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ORIGINAL RESEARCH PAPER

Fully probabilistic seismic risk assessment considering local site effects for the portfolio of buildings in Medellín, Colombia

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Abstract A fully probabilistic seismic risk analysis using a comprehensive approach is conducted for Medellin, the second largest city of Colombia, using a building by building database constructed and complemented from aerial images, considering characteristics such as building use categories, socio-economic levels and replacement values. The seismic hazard used for the analysis corresponds to the most updated study available in the country with the same model that was included in the national building code maps definition. Spectral transfer functions are determined for each of the seismic microzonation zones in order to take into account the dynamic soil response and amplification effects in the risk analysis. Several building types are defined for the city and individual vulnerability functions are assigned to each of them. Risk results are presented in the state of the art metrics such as the loss exceedance curve, probable maximum losses for different return periods, average annual losses and risk maps. The obtained results can be classified by use and socio-economic sectors as well as by structural systems that may help the stakeholders to identify where the risk concentrates.

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1 Introduction

Several tools have been developed in order to assess the risk associated with natural events since the importance of this issue has now been understood at different decision-maker levels, and thus it has been incorporated in governments as a development issue that considers failures and achievements at local, regional and country level. CAPRA[1] (ERN-AL 2010; Cardona et al. 2010), a tool developed by the ERN-AL Consortium with the support of the World Bank, the Inter-American Development Bank and the United Nations International Strategy for Disaster Risk Reduction, is one of the available tools for this purpose and its seismic hazard, vulnerability and probabilistic risk analysis modules have been used in this study because of its open architecture and open source characteristics. The results that are presented here are part of a fully probabilistic seismic risk analysis performed for the public and private portfolio of buildings, using the most updated seismic hazard model for the country (in terms of seismic intensities at bedrock level) and for the city (considering the seismic microzonation).

Because of the convergence of different tectonic plates, Medellín is located in an active seismic region and as a result of this interaction the city has an intermediate hazard level with possible events associated to three main systems: the Romeral Fault System, Murindó Fault System and Benioff Intermediate Zone (Salgado et al. 2010; Pulido 2003). No destructive earthquakes have yet occurred in the vicinities of the city but historical records account for a quake in 7 September 1882, a shallow 5.2 magnitude earthquake in 12 November 1979 and also a shallow 7.1 magnitude event on 18 October 1992 that generated considerable damage in different parts of the city, specifically on facades and division walls (Ramírez 2004). The consideration of the local site-effects in Medellin is of the upmost importance due to the characteristics of some soft soil and clay deposits that may give some important amplification factors for the fundamental periods.

The exposure portfolio is a building by building resolution level database where every element is individually identified and characterized with the relevant parameters in terms of building class, number of stories and age in order to assign an adequate and representative vulnerability function. Building's use and replacement values are required too in order to obtain the risk results in terms of sectors and monetary units respectively. For the definition of those parameters, official indexes and statistics are employed. (Alcaldía de Medellín 2010). The information was complemented in some zones using aerial images. Several building classes were identified in order to define a set of vulnerability functions that relate the intensity (spectral acceleration) with the expected loss (relative to the exposed value) in each element.

The risk identification process is the first of the disaster risk management steps (Cardona 2009) that may lead to the identification of the order of magnitude of the required budget to proceed to the following steps regarding mitigation strategies such as structural intervention or retrofitting of existing structures, urban planning regulations, long-term financial protection strategies (Freeman et al. 2003; Andersen 2002) and emergency planning. Since the losses are quantified before the occurrence of the disaster (that can be understood as the materialization of existent risk conditions), *ex-ante* measures such as cat-bonds, contingent loans, disaster

[1] Comprehensive approach to probabilistic risk assessment (www.ecapra.org).

reserve funds, traditional insurance and reinsurance mechanisms can be considered instead of the *ex-post* measures that are usually followed (Marulanda et al. 2008; Marulanda 2013).

Previous works related to the subject exist for the city quantifying the expected damages for selected earthquake scenarios (Alcaldía de Medellín 1994) and also analyzing the city's physical earthquake vulnerability (Jaramillo and Ortega 1994). This is a new fully probabilistic seismic risk analysis, considering a stochastic set of earthquake scenarios, including the local site effects and accounting for the uncertainties in the hazard intensities and physical vulnerability parameters that has been conducted in a building by building resolution level for Medellín.

Also, since the risk is calculated using a geographical information system (GIS) platform, the expected losses are geo-referenced to each asset. Moreover, besides obtaining the risk metrics for the portfolio of buildings in terms of the loss exceedance curve -from which risk indicators such as the average annual loss and probable maximum losses can be derived- the geographical distribution of the expected losses can be visualized through seismic risk maps. Finally, the results can be grouped into counties, economic sectors and categories in terms of socio-economic level and building classes. Those results may be used by decision-makers at city level in order to identify the risk driver factors and design disaster risk management strategies.

2 Methodology

Since the occurrence of earthquakes over the time cannot be predicted and a complete time window is an unknown quantity, a set of stochastic events is generated. Each scenario is characterized with an annual frequency of occurrence and the first two statistical moments for the selected intensity (spectral acceleration and 5 % damping) allow a fully probabilistic hazard representation. Then, for each scenario and for each asset included in the portfolio of buildings, considering its geographical location and the estimation of the hazard intensity at that point, including the local site effects, the expected loss and its variance are calculated using the associated vulnerability function to the asset. This is repeated for all the assets included in the database and when this calculation is finished, the loss probability distribution function is calculated for the event in consideration. When this procedure is concluded for all the events in the set of stochastic scenarios, the loss exceedance rate for the whole portfolio is calculated from the event's loss probability distribution functions and their occurrence frequencies. Figure 1 presents a flowchart of the process

The scenario approach allows the risk calculation in terms of a loss exceedance curve (LEC) since the future losses and most importantly, their occurrence rates are calculated. Once the LEC is obtained, information regarding the average annual loss (AAL) and probable maximum losses (PML) for several return periods can be estimated.

All input information for the risk analysis was generated using the CAPRA modules such as CRISIS2007 (Ordaz et al. 2007) for the seismic hazard assessment, SiteEffects (ERN-AL 2011b) to generate the spectral transfer functions, and ERN-Vulnerability (ERN-AL 2009) to define, select and assign the vulnerability functions. The risk analysis was done in the CAPRA-GIS platform (ERN-AL 2011a) that constitutes the risk calculator of the initiative. These modules have been used in several projects and studies at global level for estimating seismic hazard at country level (IGN 2013; AIS 2010a; Salgado et al. 2010) at local level (Ramana and Dogagoudar 2012; Panzera et al. 2011) and also to calculate vulnerability and risk at country and local level (ISDR 2013; Salgado et al. 2013; Marulanda et al. 2013).

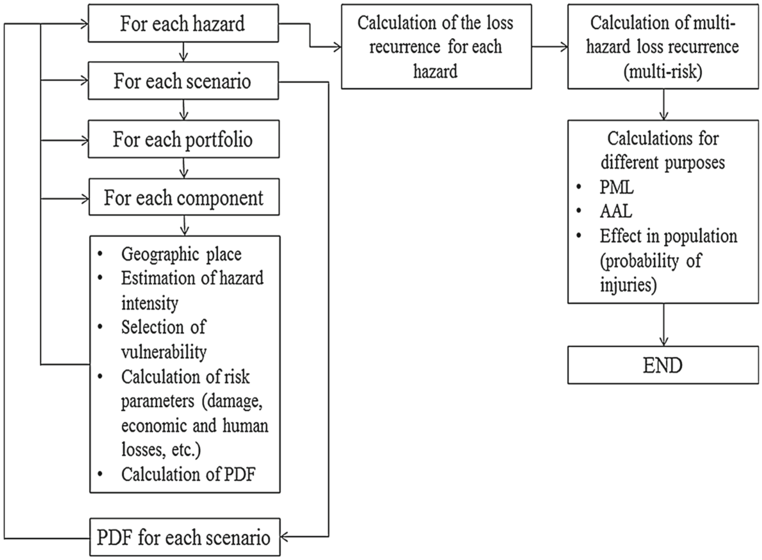

Fig. 1 Probabilistic risk analysis flowchart (ERN-AL 2011a)

3 Seismic hazard

Medellín is located on an intermediate level seismic hazard zone according to the national seismic hazard assessment study (AIS 2010a), and important seismic sources (in shallow and subduction zones) can generate high intensities in the analysis area. Because its location on the northwestern South America's corner, Colombia has been subjected from the geological past to big stresses because of the convergence of three tectonic plates: the Caribbean, Nazca and South America plates (Pulido 2003). The interaction between the Nazca and South American plates generates a subduction zone along the Pacific Coast to which earthquakes of considerable magnitude have been associated, mainly located in the south of the country. The displacement rate of the Nazca Plate has been estimated in approximately 69 mm/year towards the east (Kellogg and Vega 1995).

The Caribbean plate has a displacement with south–east direction that creates a compression zone between itself and the South American plate. Even though there are records of earthquakes associated to this interaction, their frequencies and magnitudes are very low. The displacement rate has been estimated in approximately 10 mm/year (Kellogg and Vega 1995).

Intraplate fault systems, to which shallow seismicity is associated, exist along the Andean zone which is relevant to Medellín, with reverse, normal and strike-slip fault mechanisms (Paris et al. 2000). Of special importance to Medellín are the Romeral and Murindó Fault Systems which are highly active and contribute to the seismic hazard in the city (Salgado et al. 2010). Additionally, deep earthquakes also contribute to the total seismic hazard in Medellín, especially those associated to the Intermediate Benioff Zone (Taboada et al. 2000) which have an associated depth between 60 and 120 km just beneath the city.

Colombia has several seismic hazard assessment studies (AIS 1984, 1996; Gallego 2000; Shedlock and Tanner 1999) and in the framework of the latest building code update in 2010 (AIS 2010b) a new seismic hazard study at national level was conducted

(AIS 2010a; Salgado et al. 2010). The seismic hazard model for the generation of the stochastic set of scenarios at country level was the same, in terms of catalogue, seismogenetic sources and ground motion prediction equations (GMPE's) used for the update of the Colombia's seismic hazard map (AIS 2010a; Salgado et al. 2010). A moment magnitude homologated catalogue with 7,401 events was used for the study and then the country was divided into 38 seismogenetic sources, following the Esteva approach (1970) where for each of them an independent earthquake generation process was calculated. An area-source geometrical model is selected in order to take into account the slip angle and depth distribution, since the information for the definition of the required parameters is available. Spectral GMPE's calibrated with local registers (Gallego 2000) were used for the analysis.

Figure 2 presents the considered shallow (blue) and deep (purple) sources for Colombia and their location with respect to Medellín (red point). The Romeral and, Murindó Fault

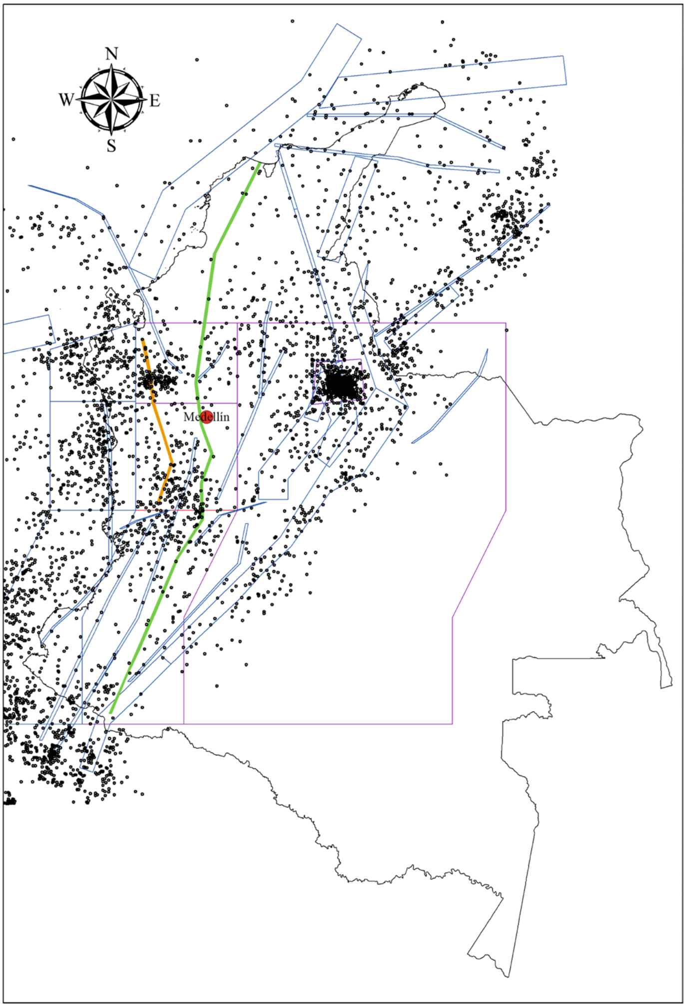

Fig. 2 Seismogenetic sources for Colombia (adapted from Salgado et al. 2010)

Systems are highlighted in green and orange respectively. Also the location of epicentres of events with magnitude equal or higher to 4.5 are shown in the figure.

A local seismicity Poisson model was employed, from where the activity of each seismic source is calculated based on the magnitudes' exceedance rates generated by each one of them. Said rate measures the frequency that, in average, in each source, earthquakes with magnitude equal or higher to the selected threshold are generated. Seismicity can be defined following this expression (Cornell 1968).

$$\lambda(M) = \lambda_0 \frac{e^{-\beta M} - e^{-\beta M_u}}{e^{-\beta \mathrm{M}_o} - e^{-\beta M_u}}, \quad M_0 \leq M \leq M_U \tag{1}$$

where $\lambda(M)$ is the occurrence frequency for events equal or higher to the selected magnitude; λ_0, β and M_U are the seismicity parameters calculated and defined for each source and M is the general random variable that represents the magnitude for each source. λ_0 describes the annual rate of occurrence of events with magnitude equal or higher than the selected threshold, which was set equal to 4.0 for all sources in this case, β represents the initial slope of the logarithmic regression and M_U the maximum magnitude associated to each source, which is the largest earthquake expected to be generated from each source. The λ_0 and β parameters were calculated using the maximum likelihood method (McGuire 2004).

Once the seismicity parameters are defined for each one of the sources, and appropriate GMPE's are assigned to each of them, it is possible to assess the seismic hazard at the sites of interest by integrating the contribution of each source considering the distance from each one to the point of interest. The hazard is computed by the following expression:

$$\nu(a) = \sum_{n=1}^{N} \int_{M_0}^{M_U} -\frac{\partial \lambda}{\partial M} Pr(A > a|M, R_i) dM \tag{2}$$

where a is the selected seismic intensity, R_i is the distance, N the total number of seismic sources and $Pr(A > a|M, R_i)$ the probability that the selected intensity is exceeded given the magnitude and the distance of the ith source and the analysis point, R_i.

Since the hazard assessment information was defined at national level, some sources and their associated generated scenarios are located far from the analysis area and do not generate intensities that could cause damages on the exposed assets. As a result of this, from the complete set that is comprised by 22,434 scenarios, only those with intensities equal or higher to 15 cm/s^2 are considered in the analysis leading to a total of 2,544 scenarios.

The events' intensities are calculated for several spectral ordinates ranging from 0.0 to 2.2 s, to consider that different structures respond in distinct ways to the same event. Figure 3 presents the uniform hazard spectrum (UHS) at bedrock level in Medellin for different return periods. Peak ground acceleration (PGA) for 475 and 2,500 years is equal to 195 and 290 cm/s^2, respectively which represent a considerable seismic hazard level.

3.1 Site effects

Medellín is located in a valley with a variety of geological, geotechnical and geomorphological characteristics from where different types of clays and limes can be identified (SIMPAD et al. 1999). No soft soil deposits exist in the city but the existent soils deposits can generate important amplification factors for high to medium range frequencies. Furthermore, the valley is surrounded by mountains in the eastern and western areas which also generate important topographical amplification conditions.

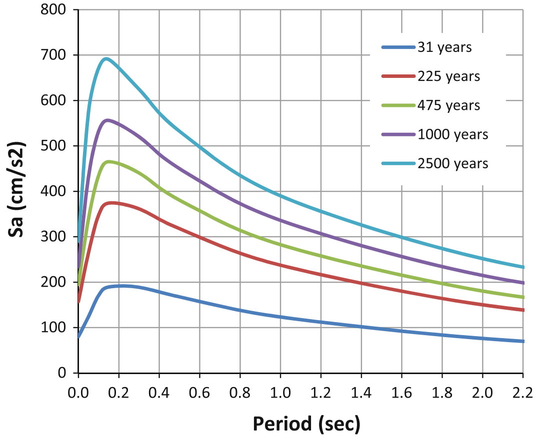

Fig. 3 Uniform hazard spectrums for Medellín

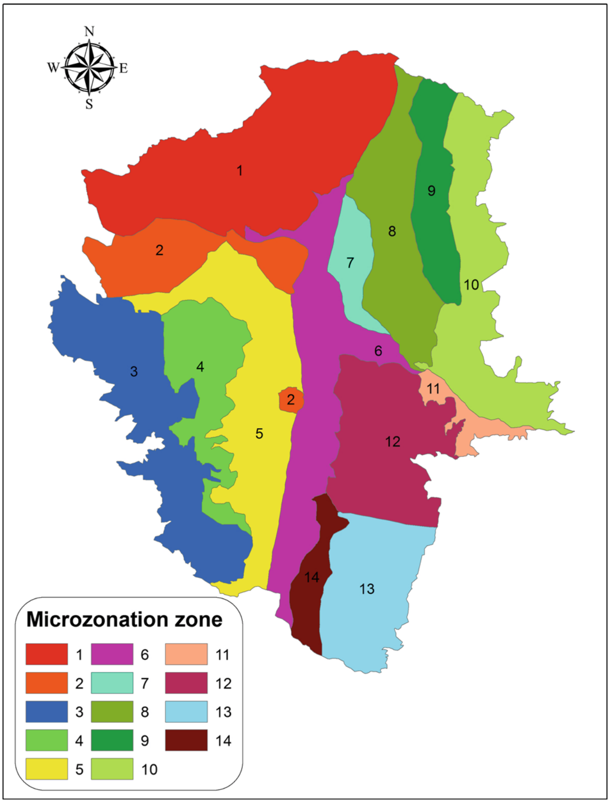

Fig. 4 Seismic microzonation zones for Medellín (adapted from SIMPAD et al. 1999)

The city has a seismic microzonation study (SIMPAD et al. 1999) that has defined 14 different homogeneous soil zones. The geographical location of each zone, as well as the numerical ID's linked to the spectral transfer functions are presented in Fig. 4.

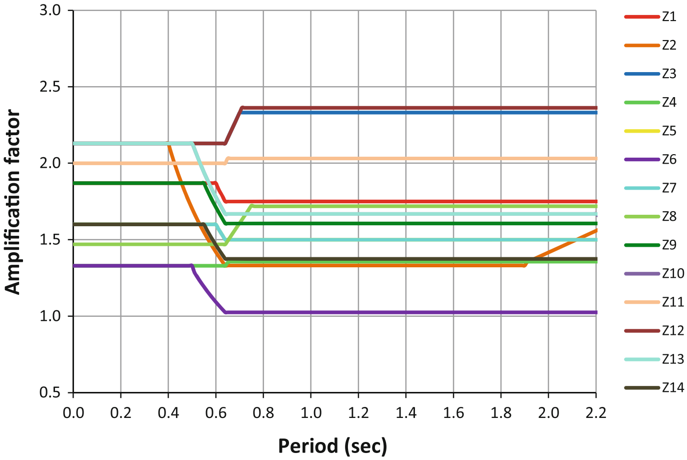

Fig. 5 Amplification factors for the seismic microzonation zones in Medellín

The soil information with downhole and laboratory tests was not available and thus it was not possible to compute the dynamic soil response with a typical non-linear and one dimensional propagation model in order to compute the response spectra at ground level. However, the transfer functions presented in Fig. 4 were calculated from the elastic parametrical design spectra defined in the microzonation for each zone, divided by the elastic parametrical design spectra for stiff soil (rock) to take into account the site effects in the seismic probabilistic risk assessment.

A binary file containing the spectral transfer functions was prepared for the area of analysis using the SiteEffects program (ERN-AL 2011b). For this purpose, a raster file with the ID of the zones is generated from the information presented in Fig. 4 and then, for each zone, a spectral transfer function, as the ones presented in Fig. 5, ranging from 0.0 to 2.2 s is included. This file is then used to multiply each event's intensity for each spectral ordinate by the corresponding amplification factor value before calculating damage in the buildings as part of the risk calculation. Table 1 presents the amplification factors for selected spectral ordinates between 0.0 and 2.2 s.

4 Exposed assets database

A building by building resolution database was compiled for the city using the official cadastral office information which was then complemented using aerial images for some zones in the city in order to identify and characterize every single asset within the urban area. The total number of buildings is equal to 241,876 within the urban area (not including neighboring municipalities that constitute the Metropolitan Area). After the identification process was completed, a characterization phase was required in order to assign to each of the elements the required information for the risk analysis. First of all, a set of parameters related with the buildings' physical characteristics was defined including building class, number of stories and building's age, followed by a classification by usage and socio-economic level in order to assign the replacement value. Figure 6 presents two of the main attributes included in this database, socio-economic level and the building's main use, in terms of maps. With respect to the socio-economic level, for which there are 6 levels defined for the city with 1 being the

Table 1 Amplification factors for selected spectral ordinates

Zone ID	Spectral ordinate (s)											
	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2
Z1	1.87	1.87	1.87	1.87	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Z2	2.13	2.13	2.13	1.42	1.33	1.33	1.33	1.33	1.33	1.33	1.42	1.56
Z3	2.13	2.13	2.13	2.13	2.33	2.33	2.33	2.33	2.33	2.33	2.33	2.33
Z4	1.33	1.33	1.33	1.33	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36
Z5	1.60	1.60	1.60	1.60	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Z6	1.33	1.33	1.33	1.09	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
Z7	1.60	1.60	1.60	1.60	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Z8	1.47	1.47	1.47	1.47	1.72	1.72	1.72	1.72	1.72	1.72	1.72	1.72
Z9	1.87	1.87	1.87	1.71	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61
Z10	2.13	2.13	2.13	1.78	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
Z11	2.00	2.00	2.00	2.00	2.03	2.03	2.03	2.03	2.03	2.03	2.03	2.03
Z12	2.13	2.13	2.13	2.13	2.36	2.36	2.36	2.36	2.36	2.36	2.36	2.36
Z13	2.13	2.13	2.13	1.78	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
Z14	1.60	1.60	1.60	1.47	1.38	1.38	1.38	1.38	1.38	1.38	1.38	1.38

poorest and 6 the richest, the map on the left shows that distribution throughout the city is not homogeneous. On the other hand, the figure on the right shows that most of the buildings within the urban area correspond to residential dwellings. The information is considered to be highly accurate in terms of geometry, appraisement in terms of replacement values and building class, which together represent some of the key inputs for a detailed probabilistic risk assessment.

4.1 Building stock appraisement

For the purpose of a seismic risk assessment, the replacement value of each asset contained in the exposure database must be determined in order to quantify in monetary units its expected loss. This value intends to represent the cost of repairing the asset to the same conditions as it is today after an event occurs. Given that no official cadastral values are published by the official entities due to the confidential characteristics of that information and that those values does not necessarily represent the replacement value of each asset, a set of indexes was defined for each county (*comuna*).

Based on the predominant socio-economic level distribution in each county (Alcaldía de Medellín 2010) and also considering the building's main use and class, a set of replacement value indexes (per constructed square meter) was determined. These values were then multiplied by the total constructed area of each dwelling and the replacement value for each of them was obtained. There is a direct relationship between the existing building classes, the replacement values and the socio-economic levels in Medellín. For example, building classes such as non-engineering and unreinforced masonry exist mainly in the poorest areas of the city while reinforced concrete frames, steel frames and dual systems (R/C frames and walls) are common in the middle to high income areas.

Table 2 presents the proposed indexes for each county while Fig. 7 presents the replacement values of each dwelling. It is worth noting that since the total constructed area is required

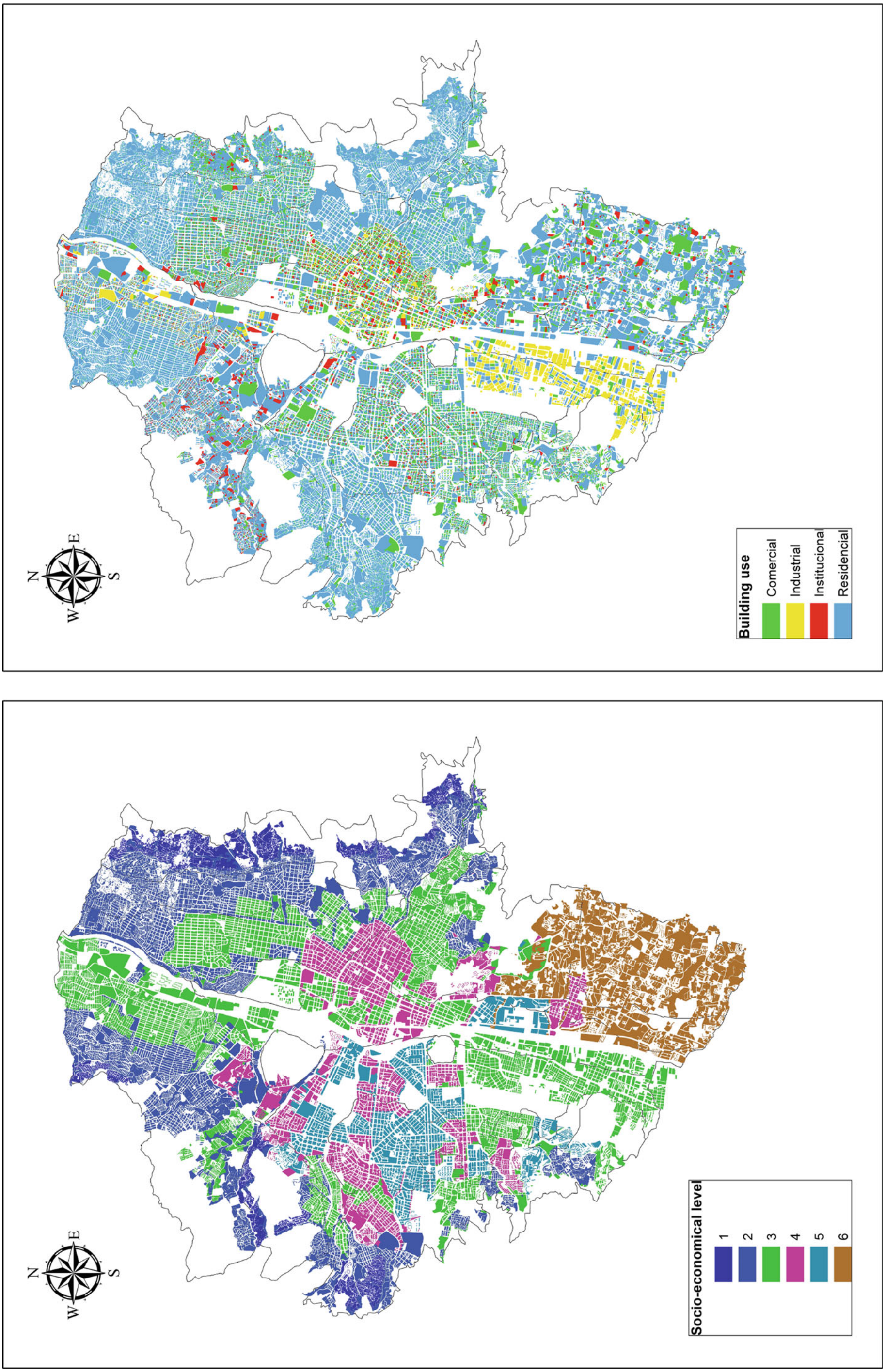

Fig. 6 Socio-economical level (*left*) and main usage distribution (*right*) for Medellín

Table 2 Replacement value indexes for Medellín's counties

County	Replacement value index (usd/m^2)
Popular	$ 282.2
Santa Cruz	$ 282.2
Manrique	$ 361.1
Aranjuez	$ 583.3
Castilla	$ 555.6
12 de Octubre	$ 527.8
Robledo	$ 784.2
Villa Hermosa	$ 500.0
Buenos Aires	$ 887.4
La Candelaria	$ 876.2
Laureles Estadio	$ 1,060.5
La América	$ 844.3
San Javier	$ 649.9
Poblado	$ 1,521.9
Guayabal	$ 662.3
Belén	$ 945.5

for this calculation, the number of stories plays a fundamental role in this quantification process. The procedure for the definition of that parameter is presented in the following section.

4.2 Definition of building classes and number of stories

Medellín, as many other cities in Colombia and Latin America has a portfolio of buildings mainly comprised by low and intermediate rise masonry structures and reinforced concrete structures of medium and high rise in the developing residential areas. Moreover, different construction methods are found within the masonry building classes, and as mentioned above, depending mainly on the socio-economic level it is common to find unreinforced masonry dwellings in the low-income neighborhoods while reinforced masonry and reinforced concrete dwellings can be found in the middle to high-income level areas.

Code compliance and enforcement can be classified as high in the medium- and high-income areas since most of the newest urban developments have occurred on these zones where usually old 1–2 stories masonry units have been demolished to build high-rise reinforced concrete structures. In the low-income areas code compliance and enforcement is low because of social and economic fragilities, where poor structural systems ranging from non-technical typologies to poorly designed and constructed masonry structures constitute a large amount of the building class distribution. Steel structures are found mainly in industrial storage facilities and only constitute a small proportion of buildings into the city.

Since the number of story distribution is available at county level from the cadastral information (Alcaldía de Medellín 2010) this value was assigned to the dwellings in each county. Additionally, with information available from the same source in terms of the wall and floor materials, a distribution of building classes was determined for each county (compatible with the number of stories assignation). Finally, a field visit was conducted to verify and/or correct the initial building class distribution for all counties and generate the final database.

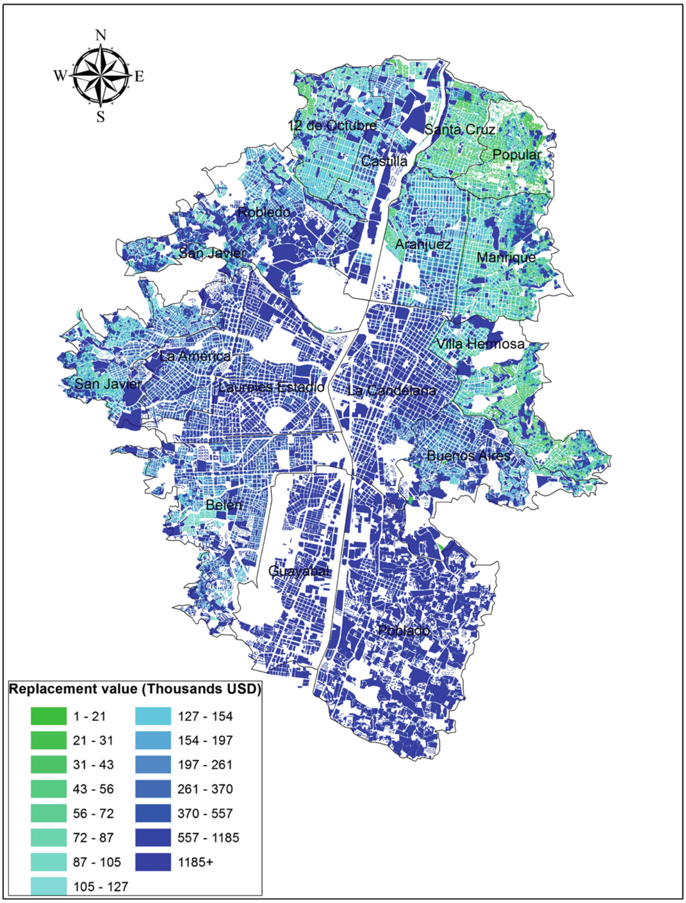

Fig. 7 Replacement value index per constructed square meter in USD (thousands) by dwelling

With all this information, a set of building classes that covers all the relevant parameters identified above was defined for the city. In total, 43 building classes were identified considering different height ranges for some of them since this parameter is critical when defining their vulnerability.

5 Seismic vulnerability of the exposed assets

A vulnerability function is defined for each of the identified building classes. The vulnerability functions relate the expected loss with the local intensities at ground level (Miranda 1999), which in this case are spectral accelerations.

Vulnerability functions are a description of the variation of the statistical moments of loss with respect to the intensity. A Beta probability function is assigned with the mean value and standard deviation as the first and second moments respectively. Once this is computed all the required parameters to compute risk in a probabilistic way are complete (Ordaz 2000).

For all cases, a continuous function, instead of qualitative scales, is defined relating hazard intensities to expected loss also considering the dispersion. Dispersion varies through the

Table 3 Vulnerability function assignment

ID	Building type	Vulnerability function	ID	Building type	Vulnerability function
1	MC_1	MC_1p	23	PAA_6	PA + DIAG_6p
2	MC_2	MC_2p	24	PAA_7	PA + DIAG_7p
3	MC_3	MC_3p	25	PCM_10	PCR + MCR_10p
4	MC_4	MC_4p	26	PCM_5	PCR + MCR_5p
5	MC_5	MC_5p	27	PCM_6	PCR + MCR_6p
6	MC_6	MC_6p	28	PCM_7	PCR + MCR_7p
7	MC_7	MC_7p	29	PCR_1	PCR_1p
8	MR_1	MR_1p	30	PCR_10	PCR_10p
9	MR_2	MR_2p	31	PCR_2	PCR_2p
10	MR_3	MR_3p	32	PCR_3	PCR_3p
11	MR_4	MR_4p	33	PCR 4	PCR_4p
12	MR_5	MR_5p	34	PCR 5	PCR_5p
13	MS_1	MS	35	PCR 6	PCR_6p
14	MS_2	MC_2p	36	PCR_7	PCR_7p
15	MS_3	MC_3p	37	RI_1	W1
16	MS_4	MC_4p	38	RI_2	W1
17	PAA_1	PA + DIAG_1p	39	W_1	W1
18	PAA_10	PA + DIAG_10p	40	W_2	W1
19	PAA_2	PA + DIAG_2p	41	W_3	W1
20	PAA_3	PA + DIAG_4p	42	AC_1	PA_1p
21	PAA_4	PA + DIAG_4p	43	AC_2	PA_2p
22	PAA_5	PA + DIAG_5p			

hazard intensities being not significant at the starting and ending point of the functions and maximum where the expected damage is equal to 50 %.

It is because of this approach that the replacement value of each asset is required to be quantified given that what is being represented is the ratio of the repair cost relative to the total value of the building, after which the expected damage is used to compute the direct physical loss value.

A set of 35 vulnerability functions were used for the analysis as presented in Table 3. Figures 8 and 9 present a comparison of the different vulnerability functions, where it is evident that some of the identified classes are more vulnerable than others by having higher expected losses for the same intensity at ground level, that is, after the consideration of the local site effects.

6 Risk analysis

When conducting a probabilistic risk assessment, each input must be modeled in a probabilistic way following the concepts given by probability theory in order to take into account the series of uncertainties that are inherent to the hazard and structural vulnerability. For a fully probabilistic risk assessment the principal inputs and their associated probability distributions are as follows:

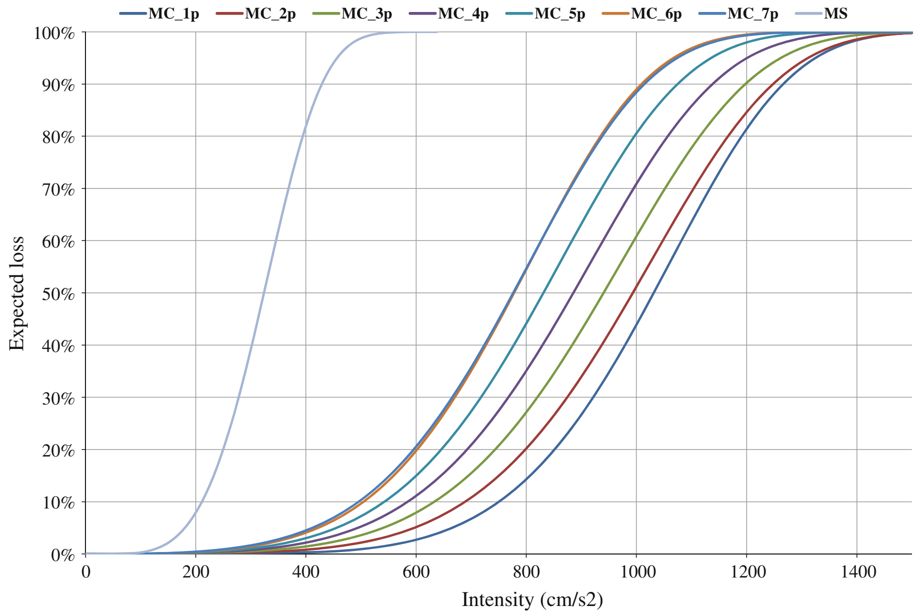

Fig. 8 Vulnerability functions used in the assessment for masonry

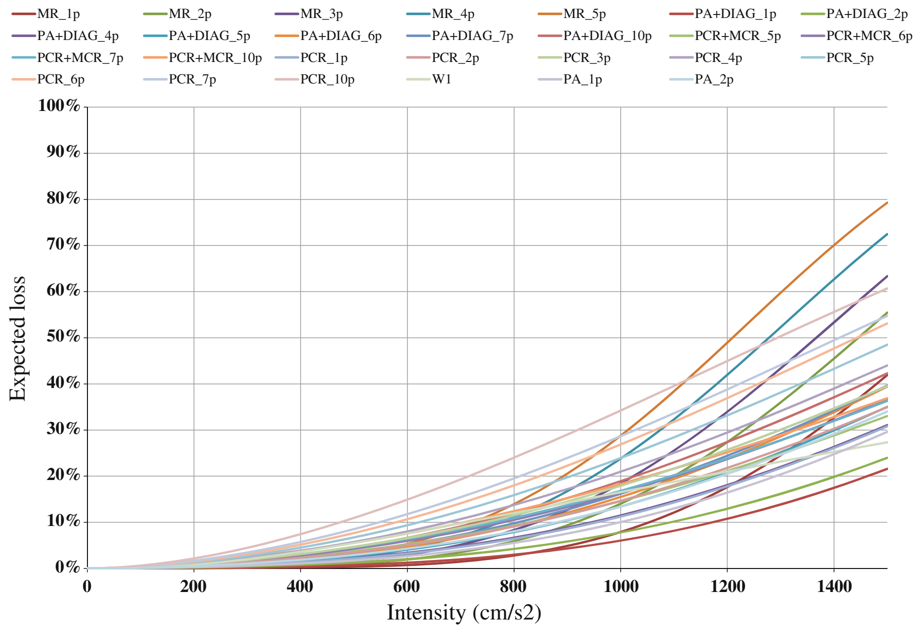

Fig. 9 Vulnerability functions used in the assessment for frames and dual systems

- Seismic hazard events occurrence: Poisson process (no memory).
- Time between events: Exponential distribution.
- Hazard intensity: Lognormal distribution.
- Loss: Beta distribution.

6.1 Loss generation process

According the analytical procedure proposed by Ordaz (2000) and used in the CAPRA platform (ERN-AL 2011a), the probability density function for the loss on the *jth* exposed asset, conditional to the occurrence of the ith scenario, is computed using the following relationship:

$$f(p_j|Event_i) \tag{3}$$

because it is not possible to compute this probability distribution directly, it is computed by chaining two separate conditional probability distributions where the first part has to do with the vulnerability (the expected loss given a hazard intensity) and the second with the hazard (the hazard intensity given the occurrence of the event):

$$f(p_j|Event_i) = \int_0^\infty f(p_j|Sa) f(Sa|Event_i) dSa \tag{4}$$

the probability density function of the loss for each scenario is computed by aggregating losses from each individual exposed asset. Since loss is computed as a random variable, it has to be aggregated in a proper way; that the following expressions are used for the expected value of the loss, $E(p|Event_i)$, and its corresponding variance, $\sigma^2(p|Event_i)$, for each scenario:

$$E(p|Event_i) = \sum_{j=1}^{NE} E(p_j) \tag{5}$$

$$\sigma^2(p|Event_i) = \sum_{j=1}^{NE} \sigma^2(p_j) + 2\sum_{\substack{k=1 \\ k<j}}^{NE-1} \sum_{j=2}^{NE} \text{cov}\left(p_k, p_j\right) \tag{6}$$

where *NE* is the total number of exposed assets, $E(p_j)$ is the expected value of the loss at the *jth* exposed element given the occurrence of the *ith* scenario, $\sigma^2(pj)$ is the variance of the loss at the *jth* exposed element given the occurrence of the *ith* scenario, and $\text{cov}(p_k, p_j)$ is the covariance of the loss of two different exposed elements. The covariance is calculated using a correlation coefficient $\rho_{k,j}$ set equal to 0.3 and taking into account the standard deviations for losses in different assets:

$$\sigma^2(p|Event_i) = \sum_{j=1}^{NE} \sigma^2(p_j) + 2\sum_{\substack{k=1 \\ k<j}}^{NE-1} \sum_{j=2}^{NE} \rho_{k,j}\sigma(p_k)\sigma(p_j) \tag{7}$$

Seismic risk should be expressed in terms of an exceedance curve, which specifies the frequencies with which events will occur that reach or exceed a specified value of loss. This annual loss frequency is also known as the exceedance rate, and it can be calculated using the following equation, which is one of the many ways adopted by the theorem of total probability:

$$\nu(p) = \sum_{i=1}^{N} \Pr(P > p\,|Event_\text{i}) \cdot F_A(Event_\text{i}) \tag{8}$$

where $\upsilon(p)$ is the rate of exceedance of loss p, N is the total number of hazard scenarios, $F_A(Event_i)$ is the annual frequency of occurrence of the *ith* hazard event, while $\Pr(P >$

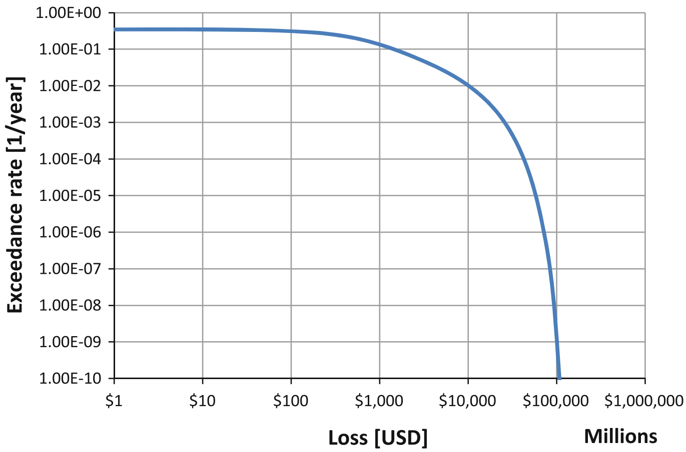

Fig. 10 Seismic LEC for Medellin

$p|Event_i$) is the probability of exceeding p, given that the *ith* event occurred. The sum of the equation is made for all potentially damaging events. The inverse of $v(p)$ is the return period of loss p, identified as *Tr.* One of the main advantages of the loss curve is that it contains all the information required to describe the process of occurrence of events which produce loss in terms of probability.

Once the convolution process of the hazard, exposure and vulnerability input information is performed, the expected loss information is obtained for the whole portfolio. These results include the consideration of the complete set of stochastic events, the representation of small, moderate and big events, the amplification provided by the soil conditions through the transfer functions, and finally the expected losses in each exposed element according to the assigned vulnerability function (ERN-AL 2011a).

6.2 Grouped risk results

The grouped seismic risk results for the portfolio of buildings of Medellín are obtained in terms of the LEC that is shown in Fig. 10. The LEC contains all relevant information about the risk levels and it is clear that for disaster risk management purposes, the contribution of all possible scenarios can be inferred from the loss values and their exceedance rates. This approach is preferred to the single scenario where the contribution of an event in a time window is set equal to 1.

Calculating the area under the LEC, the AAL for the complete portfolio can be obtained. This metric is considered to be a robust indicator since it is a compact probabilistic metric and can be used to express the risk value of a single dwelling, of a county, of a city and even of a country (Marulanda 2013). The calculated AAL or pure premium for Medellín is equal to 4.1 per thousand (Table 4), relative to the total exposed value which is almost double the value of the calculated AAL for Bogotá, Colombia's capital city (Zuloaga 2011; Salgado et al. 2013) indicating a high risk index for Medellín.

Rearranging the information obtained in the LEC, the PML plot can be obtained as the one presented in Fig. 11. This parameter is of interest for large return periods, usually ranging from 200 to 2,500 years. For Medellín, the calculated PML for 500 years return period is equal

Table 4 summarizes the obtained seismic risk results

Results		
Exposed value	USD$ $\times 10^6$	146,608
Average annual loss	USD$ $\times 10^6$	604.6
	$^0/_{00}$	4.1
PML		
Return period (years)	Loss	
	USD$ $\times 10^6$	(%)
100	$10,033	6.8
250	$15,716	10.7
500	$20,356	13.9
1000	$24,930	17.0

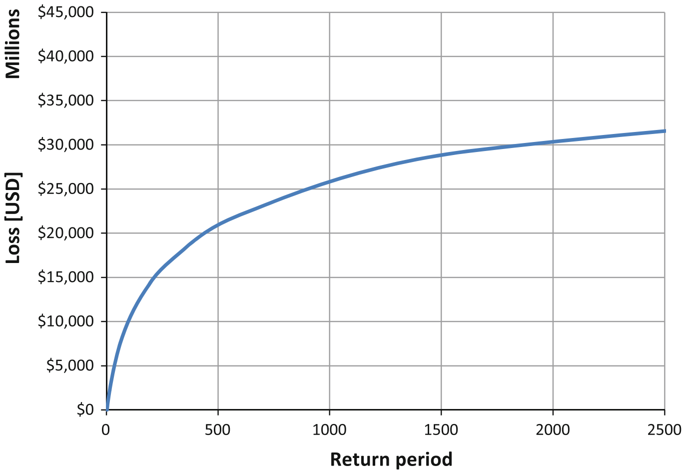

Fig. 11 Seismic PML plot for Medellín

to 14 % of the total exposed value which is a large value. This return period is associated to the loss and does not necessarily correspond to the hazard scenario since there is correlation between the losses as explained previously.

Figure 12 presents the loss exceedance probability for different monetary values considering different exposure time windows (50, 100 and 200 years). This value can also been understood as the bankruptcy probability in those time segments or frames.

Another common way to express the risk results is through maps, where the spatial distribution of the expected losses can be visualized. Figures 13 and 14 present the AAL relative to its replacement value at city level and for a detail of the city centre area. Damage distribution is located mainly on the eastern and northwestern areas of the city. These zones have important amplification factors due to geotechnical and topographical effects as can be seen in Fig. 4. The risk results are obtained on an individual basis for each of the 241,876 dwellings and are associated to the original database in order to add the risk attribute.

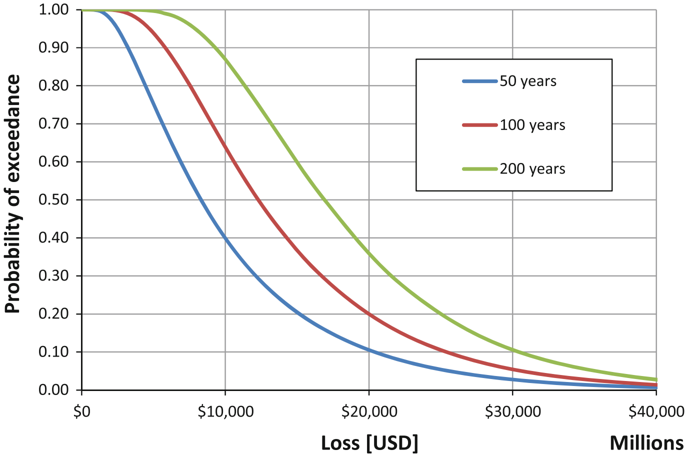

Fig. 12 Loss exceedance probability for different exposure time frames

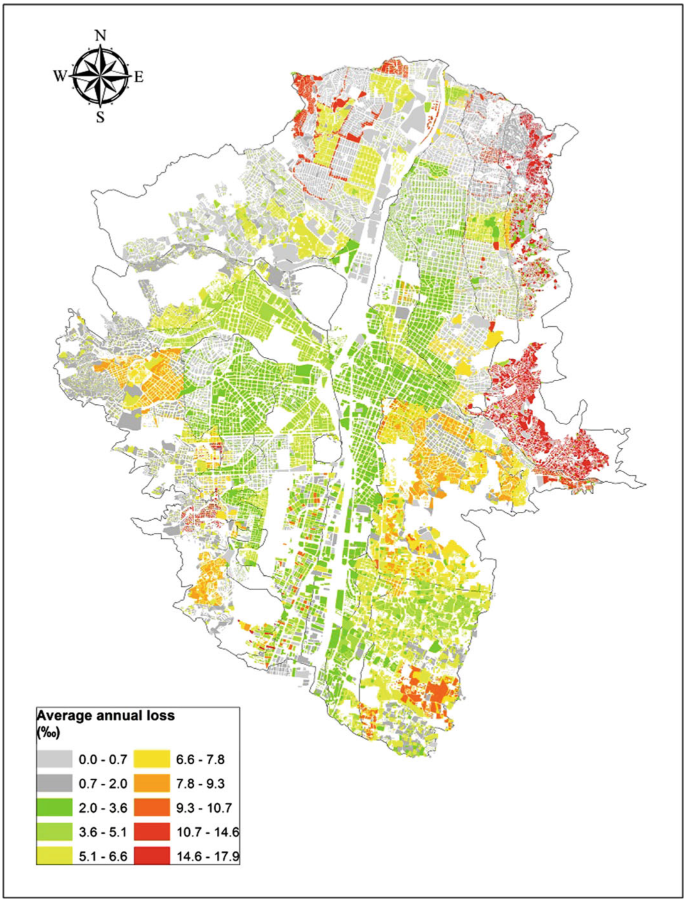

Fig. 13 Risk map in terms of AAL for Medellin by dwelling

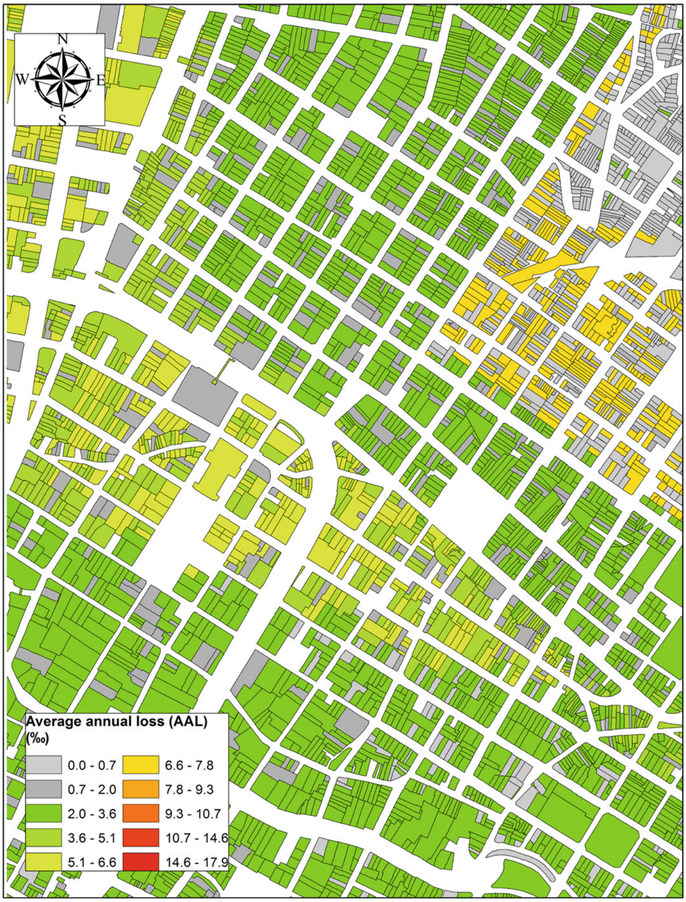

Fig. 14 Risk map in terms of AAL for the Medellin's downtown

In the generation of these maps it is important to normalize the obtained AAL by the replacement cost of each asset since this allows for comparison of the risk levels between each of them. Notice that by plotting the expected losses in terms of monetary units, it is possible only to identify the most expensive elements and not necessarily point out the dwellings with the highest risk indexes.

6.3 Risk results by county

Since the procedure to calculate the AAL allows an arithmetical aggregation of individual elements and since each dwelling in the database is associated to one of the 16 counties, the AAL was calculated for each county. This information is useful at this resolution level because it allows local municipalities to identify their own risk values and use them for retrofitting, financial protection and emergency planning schemes that may differ from one to another, not only by their AAL value but because of the different building classes and number of stories composition.

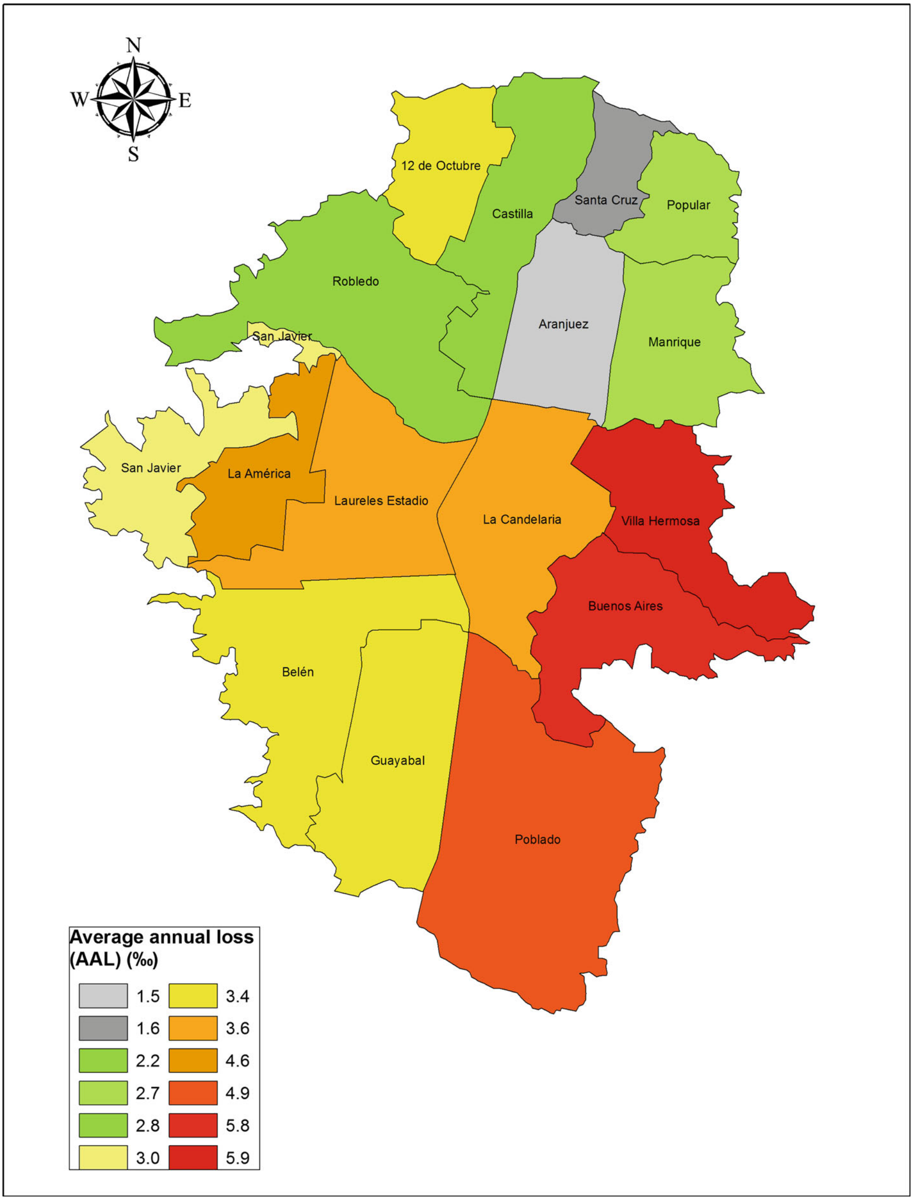

Fig. 15 Risk map in terms of AAL for Medellin by county

Figure 15 presents the AAL distribution by county, again normalizing the expected losses by the replacement values. From the figure it is evident that a non-homogeneous distribution of the seismic risk exists across the city. Counties with the highest AAL have almost 6 times more risk than *Aranjuez* County, which is the one with the lowest relative risk value.

Table 5 presents a summary of the obtained results by county where the total exposed values and AAL in monetary and relative units are presented for each of them.

Table 5 Summary of the risk results by counties

County	Exposed value		Average annual loss	
	(USD) Millions	(%)	(USD) Millions	($^0/_{00}$)
Popular	$ 721.8	0.5	$ 1.9	2.7
Santa Cruz	$ 813.6	0.6	$ 1.3	1.6
Manrique	$ 1,940.9	1.3	$ 5.3	2.7
Aranjuez	$ 3,269.3	2.2	$ 5.0	1.5
Castilla	$ 4,131.8	2.8	$ 11.5	2.8
12 de Octubre	$ 2,770.0	1.9	$ 9.4	3.4
Robledo	$ 8,670.0	5.9	$ 18.9	2.2
Villa Hermosa	$ 1,881.6	1.3	$ 11.2	5.9
Buenos Aires	$ 7,823.3	5.3	$ 45.1	5.8
La Candelaria	$ 12,788.9	8.7	$ 45.9	3.6
Laureles Estadio	$ 13,434.9	9.2	$ 48.0	3.6
La América	$ 5,485.8	3.7	$ 25.4	4.6
San Javier	$ 4,746.6	3.2	$ 14.1	3.0
Poblado	$ 64,140.6	43.7	$ 313.8	4.9
Guayabal	$ 3,708.8	2.5	$ 12.7	3.4
Belén	$ 10,280.4	7.0	$ 35.3	3.4
Total	$ 146,608	100.0	$ 604.6	4.1

6.4 Risk results by building class

Due to the characterization process in the exposure database, it is possible to disaggregate the risk results in several categories. The results grouped by building classes show that the highest risk values in monetary and relative units are associated to unreinforced masonry structures as well as high-rise confined masonry units. As was explained above, masonry structures constitute the majority of Medellin's buildings portfolio and also, as can be seen from Fig. 6, their expected damages can be high even with low hazard intensities due to the poor construction quality and lack of building code compliance for most of the unreinforced masonry dwellings.

Among the masonry categories it is also evident the different behavior associated to the number of stories; for example, up to two stories reinforced masonry structures present an adequate behavior and a low risk index value but when more stories (up to five) are considered, the expected losses increase in a considerable way. The same can be found for other building classes such as steel and reinforced concrete frames.

Reinforced concrete structures that constitute a considerable number of units across the city also have considerably high expected losses, although the dual systems (R/C frames and walls) have lower risk values than the frames.

Table 6 summarizes the results from a building class perspective, where it is evident that the structural types that have the highest risk values is unreinforced masonry and high-rise confined masonry.

Table 6 Summary of the risk results by building class

Construction material	Building type	Number of elements	Exposed value		Average annual loss	
			(USD) Millions	(%)	(USD) Millions	($^0/_{00}$)
Steel frames	AC_1	88	$ 256	0.17	$ 0.42	1.6
	AC_2	101	$ 591	0.40	$ 1.54	2.6
Confined masonry	MC_1	13,088	$ 1,198	0.82	$ 0.54	0.5
	MC_2	24,363	$ 7,549	5.15	$ 4.92	0.7
	MC_3	11,634	$ 7,170	4.89	$ 38.70	5.4
	MC_4	4,489	$ 10,217	6.97	$ 68.55	6.7
	MC_5	69	$ 85	0.06	$ 1.04	12.2
	MC_7	2	$ 5	0.00	$ 0.07	13.8
Reinforced masonry	MR_1	2,244	$ 196	0.13	$ 0.03	0.2
	MR_2	2,570	$ 544	0.37	$ 0.15	0.3
	MR_3	1,192	$ 438	0.30	$ 1.30	3.0
	MR_4	273	$ 237	0.16	$ 0.64	2.7
	MR_5	20	$ 26	0.02	$ 0.15	5.9
Unreinforced masonry	MS_1	21,080	$ 1,918	1.31	$ 24.55	12.8
	MS_2	67,452	$ 17,148	11.70	$ 11.03	0.7
	MS_3	24,619	$ 9,657	6.59	$ 62.08	5.4
	MS_4	1,191	$ 892	0.61	$ 3.87	6.7
Steel moment-resistent frames	PAA_10	25	$ 100	0.07	$ 0.19	1.9
	PAA_2	287	$ 615	0.42	$ 1.18	1.9
	PAA_3	1,063	$ 1,202	0.82	$ 1.60	1.3
	PAA_4	772	$ 1,605	1.09	$ 1.97	1.2
	PAA_5	557	$ 3,409	2.33	$ 6.18	1.8
	PAA_6	115	$ 418	0.28	$ 1.12	2.7
	PAA_7	225	$ 2,279	1.55	$ 6.90	3.0
Dual system (concrete frame and shear wall)	PCM_10	175	$ 1,772	1.21	$ 5.91	3.3
	PCM_5	753	$8,463	5.77	$ 37.46	4.4
	PCM_6	255	$ 1,595	1.09	$ 8.56	5.4
	PCM_7	945	$ 9,127	6.23	$ 36.94	4.0
Reinforced concrete frames	PCR_1	2,830	$ 423	0.29	$ 1.20	2.8
	PCR_10	74	$ 600	0.41	$ 2.74	4.6
	PCR_2	15,271	$ 5,569	3.80	$ 22.91	4.1
	PCR_3	8,985	$ 6,736	4.59	$ 27.25	4.0
	PCR_4	6,804	$ 8,944	6.10	$ 43.28	4.8
	PCR_5	5,340	$ 19,464	13.28	$ 99.12	5.1
	PCR_6	1,171	$ 3,655	2.49	$ 18.93	5.2
	PCR_7	959	$ 10,168	6.94	$ 59.12	5.8
Non-technified	RI_1	1,977	$ 67	0.05	$ 0.08	1.1
	RI_2	3,550	$ 175	0.12	$ 0.17	1.0
Wood	W_1	3,056	$ 149	0.10	$ 0.14	1.0
	W_2	11,131	$ 1,585	1.08	$ 1.69	1.1
	W_3	1,081	$ 362	0.25	$ 0.39	1.1
Total		241,876	$146,608	100.00	$ 605	4.1

7 Conclusions

A case study using the CAPRA platform has been developed in Medellín obtaining risk results in terms of different metrics such as the LEC, AAL and PML that constitute a common language to experts, policy makers and stakeholders. Direct physical losses on the private and public building portfolio of the city were quantified and the results obtained from this research can be used to group the risk results in terms of building classes, main use and number of stories; for instance, the building class that concentrates the highest risk is the unreinforced masonry, which is a common structural system in the poorest counties of the city, where some essential buildings such as schools and hospitals have this construction class, and hence a retrofitting scheme for these buildings could be planned.

With the obtained results, disaster risk management strategies concerning financial protection such as traditional and alternative risk retention-transfer instruments can be designed, as well as generating a good risk management cycle where good practice strategies such as risk mitigation through structural retrofitting may be incentivized by reducing agreed insurance premiums.

The counties that have highest risk in relative terms are *Villa Hermosa* and *Buenos Aires* which are located in the eastern zone of the city and have large percentages of unreinforced masonry structural systems. On the other hand, risk results of *Popular*, *Santa Cruz* and *Manrique* counties must be seen with attention since those zones are where most of the low-income population live and, in the case of a disaster, the generated losses will be a financial liability to the local and national government. The county that has the highest average annual loss in monetary units is *Poblado*, in the southeastern area of the city which is the one with highest socio-economic level and where most of the high-rise buildings are located.

The results allow to generate risk maps with a building by building resolution that allow a visualization of the geographical distribution of the future losses; however, it must be clear that the risk should be preferably expressed in terms of loss exceedance rates and probabilities of exceedance. Somehow, the results can be updated every time new information related to the hazard, seismic microzonation zones and more detailed exposed assets database becomes available.

With this same information but using a single scenario approach, studies such as emergency plans can be developed for the city and those results, combined with the physical direct losses, can be used as input for a holistic seismic risk assessment (Cardona and Hurtado 2000; Carreño et al. 2007, 2012) at local (county) level in Medellín that may identify social and economic influenced factors increasing the total risk at city level.

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