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Seismic risk assessment for the residential buildings of the major three cities in Colombia: Bogotá, Medellín, and Cali

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Abstract

This study presents a seismic risk assessment and a set of earthquake scenarios for the residential building stock of the three largest metropolitan centers of Colombia: Bogotá, Medellín and Cali (with 8.0, 2.5, and 2.4 million inhabitants, respectively). A uniform methodology was followed for the development of the seismic hazard, vulnerability, and exposure models, thus allowing a direct comparison between the seismic risk of the different cities. Risk metrics such as exceedance probability curves and average annual losses were computed for each city. The earthquake scenarios were selected considering events whose direct economic impact is similar to the aggregated loss for a probability of exceedance of 10% in 50 years. Results show a higher mean aggregate loss ratio for Cali and similar mean aggregate loss ratios for Bogotá and Medellín. All of the models used in this study are openly accessible, enabling risk modelers, engineers, and stakeholders to explore them for disaster risk management.

Keywords

Seismic hazard, residential buildings, seismic risk assessment, earthquake scenarios, risk metrics

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Introduction

Colombia is the third most populated country in South America, and has its past marked by destructive seismic events. Some examples include the 1999 M6.1 Armenia and the 1983 M5.6 Popayán earthquakes, which caused 1185 and 287 fatalities, and economic losses equivalent to 1.9% and 1.5% of the annual gross domestic product of that year, respectively (Asociación Colombiana de Ingeniería Sísmica (AIS), 2009; Cardona et al., 2004). The widespread damage in both events was mostly due to the existence of non-engineered buildings and informal construction. The need for an improved understanding of disaster risk is stressed in the Sendai Framework for Disaster Risk Reduction (United Nations Office for Disaster Risk Reduction (UNISDR), 2015b), especially in developing countries such as Colombia, where the population and infrastructure is mostly concentrated in urban areas. The top three metropolitan centers of Colombia: Bogotá (8 million inhabitants), Medellín (2.5 million inhabitants), and Cali (2.4 million inhabitants) represent 34% of the Colombian urban population (Departamento Administrativo Nacional de Estadística (DANE), 2015). Efforts to reduce or mitigate seismic risk are necessary throughout the country, and in particular, in these cities where a seismic event may have catastrophic consequences due to the high number of exposed persons and assets. In addition, although seismic regulations for building design and construction were officially introduced in 1984 (Ministerio de Obras Públicas y Transporte (MOPT), 1984), non-engineered buildings and informal construction are commonly found across the country, representing more than 90% of the urban residential building stock (Yepes-Estrada et al., 2017). In these three cities, informal settlements are commonly found in the peripheral areas, where poor socioeconomic conditions are prevalent.

This study describes the methodology, datasets, models, and results for the risk assessment of the three largest urban centers in Colombia. The recently released probabilistic seismic hazard analysis (PSHA) model developed by the Geological Survey of Colombia (SGC—known as INGEOMINAS in the past) in collaboration with the Global Earthquake Model (GEM) Foundation (Servicio Geológico Colombiano (SGC), 2018) was used for the seismic hazard evaluation. Site effects were considered by the use of frequency-dependent site-specific amplification functions (AFs) derived for each city based on the latest available microzonation study (Fondo de Previsión y Atención de Emergencias (FOPAE), 2010; INGEOMINAS, 2005; Sistema Municipal de Prevención y Atención de Desastres (SIMPAD), 1999). Intensity-dependent AFs could only be used for Bogotá. In the case of Medellin and Cali, the AFs were estimated based on the ratio between the response spectra in rock and soil conditions, since no additional information was available. The uncertainty on the site's dynamic response was considered by the use of three levels of standard deviation associated to the AFs, σ_{lnAF}: 0.3, 0.5, and 0.7. These values agree with those proposed by Bazzurro and Cornell (2004) and those that have been previously used by Bernal (2014) for Bogotá. The use of amplification factors has been previously used for the seismic hazard and/or risk assessments of Bogotá and Medellín (e.g. Bernal, 2014; Bernal and Cardona, 2018; Salgado-Gálvez et al., 2013, 2014).

The exposure models for the three cities were developed using cadastral data, virtual and on-site surveys, and the judgment of various local experts. The exposure models are publicly accessible through the OpenQuake-platform (https://platform.openquake.org). The seismic performance of the residential building stock was characterized using existing vulnerability functions developed as part of GEM's Global Seismic Risk Map (Martins and Silva, 2020). The results from the probabilistic and deterministic (scenario) analyses for each city highlight hot spots of earthquake risk, the building classes most likely to suffer losses, and the expected direct economic impact due to a number of realistic seismic ruptures. The goal of this study is to contribute to the reduction of seismic risk in Colombia, by sharing information, models, and results that can support risk mitigation activities.

Review of previous studies

The 1983 M5.6 Popayán and the 1999 M6.1 Armenia earthquakes raised awareness for earthquake risk in Colombia, as important economic and human losses were observed for two relatively moderate seismic events. As a consequence, several studies in the fields of seismic hazard and risk assessment were developed in the following two decades. The first seismic hazard study for Colombia dates from 1972 as reported by AIS (2009), in which a seismic zonation map was generated. From that date, seismic hazard assessments have been developed for the country and/or particular locations within Colombia. The current seismic code of Colombia (Ministerio de Vivienda Ciudad y Territorio (MAVDT), 2010) includes results of the national seismic hazard assessment developed by the Colombian Association of Earthquake Engineering (AIS, 2009). At the regional scale, Colombia has been included in the hazard model developed for Latin America and the Caribbean by Salgado-Gálvez et al. (2018). A new seismic hazard model for Colombia was recently developed by the SGC in collaboration with the GEM Foundation (SGC, 2018); such a model is used in this study for the seismic risk analysis as explained in the following section.

Cities like Bogotá, Medellín, Cali, Manizales, and some nearby municipalities have developed microzonation studies (Área Metropolitana del Valle de Aburrá (AMVA), 2007; Centro de Investigación en Materiales y Obras Civiles (CIMOC) and Centro de Estudios sobre Desastres y Riesgos (CEDERI), 2002; FOPAE, 2010; INGEOMINAS, 2005; INGEOMINAS and Universidad de Los Andes, 1997; SIMPAD, 1999). Earthquake loss scenarios and/or probabilistic seismic risk assessments have been performed for cities such as Bogotá, Medellín, and Manizales (AMVA, 2007; Salgado-Gálvez et al., 2013, 2014; Yamín and Cardona, 1997). More recently, earthquake scenarios were developed for the unreinforced masonry residential building stock in Cali, Medellín, and Bogotá (Acevedo et al., 2017a, 2017b). Finally, the National Unit for Disaster Risk Management of Colombia (UNGRD) published the Risk Atlas for Colombia (Unidad Nacional para la Gestión del Riesgo de Desastres (UNGRD), 2018), where earthquake risk metrics were presented at municipality level for the entire country. This study used the models proposed within the country scope of the Global Assessment Report—GAR15 (UNISDR, 2015a), which were developed for country benchmarking.

Colombia has also been included in risk studies for Latin America as part of an initiative from the Inter-American Development Bank (IDB), in which disaster risk indicators were developed (Cardona, 2005, 2010). Finally, an initiative supported by the GEM Foundation evaluated hazard (García et al., 2017) and risk (Yepes-Estrada and Silva, 2017) for seven South American countries, including Colombia. In this project, hazard, exposure, and vulnerability models were developed using a uniform approach and national or regional datasets.

Seismic hazard modeling for Colombia

Colombia is located in the northwestern part of South America, and its tectonic context is marked by the convergence of the Caribbean, Nazca, and South American plates, as well

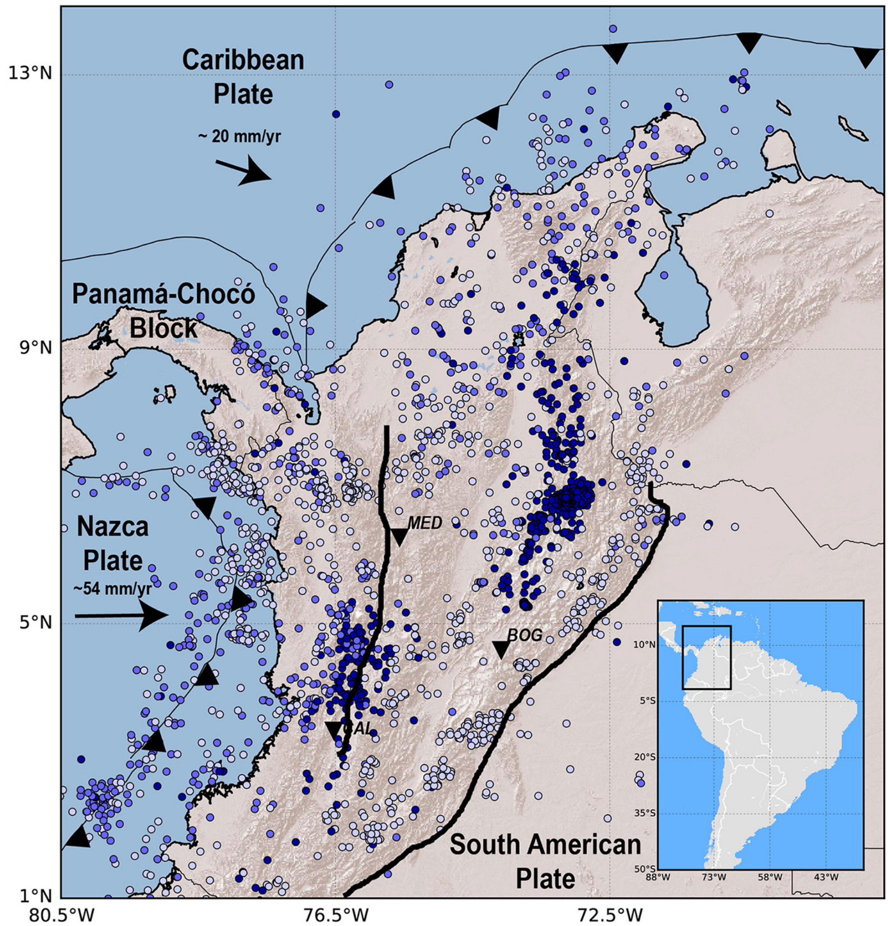

Figure 1. Seismicity in Colombia recorded by the Colombian National Seismological Network.

as by the interactions with the North Andean, Coiba, and Panama blocks. The seismicity recorded (see Figure 1) is associated with three main sources: (1) the subduction of the Nazca Plate, characterized by shallow-to-intermediate earthquakes, (2) the Bucaramanga seismic nest with seismicity characterized by deep events, and finally (3) the crustal seismicity from active geological faults, which is distributed along the Andes mountain range with trends S–N and SSW–NNE.

The PSHA performed in this study is based on a hazard model recently developed by the SGC in collaboration with the GEM Foundation (SGC, 2018). The model includes seismic sources (area sources and active faults) defined based on several datasets such as: (1) structure, characteristics, and rheology of the crust, from which it was possible to define zones of homogeneous cortical characteristics, (2) digital elevation model, geological, tectonic, and active fault maps, as well as instantaneous velocity maps of the GPS geodetic network, from which adjustments in coherent zones were done in terms of tectonics, active stress regime, and geodetic displacement, and (3) the seismic events catalog (event rates, magnitudes, and depths), from which location of the events, their focal mechanisms, and

Table 1. List of the selected ground motion prediction equations (GMPEs) per tectonic environment

Tectonic region type	GMPE	GMPE weight
Subduction interface	Abrahamson et al. (2016)	0.437
	Zhao et al. (2016)[a]	0.348
	Montalva et al. (2017)	0.215
Subduction intra-slab	Montalva et al. (2017)	0.437
	Abrahamson et al. (2016)	0.358
	Zhao et al. (2016)[b]	0.205
Deep seismicity (Bucaramanga Nest)	Zhao et al. (2016)[b]	0.443
	Abrahamson et al. (2016)	0.285
	Montalva et al. (2017)	0.272
Active shallow crust	Idriss (2014)	0.399
	Cauzzi et al. (2015)	0.390
	Abrahamson et al. (2014)	0.211

[a]Fix hypocentral depth at 20 km as defined by the National Seismic Hazard Mapping Project of the 2008 US hazard model.
[b]Magnitude capped at Mw 7.8 as defined by the 2014 US National Seismic Hazard Maps.

the stress trajectories were derived considering the tectonic environment (Arcila et al., 2017).

The shallow seismicity was characterized using an integrated model of distributed seismicity (area sources for both active shallow crust and stable continental regions) and crustal fault sources. The subduction interface seismicity was modeled using large fault sources with a three-dimensional (3D) geometry, while 3D volumes of ruptures describing the spatial distribution of the event within the area were used to represent the subduction in-slab seismicity. Four tectonic environments were considered in the model: subduction interface, subduction in-slab, active shallow crust, and deep seismicity (i.e. Bucaramanga Nest). Three ground motion prediction equations (GMPEs) were selected for each tectonic environment. The epistemic uncertainty related with the selection of the GMPEs was modeled through the use of a logic tree structure, leading to a total of 81 branches. Table 1 presents the list of the selected GMPEs per tectonic environment.

A seismic sources logic tree with two branches was used, considering a segmented/non-segmented model for interface subduction and a gridded/area seismicity source for active shallow crust. Additional information about the seismic hazard model can be found in https://amenazasismica.sgc.gov.co/.

In accordance with the current seismic provisions of Colombia (MAVDT, 2010), Bogotá and Medellín are located in an intermediate seismic hazard zone (0.15 g of peak ground acceleration (PGA) on rock for the 475-year return period), while Cali is in a high seismic zone (0.25 g PGA on rock for the same return period). PGA values on rock for Bogotá, Medellín, and Cali according to the hazard model used in this study (SGC, 2018) are 0.19 g, 0.14 g, and 0.38 g, respectively.

Exposure model for the residential building stock

The exposure model for the residential building stock of Bogotá, Medellín, and Cali comprise the built-up area, building classes, replacement cost, and number of buildings, dwellings, and inhabitants. Cadastral data, survey data, and expert judgment were used for the

Table 2. Summary of the exposure models for the residential building stock

City	Built-up area (km^2)	Number of buildings (thousands)	Number of inhabitants (thousands)	Replacement cost (USD millions)
Bogotá	185	727	7960	141,656
Medellín	76	334	2463	52,685
Cali	69	362	2416	35,488

generation of the models. All of the models were developed at the neighborhood resolution as part of the South America Risk Assessment (SARA) project and 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).

The cadastral information included building footprints, built-up area, and/or the number of stories. Information about the socio-economic level (SEL) was available for the three cities. The SEL is used in Colombia to classify the neighborhoods of the cities according to the average income per household. This parameter ranges from one (i.e. low-income area) to six (i.e. high-income area). Information about the SEL was used in the development of the exposure model to identify the expected building classes (i.e. for high-income areas construction tends to be better and in compliance with building regulation, and thus less vulnerable to earthquakes). The exposure models were developed in the following five steps: (1) the neighborhoods in each city were grouped in homogeneous zones based on the predominant number of stories and SEL, (2) building surveys were performed for each homogeneous zone to collect information about the lateral load resisting system (LLRS), the number of stories, and the ductility level (a total of 1359, 11,381, and 1093 buildings were surveyed in Bogotá, Medellín, and Cali, respectively), (3) collected data, census information, and expert judgment were used to establish a relationship between building typology, number of stories, and SEL, (4) the aforementioned relationship was used to assign a building typology to the non-surveyed buildings in the homogeneous zone, and finally (5) the results were aggregated at the neighborhood level. A summary of the exposure model is given in Table 2.

The number of residential buildings for Bogotá agrees with that reported by Departamento de Prevención y Atención de Emergencias (DPAE; 2005) and Yamín et al. (2013). It is worth mentioning that a detailed building-by-building model for multiple sectors was developed by Instituto Distrital de Gestión de Riesgos y Cambio Climático (IDIGER; 2017) using detailed cadastral information, but it is not publicly available. It should be noted that results from this work can be upgraded if the IDIGER model is released to the public. However, the number of buildings reported in the present study for Medellín is 38% higher than the one reported in the study by Salgado-Gálvez et al. (2014). This discrepancy is due to the fact that the present study included a larger area (the five *corregimientos* of Medellin). To the best knowledge of the authors, there is no equivalent study for Cali that could be used as a reference.

The residential building stock of each city was classified following the updated version of the GEM taxonomy (Brzev et al., 2013). Three attributes were used for building classification: main construction material, LLRS, and the expected level of ductility, leading to the following construction types: ductile reinforced concrete infilled frames (CR/LFINF + DUC), low-ductile reinforced concrete infilled frames (CR/LFINF + DUL),

Table 3. Building classes and fragility functions used in the seismic risk assessment

Building class in exposure model	No. of stories in the model	Percentage of the building stock			Adopted fragility functions	
		Bogotá	Medellín	Cali	No. of stories	Building class in the study
CR/LINF + DUL	1–9	5.5	8.3	2.1	1–9	CR/LINF + DUL/H:1 to H:9
MCF/LWAL + DUL	1–6	24.8	1.8	20.2	1–6	MCF/LWAL + DUL/H:1 to H:6
MUR/LWAL	1–6	35.3	71.5	24.3	1–4	MUR/LWAL/H:1 to H:4
					⩾5	MUR/LWAL/H:5
UNK/LN + DNO	1–2	0.9	0.8	1.5	1–2	UNK/LN + DNO/H:1 to H:2
MUR + ADO/LWAL	1	0.6	–	–	1	MUR + ADO/LWAL/H:1
CR/LDUAL + DUM	4–37; 39	0.1	0.3	–	4–11	CR/LDUAL + DUM/H:4 to H:11
					⩾12	CR/LDUAL + DUM/H:12
CR/LFINF + DUM	1–10	4.2	5.5	–	1–10	CR/LFINF + DUM/H:1 to H:10
CR/LWAL + DUM	2–28; 30–31	1.1	0.3	–	2–11	CR/LWAL + DUM/H:2 to H:11
					⩾12	CR/LWAL + DUM/H:12
MCF/LWAL + DUM	1–5	10.2	3.3	–	1–5	MCF/LWAL + DUM/H:1 to H:5
MR/LWAL + DUM	1–8	17.3	8.2	–	1–4	MR/LWAL + DUM/H:1 to H:4
					⩾5	MR/LWAL + DUM/H:5
CR/LDUAL + DUH	11–20	–	–	0.0[a]	11	CR/LDUAL + DUH/H:11
					⩾12	CR/LDUAL + DUH/H:12
CR/LFINF + DUH	1–20	–	–	1.4	1–9	CR/LFINF + DUH/H:1 to H:9
					⩾10	CR/LFINF + DUH/H:10
CR/LWAL + DUH	4–20	–	–	0.4	4–11	CR/LWAL + DUH/H:4 to H:11
					⩾12	CR/LWAL + DUH/H:12
MCF/LWAL + DUH	1–4	–	–	40.4	1–4	MCF/LWAL + DUH/H:1 to H:4
MR/LWAL + DUH	1–5	–	–	9.7	1–5	MR/LWAL + DUH/H:1 to H:5

CR/LFINF + DUL: low-ductile reinforced concrete infilled frames; MCF/LWAL + DUL: low-ductile confined masonry walls; MUR/LWAL: unreinforced masonry walls; UNK/LN + DNO: other building classes with no lateral load resisting system; MUR + ADO/LWAL: adobe and rammed earth walls; CR/LDUAL + DUM: medium-ductile reinforced concrete dual frame-walls; CR/LFINF + DUM: medium-ductile reinforced concrete infilled frames; CR/LWAL + DUM: medium-ductile reinforced concrete shear walls; MCF/LWAL + DUM: medium-ductile confined masonry walls; MR/LWAL + DUM: medium-ductile reinforced masonry walls; CR/LDUAL + DUH: high-ductile reinforced concrete dual frame-walls; CR/LFINF + DUH: high-ductile reinforced concrete infilled frames; CR/LWAL + DUH: high-ductile reinforced concrete shear walls; MCF/LWAL + DUH: high-ductile confined masonry walls; MR/LWAL + DUH: high-ductile reinforced masonry walls.

[a]Four buildings (0.001% of total).

ductile reinforced concrete shear walls (CR/LWAL + DUC), ductile reinforced concrete dual frame-walls (CR/LDUAL + DUC), ductile confined masonry walls (MCF/LWAL + DUC), low-ductile confined masonry walls (MCF/LWAL + DUL), ductile reinforced masonry walls (MR/LWAL + DUC), unreinforced masonry walls (MUR/LWAL), adobe and rammed earth walls (MUR + ADO/LWAL), and other building classes with no LLRS (UNK/LN + DNO). Two levels of ductility were considered for the ductile building classes (DUC) based on the seismic hazard zone defined in the national building code for each city. A medium ductility level (DUM) was assumed for Bogotá and Medellín and a high ductility level (DUH) was assumed for Cali. Table 3 presents the building classes used in the exposure models, as well as the distribution of the number of buildings within each building class for each city. A total of 167 building classes were identified in the three cities (84, 104, and 69 for Bogotá, Medellín, and Cali, respectively).

Table 3 also presents the fragility functions used for the risk assessment, as explained in the following section. An average replacement cost per square meter was assigned for each city based on the SEL, ranging from 200 to 1200 USD/m^2. This cost differs from the commercial value as land price is not included, and it was estimated based on the judgment of various local engineers and practitioners.

Figure 2 shows the number of buildings of the two most prominent building classes in each city. Unreinforced masonry (MUR/LWAL) is the most common typology in Bogotá and Medellín (35% and 72% of the building stock, respectively), while ductile confined masonry (MCF/LWAL + DUH) is the predominant class in Cali (40% of the building stock). Masonry buildings (unreinforced, confined, or reinforced) represent 88%, 85%, and 95% of the total residential building stock of Bogotá, Medellín, and Cali, respectively. Figure 3 presents the replacement cost distribution across each city. For the sake of comparison, in Figure 2 and forward results for Medellín exclude the *corregimientos*.

Fragility and vulnerability models

Structural fragility functions were used in order to represent the probability of exceeding a level of damage conditioned to ground shaking intensity. A total of 93 fragility functions were used in the present study to represent the 167 building classes of the exposure model (see Table 3). These fragility functions were developed as part of GEM's Global Seismic Risk Model (Martins and Silva, 2020). The fragility functions were generated using nonlinear time history analysis (NLTHA) on single degree of freedom (SDOF). The structural capacity of each building class was represented by a set of SDOF oscillators that captured the building-to-building variability. Each oscillator was subjected to a large set of ground motions and the maximum spectral displacement was used to allocate each SDOF into a damage state. The resulting damage distribution, conditioned to several ground motion levels, was used to fit a set of cumulative lognormal distributions for each building class. Four damage states dependent on the spectral displacement at the yielding point (S_{dy}) and the ultimate displacement (S_{du}) were used in the development of the fragility functions: slight ($0.7S_{dy}$), moderate ($0.75S_{dy} + 0.25S_{du}$), extensive ($(S_{dy} + S_{du})/2$), and complete (S_{du}) damage. These damage states are based on the proposal by Lagomarsino and Giovinazzi (2006) with minor modifications to prevent crossing between the damage thresholds. Different intensity measure types were considered to account for the dynamic properties of the various building classes: PGA and spectral acceleration (SA) at 0.3 s, 0.6 s, and 1 s.

The structural fragility functions were transformed into vulnerability functions (which define a probabilistic distribution of loss ratio conditioned to a level of ground shaking) through the use of a damage-to-loss model. Damage ratios (i.e. cost of repair to cost of replacement) of 0.05, 0.25, 0.6, and 1 were considered for slight, moderate, extensive, and complete damage, respectively. The percentage of buildings in each damage state is computed and multiplied by the respective damage ratio, thus leading to a loss ratio for each intensity measure level. The resultant vulnerability functions were used to calculate the direct economic impact of earthquakes in the cities.

In addition to the calculation of economic losses, this study also covered the estimation of fatalities (i.e. occupants instantaneously killed or mortally injured) considering the HAZUS casualty model (Federal Emergency Management Agency (FEMA), 2013). This model establishes a relation between fatality rates and a level of damage (slight, moderate, extensive, and complete damage) per building class. Only a portion of the buildings in the complete damage state were assumed to actually collapse, following the recommendations from HAZUS. Table 4 presents the correspondence between the HAZUS building classes

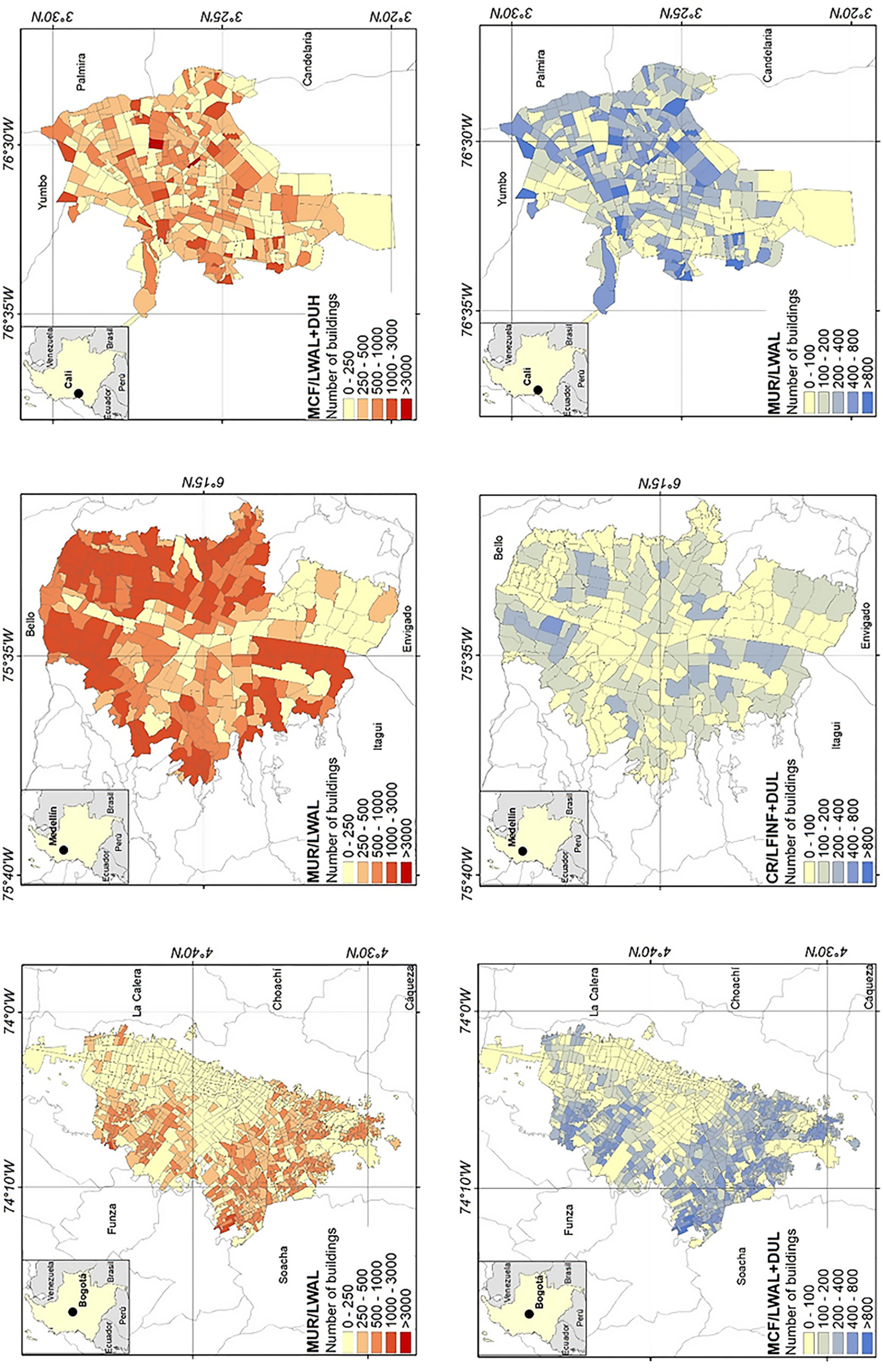

Figure 2. First (top) and second (bottom) most common residential building class in each city: Bogotá (left), Medellín (center), and Cali (right).

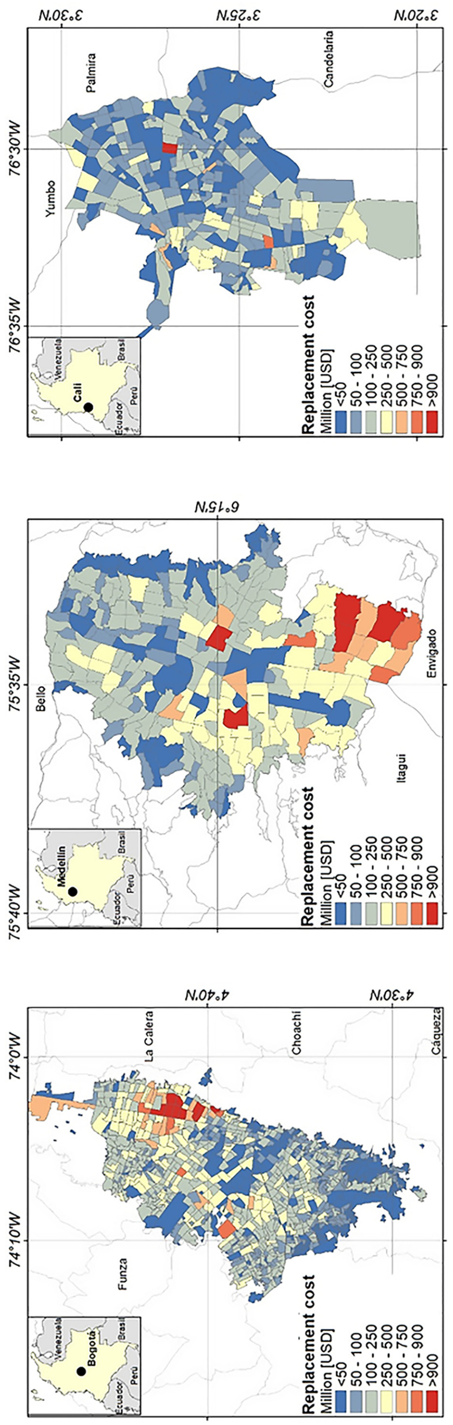

Figure 3. Replacement cost distribution of residential buildings in each city: Bogotá (left), Medellín (center), and Cali (right).

Table 4. Building classes used for the estimation of fatalities

HAZUS building class			Building classes in this study
Description	Label	No. of stories	
Concrete shear walls	C2L	1–3	CR/LDUAL + DUM; CR/LDUAL + DUH;
	C2M	4–7	CR/LWAL + DUM; CR/
	C2H	8 +	LWAL + DUH
Concrete frames with unreinforced masonry infill walls	C3L	1–3	CR/LINF + DUL; CR/
	C3M	4–7	LINF + DUM; CR/
	C3H	8 +	LINF + DUH
Reinforced masonry bearings walls with precast concrete diaphragms	RM2L	1–3	MCF/LWAL + DUL; MCF/
	RM2M	4–7	LWAL + DUM; MCF/
	RM2H	8 +	LWAL + DUH; MR/ LWAL + DUM; MR/LWAL + DUH
Unreinforced masonry bearing walls	URML	1–2	MUR/LWAL;
	URMM	3 +	MUR + ADO/LWAL
Wood, light frame	W1	1–2	UNK/LN + DNO

DUM: medium ductility; DUH: high ductility; DUL: low ductility; DNO: no lateral load resisting system.

and the typologies used in this study. A nighttime scenario was considered (earthquake striking at 2 a.m.), which is expected to generate the highest casualties due to the greater proportion of population at home.

Probabilistic seismic risk assessment

For the calculation of the risk metrics, the PSHA model, exposure dataset, and vulnerability functions presented in previous sections have been combined using the OpenQuake-engine (Pagani et al., 2014; Silva et al., 2014). An event-based Monte Carlo simulation approach was followed to calculate average annual losses, probable maximum losses, and loss maps at different return periods. These results allow the identification of the areas in the city where the potential for economic or human losses is highest, and thus where risk reduction activities should be prioritized.

For each city, 50,000 synthetic catalogs (or stochastic event sets—SESs), each one representative of the seismicity of the region over a period of one year were generated. In this context, an SES represents possible earthquake ruptures that can occur during a period of one year, by sampling the corresponding probability of occurrence specified in the seismic source model. For each rupture, a ground motion field is generated considering the inter- and intra-event variability defined by each GMPE. Then, the sampled ground shaking at each location is used to calculate a loss ratio per asset using the associated vulnerability function. This loss ratio is multiplied by the replacement cost of the asset, leading to a list of loss values (one per rupture). As previously mentioned, site conditions were considered through the use of site-specific AFs and three levels of uncertainty in the amplification factors.

Loss exceedance curves and average annual losses were computed for each city. Loss exceedance curves are estimated based on the total aggregated losses simulated in each event, and it associates losses with an exceedance rate or return period; this rate can be converted into a probability if a Poisson process is assumed (Silva, 2018). Three of the four tectonic environments affect the studied cities (i.e. subduction interface, subduction in-slab, and active shallow crust), for a total of 54 logic tree branches. These branches correspond to the three GMPEs considered for each tectonic region and two logic tree branches that represent the uncertainty in the source models. In addition to these 54 branches, another three levels of uncertainty were considered for the site response (i.e. σ_{lnAF}: 0.3, 0.5, and 0.7) leading to a total number of logic tree branches of 162.

Figure 4 presents the mean aggregated loss curves in each city for each σ_{lnAF} (continuous black lines) as well as the aggregated loss curves for each logic tree branch (dark gray lines). A high variability in losses by logic tree branch can be observed in Figure 4, with a greater dispersion for Bogotá and Cali, a particularity that must be considered when results are used for the development of risk-management strategies. It can be observed that Bogotá has the largest mean aggregated loss, while Medellín and Cali have similar aggregated losses. However, if the mean aggregated loss ratio is compared, Medellín and Bogotá have relatively similar curves that are smaller than the one for Cali. For comparison reasons, Figure 4 includes aggregated loss curves assuming rock conditions in each city: black dashed line for mean values and continuous light gray lines for each logic tree branch. The comparison of soil and rock results highlights the influence of soil conditions in the relative risk.

The average annual losses (AALs) for $\sigma_{lnAF} = 0.5$ were estimated as USD 87, 30, and 29 million for Bogotá, Medellín, and Cali, respectively. For the three cities, AAL values for $\sigma_{lnAF} = 0.3$ and $\sigma_{lnAF} = 0.7$ are approximately 74% and 150% of those for $\sigma_{lnAF} = 0.5$, respectively. The corresponding average annual loss ratios (AALRs—ratio between the AAL and the associated exposed value) are 0.62‰ for Bogotá, 0.58‰ for Medellín, and 0.81‰ for Cali ($\sigma_{lnAF} = 0.5$). AALR values for Bogotá and Medellín are smaller than those reported by other authors (i.e. Salgado-Gálvez et al., 2013, 2014; UNGRD, 2018). A reference study for Cali was not found.

Figure 5 presents the geographical distribution of the AALR for each city considering $\sigma_{lnAF} = 0.5$, as well as the contribution of each building class to the AALR. For the three cities, the building class with the highest contribution to the AALR is unreinforced masonry walls (MUR/LWAL), followed by low-ductile confined masonry walls (MCF/LWAL + DUL) in Bogotá and Cali, and low-ductile reinforced concrete infilled frames (CR/LFINF + DUL) in Medellín.

Earthquake scenarios for the three cities

The risk metrics presented in the previous section evaluated earthquake risk from a probabilistic perspective. However, equally valuable information can be obtained from earthquake scenarios. These scenarios contribute to the understanding of the consequences that an earthquake can cause in a region in terms of the number and distribution of damaged buildings, casualties, and economic losses.

The consequences due to a given seismic scenario can change significantly depending on the characteristics of the earthquake (e.g. hypocentral depth, magnitude, and distance to the exposed assets). In this study, two scenarios were selected for each city based on the loss exceedance curves (see Figure 4). The events that generated losses of the same order of magnitude of the weighted mean for the 475-year return period and $\sigma_{lnAF} = 0.5$ were used to evaluate the contribution from each tectonic environment. The majority of the events

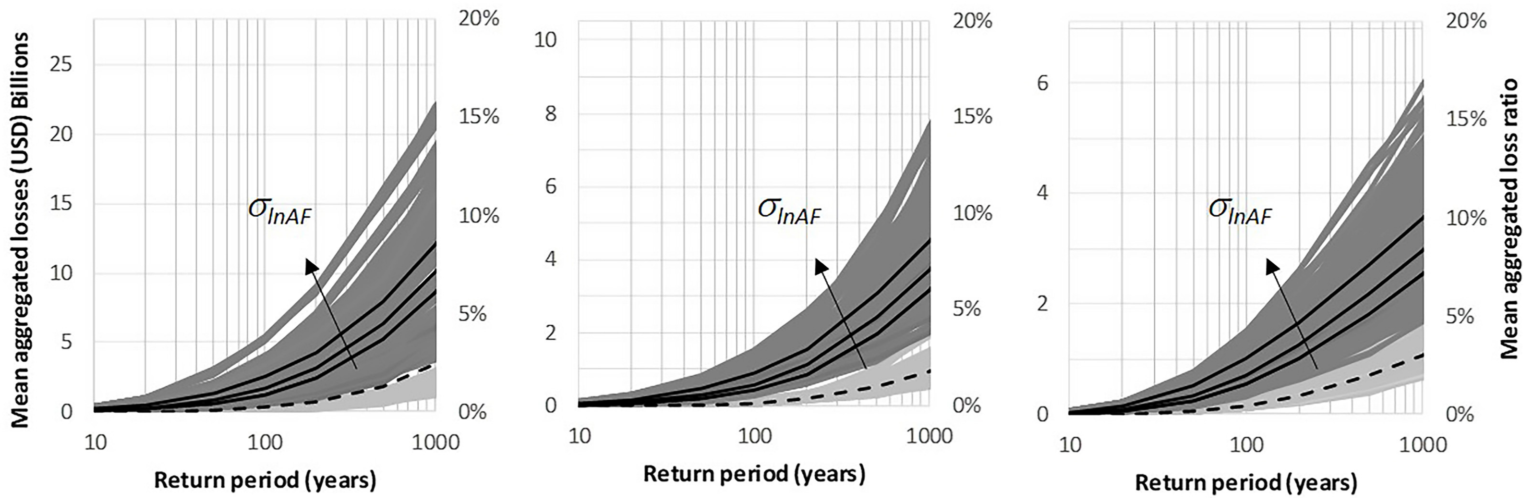

Figure 4. Loss exceedance curves for Bogotá (left), Medellín (center) and Cali (right) for rock and soil conditions. Black lines: mean values for rock (dashed lines) and soil (continuous lines). Gray lines: logic tree-branch for rock (lighter lines) and soil (darker lines).

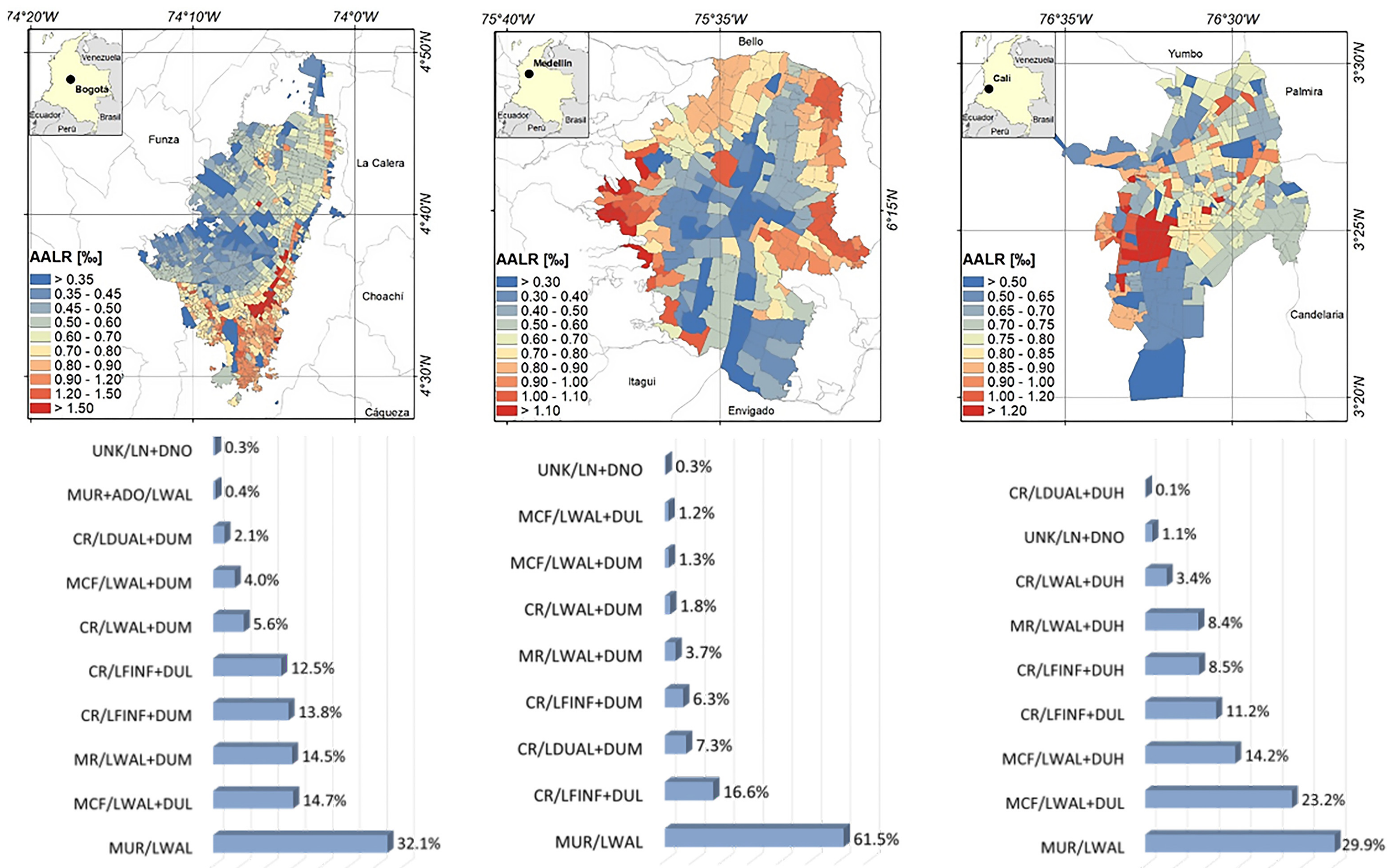

Figure 5. Distribution of average annual loss ratio, AALR, for σ_{lnAF} = 0.5 (top) and contribution of building classes to the AALR (bottom) for Bogotá (left), Medellín (center), and Cali (right).

Table 5. Selected seismic scenarios in each city

City	Tectonic region	Magnitude (Mw)	Depth (km)	Epicenter
Bogotá	Active shallow (1)	6.8	20.0	4°22′ N, 73°57′ W
	Active shallow (2)	6.0	5.0	4°49′ N, 74°02′ W
Medellín	Active shallow	7.5	7.5	6°18′ N, 76°05′ W
	Subduction interface	8.4	29.1	5°27′ N, 77°09′ W
Cali	Subduction intra-slab	7.2	63.1	3°28′ N, 77°05′ W
	Subduction interface	8.5	19.2	4°01′ N, 77°31′ W

affecting Bogotá (91%) are active shallow crustal events; the remaining 9% are subduction interface (3%) and intra-slab (6%) events. Losses with a frequency close to the 475-year return period for Medellín are dominated by active shallow crustal events (52%), followed by subduction interface events (42%), and the remaining 6% are subduction intra-slab events. The same level of losses for Cali correspond to subduction intra-slab events (58%), subduction interface events (32%), and active shallow crust events (10%).

Two ruptures from different tectonic environments were selected for each city, with the exception of Bogotá whose hazard is heavily dominated by active shallow events. Table 5 presents the characteristics of the selected earthquake scenarios. The aleatory uncertainty in the ground motion was considered by the generation of 1000 ground motion fields (Silva, 2016) for each intensity measure used in the fragility/vulnerability model.

Table 6 presents a summary of the consequences of the selected scenarios in terms of the number of buildings that suffered complete damage, economic losses, and number of fatalities, considering $\sigma_{lnAF} = 0.5$. The results are presented for each GMPE, as well as the weighted mean (considering the weights presented in Table 1). Figures 6 to 8 depict the weighted mean ground motion field (in terms of PGA) estimated on soil surface, a map with the spatial distribution of the weighted mean number of buildings in complete damage, and a map with the distribution of the weighted mean economic losses and number of fatalities.

Conclusion

This study presented a seismic risk assessment for the three largest metropolitan centers of Colombia: Bogotá, Medellín, and Cali. A recent model, PSHA, developed by the SGC in collaboration with the GEM Foundation was used. Exposure models at the neighborhood resolution were developed for each city, and are currently accessible to the general public. Structural fragility functions developed as part of GEM's Global Seismic Risk Model (Martins and Silva, 2020) were used, and a casualty model was explored for the estimation of fatalities.

Seismic risk metrics were computed for each city following an event-based Monte Carlo simulation approach with the OpenQuake-engine (Pagani et al., 2014; Silva et al., 2014). Site effects were considered using site-specific AFs with three different levels of uncertainty ($\sigma_{lnAF} = 0.3$, 0.5, and 0.7). The AFs were computed based on the latest available microzonation study for each city, which imposed some constraints in the analysis: intensity-dependent AFs were only available for Bogotá and none of the studies reported the uncertainty in the site response.

Table 6. Consequences of seismic scenarios for σ_{lnAF} = 0.5

City	Tectonic region	GMPE[a]	Complete damaged buildings		Economic loss (USD millions)		Number of fatalities (nighttime scenario)	
			Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Bogotá	Active shallow (1)	(a)	14,644	1796	7361	490	1687	214
		(b)	15,380	14,001	6479	3404	1755	1644
		(c)	54,561	31,944	18,209	6211	6165	3835
		Mean[b]	23,353		9306		2658	
	Active shallow (2)	(a)	16,048	1982	9422	661	2402	315
		(b)	11,697	9594	7331	3348	1832	1421
		(c)	15,314	11,005	9633	3674	2370	1648
		Mean[b]	14,196		8651		2173	
Medellín	Active shallow	(a)	3763	1327	1305	196	271	86
		(b)	9008	9252	2351	1351	647	594
		(c)	9409	8073	2827	1221	713	518
		Mean[b]	7000		2034		511	
	Subduction interface	(d)	10,738	10,535	2824	1496	773	751
		(e)	9467	8139	2823	1249	709	582
		(f)	21,382	14,659	4684	1894	1560	1062
		Mean[b]	12,584		3224		920	
Cali	Subduction intra-slab	(g)	11,414	8265	2041	1031	637	495
		(h)	8072	7664	1674	1024	462	456
		(i)	7267	4723	1640	656	427	279
		Mean[b]	9368		1827		531	
	Subduction interface	(d)	8620	7973	1979	1084	502	473
		(e)	6079	5295	1588	776	370	312
		(f)	16,246	11,035	3027	1332	969	675
		Mean[b]	9376		2068		556	

GMPE: ground motion prediction equation.
[a]GMPEs: (a) Idriss (2014) / weight: 0.399; (b) Cauzzi et al. (2015) / weight: 0.390; (c) Abrahamson et al. (2014) / weight: 0.211; (d) Abrahamson et al. (2016) / weight: 0.437; (e) Zhao et al. (2016)—fix hypocentral depth at 20 km / weight: 0.348; (f) Montalva et al. (2017) / weight: 0.215; (g) Montalva et al. (2017) / weight: 0.437; (h) Abrahamson et al. (2016) / weight: 0.358; (i) Zhao et al. (2016)—magnitude capped at Mw 7.8 / weight: 0.205.
[b]Weighted mean with GMPEs weight.

AALs were estimated as USD 87, 30, and 29 million for Bogotá, Medellín, and Cali, respectively, for $\sigma_{lnAF} = 0.5$. The AALs for $\sigma_{lnAF} = 0.3$ and $\sigma_{lnAF} = 0.7$ are approximately 74% and 150% of those for $\sigma_{lnAF} = 0.5$, respectively. AALRs were estimated as 0.62‰ for Bogotá, 0.58‰ for Medellín, and 0.81‰ for Cali (for $\sigma_{lnAF} = 0.5$).

In addition to the variability in the site response, a high variability in the loss exceedance curves was observed in all of the cities due to the different GMPEs and source models (this situation was also observed in the city scenarios where only GMPE uncertainty is included). Therefore, it might be misleading to express risk metrics based only on mean values, as users of the results should be aware of the whole range of possibilities.

Although a direct comparison of the presented results with other existing studies cannot be performed (as only residential buildings were considered in this study), results from the Risk Atlas for Colombia (UNGRD, 2018) and Salgado et al. (2013) are used as reference for Bogotá, and Salgado-Gálvez et al. (2014) for Medellín. All of the studies assessed

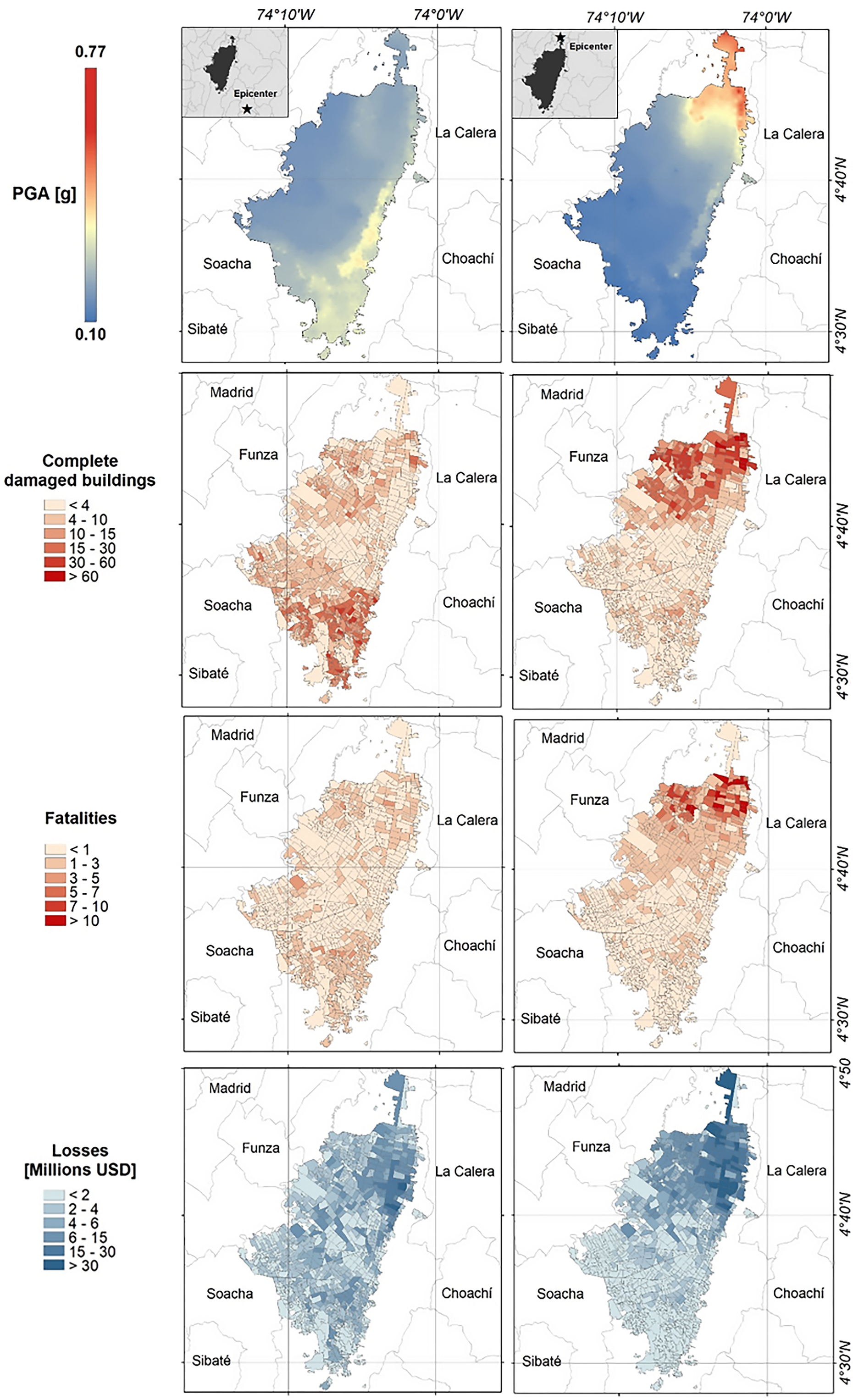

Figure 6. Distribution of weighted mean values for ground shaking, complete damaged buildings, fatalities, and economic losses in Bogotá for two active shallow events: Mw = 6.8 (left) and Mw = 6.0 (right). Maximum reached PGA of 0.49 g and 0.77 g, respectively.

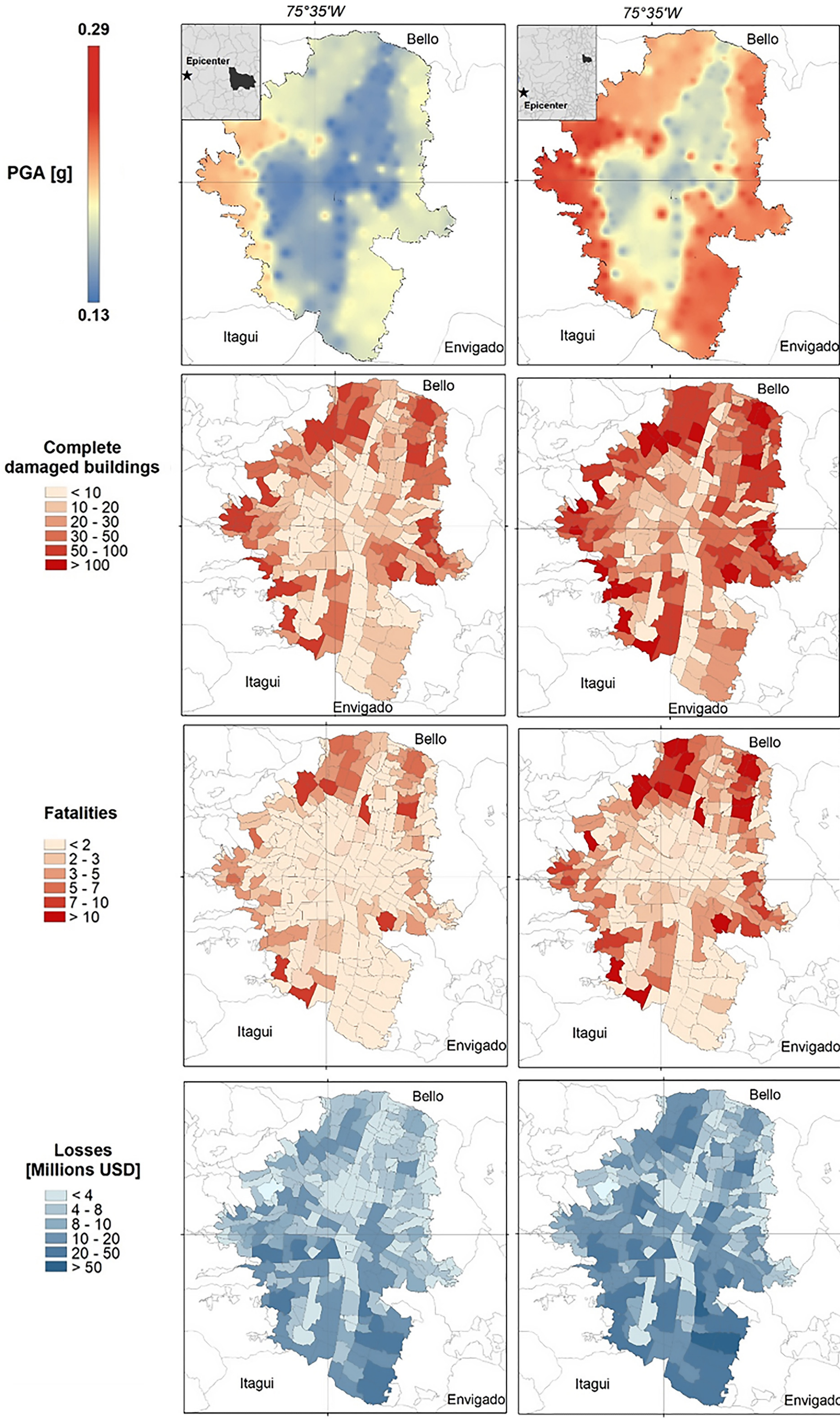

Figure 7. Distribution of weighted mean values for ground shaking, complete damage buildings, fatalities, and economic losses in Medellín for an active shallow event Mw = 7.5 (left) and a subduction interface event Mw = 8.4 (right). Maximum reached PGA of 0.24 g and 0.29 g, respectively.

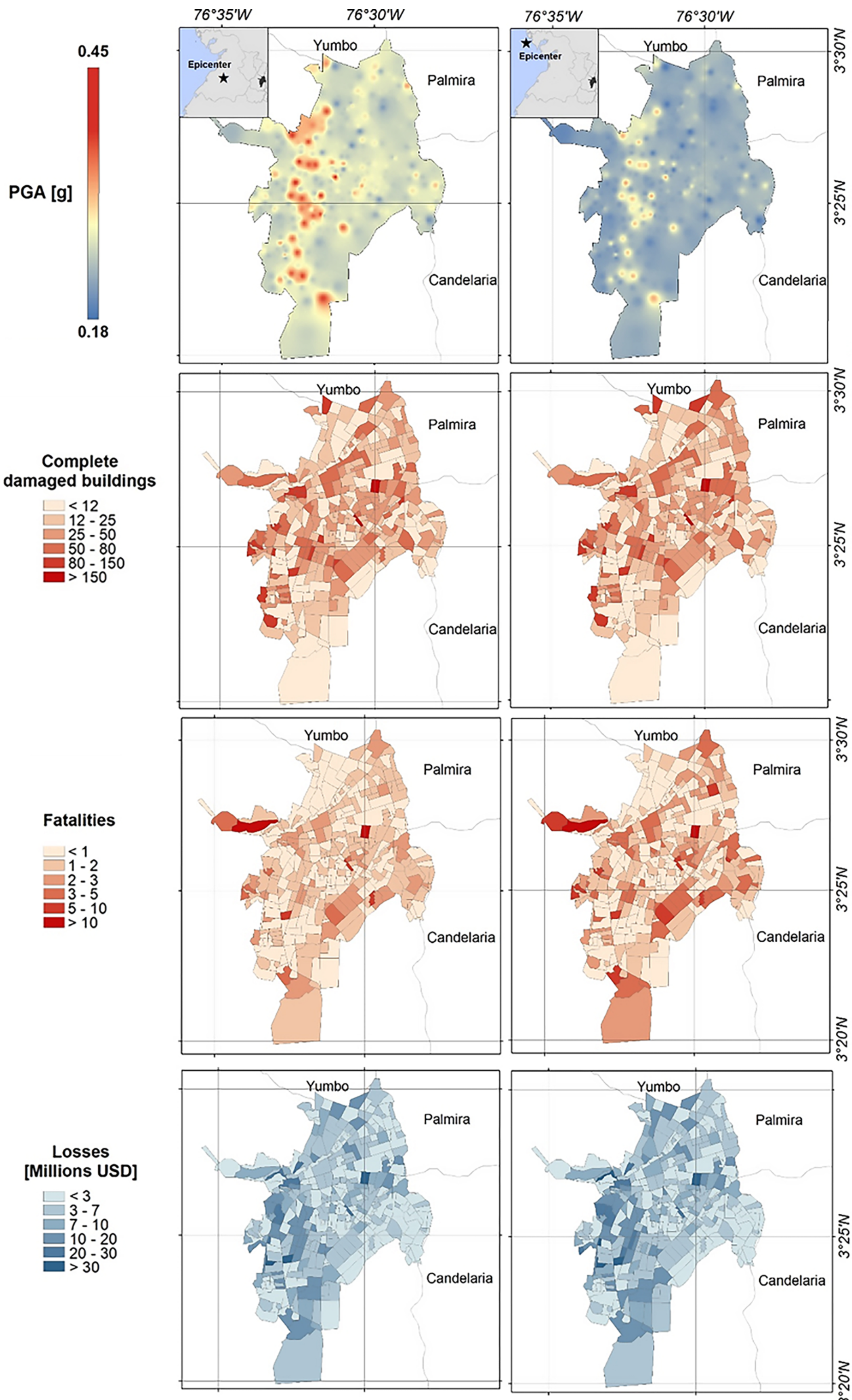

Figure 8. Distribution of weighted mean values for ground shaking, complete damage buildings, fatalities, and economic losses in Cali for a subduction intra-slab event Mw = 7.2 (left) and a subduction interface event Mw = 8.5 (right). Maximum reached PGA of 0.45 g and 0.37 g, respectively.

seismic risk for public and private buildings (regardless of the building use). The maximum probable seismic loss for the 475-year return period for Bogotá is indicated in the range of 11% and 21% of the exposed value by the addressed references; the same value for Medellín corresponds to 14% (Salgado-Gálvez et al., 2014). Values from this work indicate mean aggregated loss ratios for the same return period between 4% and 6% for both Bogotá and Medellín and 5% to 8% for Cali. An analysis of the drivers behind the differences between the results of this study and those from past studies could not be done as none of the models are publicly available.

The building class with the higher contribution to the AALR is unreinforced masonry walls (MUR/LWAL) for the three cities, which indicates the high vulnerability of this type of construction. As expected, the higher contribution of MUR/LWAL to the AALR occurs in Medellín, a city in which this building typology represents 70% of the residential building stock. The contribution of the remaining building typologies to the AALR is different for each city, which highlights the importance to assess seismic risk at the city level.

Two earthquake scenarios were analyzed for each city based on weighted mean losses for the 475-year return period considering $\sigma_{lnAF} = 0.5$. The consequences of the selected scenarios were presented for each GMPE, as well as for the weighted mean. A high variability in the loss metrics (completely damaged buildings, economic losses, and number of fatalities) was observed due to the epistemic and aleatory variability from the GMPEs. Once again, these results highlight the importance in considering the uncertainty in the GMPEs. Users of scenario results must be aware that several scenarios may cause the same level of losses, but consequences will differ based on the earthquake rupture characteristics. It is advised to assess more than two scenarios for different levels of loss.

The models and datasets from this study are available to the public. The authors of this study encourage users to access the models and explore them for seismic risk assessment and disaster risk management.

Author's Note

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