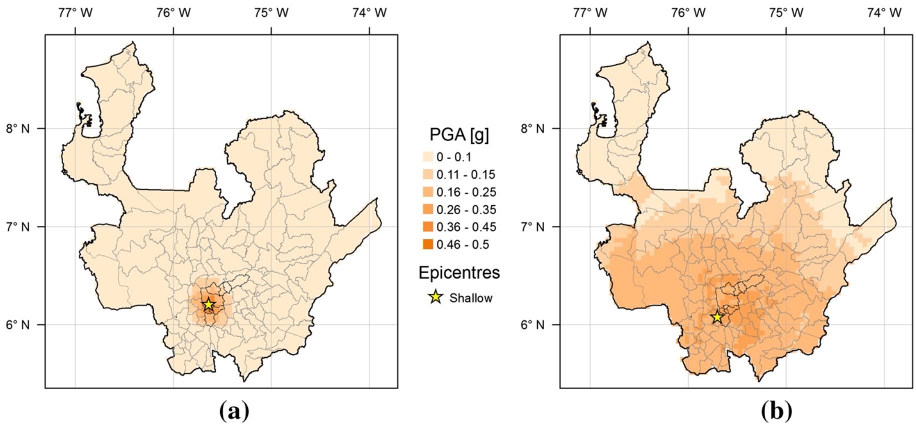


Fig. 14 Earthquake scenarios in Antioquia: epicentre and mean ground motion. **a** Active shallow. **b** Subduction intraslab

Results of the shallow event demonstrate that for a moderate earthquake southwest of the Aburrá Valley, almost 133 thousand buildings can be significantly affected (26% of Antioquia's UMR building stock). From these affected buildings, 72% will experience slight and moderate damage, and the remaining 28% will undergo extensive damage or collapse. Similar results are produced by the subduction event assessment, in which 129 thousand buildings would be affected. 25% of those affected buildings would experience extensive damage or collapse.

Figure 16a shows mean and standard deviation of the fraction of assets in each damage state for each of the ground motion attenuation equation considered in both scenarios. Figure 16b shows the distribution of damage buildings per class. Both events indicate that the most vulnerable building classes are the unreinforced masonry damage structures between four and six storeys (around 65% of the buildings suffered extensive damage or collapsed). These results highlight the importance of accurate vulnerability and risk studies and the need to develop appropriate risk mitigation actions for this type of construction.

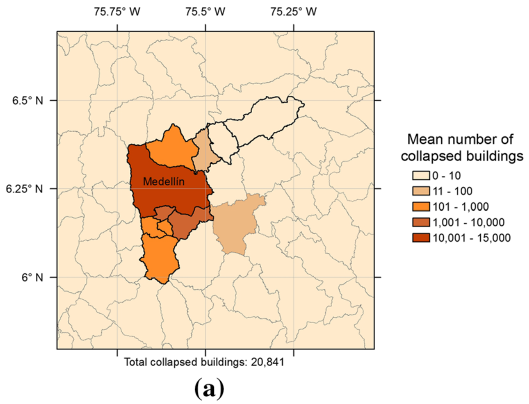


Fig. 15 Spatial distribution of number of collapse buildings in the Aburrá Valley: active shallow event (**a**) and subduction event (**b**)

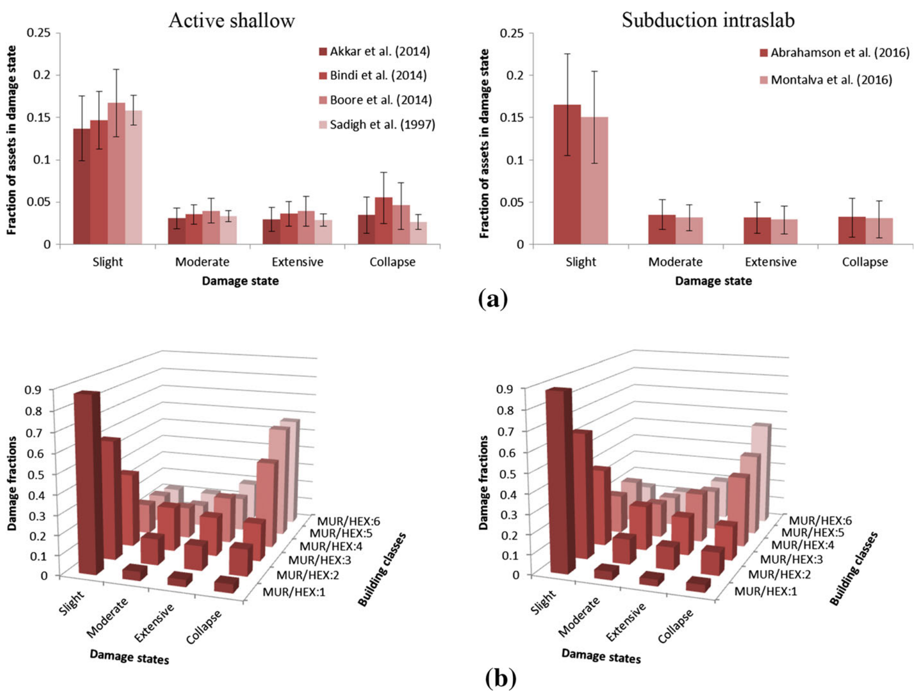


Fig. 16 Damage assessment for a shallow M5.9 event in southwest Aburrá Valley and a subduction M7.1 event. **a** Total damage distribution. **b** Damage distribution per building class

7 Conclusions

An exposure model for the residential building stock of the Department of Antioquia, as well as fragility functions for unreinforced masonry buildings (the most common type of construction) were developed for the purposes of assessing seismic risk.

The development of an ideal exposure model requires detailed information that might not be accessible. Nevertheless, as long as aerial imagery and images of the building stock (as those provided by Google Street View) are available, an approximated exposure model—in a reasonable amount of time—can be generated with the methodology presented in this work. Three different regions were considered due to data availability: Medellín (Antioquia's capital), Aburrá Valley (metropolitan area of Medellín) and municipalities outside the Aburrá Valley. The methodology used for the development of these models has been thoroughly described and could be extended to other regions, even outside of Colombia. The exposure model includes data on built-up area, number of buildings and inhabitants, building class, and replacement cost. Exposure models developed with the proposed methodology would be as precise as the quality of the input data. Comparison of results of the presented exposure models with available data on number of dwellings shows a good estimation of the building stock for the exposure models developed with good quality input data: the city of Medellín and the municipalities of the metropolitan area (Aburrá Valley). Nevertheless, comparisons about the structural typology distribution of the building stock could not be performed as references were not available. The exposure model developed for the municipalities outside the Aburrá Valley incorporates many uncertainties as input data was scarce. However, the presented model constitutes an important contribution that can be used for an initial estimation of the seismic risk in the region. The models can be easily improved as new data becomes available.

The exposure models indicate unreinforced masonry structures as the main typology in Antioquia, with 53% of the built-up area, representing a total of 508 thousands buildings (61% of the building stock). Confined masonry constitutes the second most common building typology with a total of 97 thousand buildings (11% of the built-up area and 12% of the building stock).

Fragility functions for in-plane failure mechanism were derived for unreinforced masonry structures based on the local construction practice. Forty unreinforced masonry buildings were inspected in order to generate statistics of the parameters that define the structure capacity. One hundred capacity curves were generated for six different building classes (from one to six storeys) in order to consider building-to-building variability. Seismic demand was considered by the use 300 hundred real ground motion records to take into account record-to-record variability.

As both fragility and exposure model could be used for seismic assessment, two seismic scenarios for unreinforced masonry structures were performed. The scenarios considered are plausible events that could take place in the region of interest. The earthquake scenarios were performed using the *OpenQuake engine* (Silva et al. 2014; Pagani et al. 2014). Results from both scenarios indicate that about 20% of the total building stock of unreinforced masonry structures would undergo extensive damage to collapse, being the structures between four to six storeys the most vulnerable building classes. Future studies should focus on the development of fragility functions for the additional building typologies of the building stock in order to evaluate seismic risk for all building types.

Results of the considered damage scenarios clearly demonstrate the high vulnerability of Colombian unreinforced masonry buildings. Even though unreinforced masonry is forbidden by the Colombian code, this building typology represents 61% of the building stock. It becomes a necessity to endorse retrofitting campaigns for this type of buildings. Local researchers such as Vega and Torres (2015), López et al. (2012), and Bastidas et al. (2002), have addressed the issue and have proposed methods for the improvement of the seismic capacity of this type of construction. Nonetheless, it is important to understand that the majority of the unreinforced masonry buildings are inhabited by low-income residents, and thus it is unlikely that the residents will take initiative. Governmental policies should encourage the enhancement of this type of construction, such as the reduction in taxes or development of financial mechanisms.

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