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Probabilistic Assessment of the Seismic Peak Ground Acceleration (PGA) at seven Colombian Cities

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ABSTRACT

This paper presents a probabilistic assessment of peak ground acceleration (PGA) observations at seven Colombian cities located in regions with intermediate and high seismic activity. Frequency histograms of the annual exceedance rates were determined using historical data of the annual rate of exceedance for pre-established values of PGA. After determining distribution parameters by means of the method of moments, several probability density functions were examined in order to evaluate the performance of each function. In most sites, the maximum annual PGA appears to be best modeled by a lognormal distribution, which led to its adoption as parent distribution for the entire group of cities. Once the lognormal function is selected as parent distribution, series of PGA values for arbitrary periods of time may be generated through random simulation. Next, series of maximum values in fifty years of observation were simulated for the seven cities, assuming a Lognormal parent distribution. Analytical solutions for extreme values of different sample sizes of lognormal random variables are not known to the authors. However, since extreme values for large samples of lognormal random variables tend asymptotically to a Type I (Gumbel) probability distribution, the latter was adopted as a possible model for the 50 years PGA distributions suggested in the paper for several Colombian cities, as a useful tool for engineering design, whenever the PGA is regarded as an appropriate seismic intensity measure.

Keywords: Seismic Hazard, PGA, Annual exceedance rates.

Introduction

For purposes of hazard assessment, seismic events caused by a seismogenic source, such as a fault, a system of faults, or an entire region, are usually assumed to occur in time according to a discrete Poisson process (Haldar and Mahadevan, 2000). Assuming in addition that the moment magnitude m of those events is characterized by a Type III (Weibull-minimum) probability distribution (Haldar and Mahadevan, 2000), then the probability of occurrence of an event with magnitude M_w larger than m would be given by:

$$Prob(M_w > m) = exp\left[-(\beta m)^{\gamma}\right] \tag{1}$$

An exponent $\gamma = 1$ corresponds to the exponential distribution, given by:

$$Prob(M_w > m) = exp[-(\beta m)] \tag{2}$$

In such case, *i.e.*, when the distribution of amplitudes is exponential, the well-known Gutenberg-Richter (G-R) Law results, relating the logarithm of the number of events with the seismic magnitude or other measures of the size of the events:

$$\log_{10} N = a_0 - bm \tag{3}$$

It is a simple exercise to verify by simulation that the assumptions that (a) the occurrence of seismic events in time is described by a Poisson Process and (b) the probability density function of the seismic magnitudes is exponential (Weibull with $\gamma = 1$), lead to the linear relation between $\log_{10} N$ and m given by Eq. (3), widely known as Gutenberg-Richter law. Moreover, for an arbitrary Weibull (minimum) distribution characterized by $\gamma > 1$, the $\log_{10} N$ vs. m relation is a nonlinear function. For practical purposes, this nonlinear function has been approximated by Esteva's (1976) by a quadratic law:

$$\log_{10} N = a_0 + a_1 m - a_2 m^2 \tag{4}$$

Riera and Iturrioz (2015), on the other hand, employed for similar purposes the following bi-linear relation:

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$$\log N(m) = [(a_1 - b_1 m) f(m) + (a_2 - b_2 m)[1 - f(m)]] \quad (5)$$

$$f(m) = \exp\,[-(m - m_c)/s]/\{1 + \exp\,[-(m - m_c)/s]\,\} \quad (6)$$

which also constitutes an improved approximation to observed $\log_{10} N$ vs. m relations, in comparison with the linear G-R law. Note that the coefficient m_c in Eq. (6) depends on the exponent γ of the Weibull distribution given by Eq. (1), as indicated by Eq. (7):

$$m_c = 0.835\gamma \quad (7)$$

The Weibull (minimum) distribution constitutes a fairly flexible and general model of the magnitude distribution of seismic events attributed to a specific seismogenic source (Riera and Iturrioz, 2013). Since it includes the G-R law as a special case, it always fits observed instrumental data better than the G-R law, as illustrated by Figure 1.

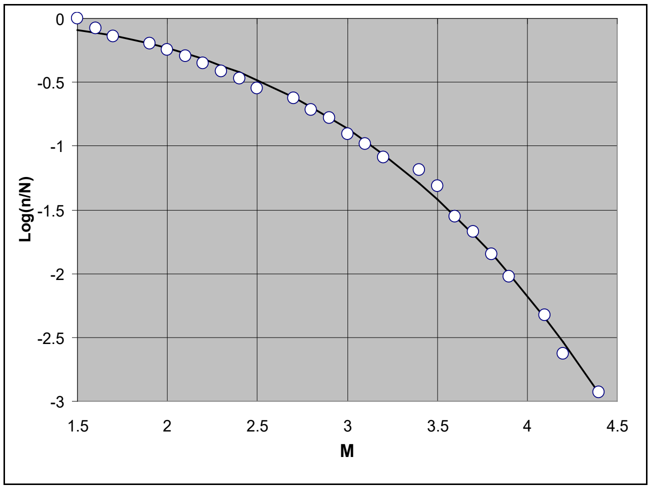


Figure 1. Relation between log(n/N) and moment magnitude M_w for a 1200km square area surrounding Angra dos Reis NPP in the South American SCR.

Attempts to fit a straight line to an obviously nonlinear relation inevitably require limiting the range of applicability of the linear function (Eq. 3), forcing seismologists to introduce artificial remedies, like a cut-off or upper limit of the magnitude. In fact, in connection with the data shown in Fig. 1, three events characterized by $M_w \geq 4.4$ observed in the region within the 50 years time window considered in the analysis, were deleted from the database in order to be assessed independently. In other words, they were considered to be caused by a different seismogenic source, characterized by a much lower frequency of occurrence of seismic events and also by a different amplitude distribution. A similar situation, in which a large earthquake occurs which cannot be predicted by the instrumental evidence recorded in the previous decades was examined by Scholtz (2002). Riera and Iturrioz (2013, 2015) point out that this second source of rare earthquakes is related to the notion of characteristic earthquake (Wesnousky, 1994).

Assuming that there is a functional relationship between the peak ground acceleration (PGA) recorded at any site of interest during a seismic event and the magnitude of the seismic event, similar relations to those discussed above may be expected to exist between the event probability and the PGA level, which should be valid for the seismogenic source that caused the available instrumental evidence and must be subjected to the same limitations. In engineering assessments, time series of the maximum PGA in a year of observation are typically collected and employed to fit a probability density function (pdf) to the observed data, designated in subsequent developments as the parent probability density function (Haldar and Mahadevan, 2000). Note that most available series of observed instrumental data, which are rarely longer than around half a century, should not be expected to contain observations of events characterized by a mean recurrence period much longer than the duration of the time series, and hence usually do not contain those observations. But recognizing such fact does not reduce the relevance of observed instrumental data for purposes of engineering design, in general, and especially for optimization studies.

The present paper provides basic information on seismic hazards for several locations in Colombia, for the purposes previously mentioned, elaborated on the basis of recorded PGA values. Thus, the starting points are observations of the maximum annual recorded PGA, which are considered samples of a random variable.

A brief overview of Colombia seismic hazard studies

The entire eastern coast of South America, including regions of Colombia, is one of the most active seismic areas of the world. In Colombia, seismic motions are caused by two subduction regions as well as by shallow active faults within three mountain ranges: the Western (WC), Central (CC), and Eastern Cordillera (EC) (Pulido, 2003). The seismic activity in Colombia has been monitored for around three decades by the National Seismological Network of Colombia (RSNC), which is sponsored by several Colombian agencies as well as by the Canadian Development Agency. The RSNC started its operation in June 1993 counting with 20 stations connected to a central station by satellite. From June 1993 to June 1999, the RSNC recorded 15581 earthquakes, located mainly in the central part of the country (Ojeda et al., 2001). In addition, according to Ojeda et al. (2002), Colombia counts with the Santa Fe de Bogotá seismic network, composed of 29 three components stations with sensors at the surface and three additional six-component borehole stations, operating in the metropolitan area of Bogotá since 1999.

The availability of instrumental data allowed several seismic hazard assessments of Colombian locations, conducted in recent years, which will be briefly described by way of introduction to the present contribution and, in some cases, to compare predictions of different approaches. Thus, the authors are not presenting a detailed review of the subject, which is outside the scope of this paper. Carreño et al. (2007) described a multi-hazard and holistic method of urban hazard based on urban hazard indicators and applied it to the hazard evaluation for the cities of Bogotá (Colombia) and Barcelona (Spain). Salgado et al. (2010) developed subsequently a methodology to estimate expected seismic intensities to be adopted in the design of seismic resistant structures in Colombia, which consists of the following stages: (i) identification and modeling each of the faults or seismogenic sources at a national level, grouping them into segments of large families of local faults;

(ii) assigning a geographical location to the seismic events listed in national seismic catalogs that are considered associated to each of the segments; (iii) determination for each of the seismic sources relevant statistical parameters, such as minimum, maximum and event frequencies for different ranges of magnitudes; (iv) determination of the seismic hazard using the CRISIS V7.2 program (Ordaz et al., 2007) and, (v) interpretation and refinement of the results for use in infrastructure design and other applications. Salgado-Gálvez et al. (2014) describe a fully probabilistic seismic hazard analysis conducted for Medellin, Colombia. In their study, the seismic hazard model for the stochastic set of scenarios, seismogenic sources, and ground motion prediction equations (GMPE's), was the same previously used by Salgado et al. (2010). Salgado-Gálvez et al. (2016a) propose a probabilistic methodology to estimate the annual cost to society of premature deaths because of earthquakes, which is applied to Medellín, the second-largest city of Colombia. Salgado-Gálvez et al. (2016b) also describe a methodology to determine an urban seismic hazard index USRi for Medellín using a fully probabilistic hazard assessment of the city, including dynamic soil response and using the holistic evaluation module of the multi-hazard hazard assessment CAPRA platform (Cardona et al., 2010; 2012). Similarly, Acevedo et al. (2017) describe the development of an exposure model for the residential building stock in Antioquia (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 publicly available and can be used to calculate damage and losses due to single events, or probabilistic seismic hazards. The exposure model includes information regarding the total built-up area, number of buildings and inhabitants, building class, and replacement cost. According to Acevedo et al. (2017), 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 of 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 suffer severe damage or collapse. Salgado-Gálvez et al. (2018) describe later a methodology for the probabilistic seismic hazard assessment of water and sewage networks for Manizales, Colombia. Acevedo et al. (2020) present a seismic risk assessment for the residential building stock of three Colombian cities: Medellín, Bogotá, and Cali. A uniform methodology was used and the results showed a similar mean aggregate loss ratio for Medellín and Bogotá, and a higher for Cali.

Following a different approach, the statistical models described in this paper are based on data reported in the CRISIS program of the PGA at seven cities (Armenia, Bogota, Bucaramanga, Cali, Cúcuta, Manizales, and Medellin), located in regions with intermediate and high seismic activity. The basic data, provided by the Colombian Association of Seismic Engineering (AIS), consists of the expected value of the annual rate of exceedance of pre-established PGA levels for each city. The procedure to determine the probability distribution of the maximum annual accelerations of the seven cities is described below.

According to Ordaz et al. (2013), the CRISIS program is one of the most versatile tools available for seismic risk determination. The software is based on the approach proposed by Esteva-Cornell to perform probabilistic evaluations. CRISIS estimates the size of future seismic movements by calculating seismic intensity's exceedance rates.

Determination of the maximum annual PGA probability density functions

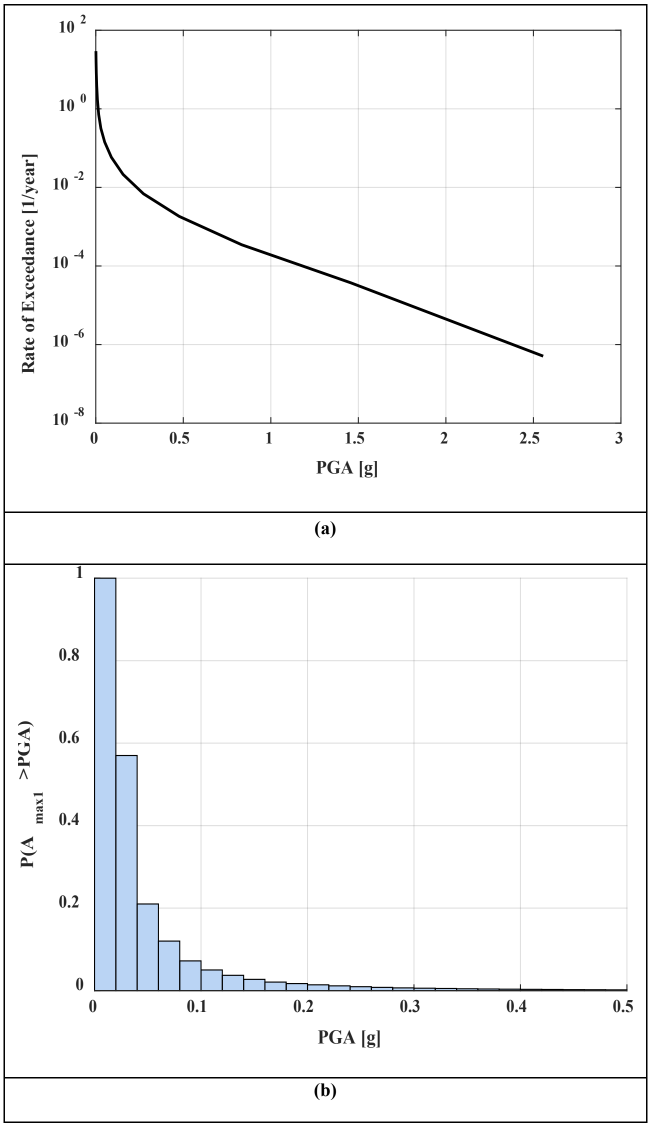
Available information on past seismic activity at known sources, the attenuation equations of seismic waves generated by each source and the effects of local geology, the rate of exceedance of intensity at the location of interest can be calculated as the sum of the effects of all seismic sources by means of Eq. (8), as described by Salgado et al. (2010):

$$v(a) = \sum_{n=1}^{N_s} \int_{Mo}^{Mu} -\frac{\partial \lambda}{\partial M} \mathrm{Prob}(A > a|M, R_i)\, dM \qquad (8)$$

in which the sum extends to all known seismic sources N_s, while $\mathrm{Prob}(A > a|M, R_i)$ denotes the probability that the intensity exceeds the value a, given the magnitude of the earthquake M and the distance between the *n-th* source and the R_i site. The functions $\lambda_i(M)$ are the activity rates of the seismic sources. According to Committee AIS-300 (2009), Eq. (8) would be exact if the seismic sources were points. Actually, they are volumes, so the epicenters may occur with equal probability at any point within the corresponding volume. To integrate the equation, the seismic sources are subdivided into sufficiently small triangles in whose center of gravity the seismicity of the triangle is considered concentrated. In view of the assumption that, given the magnitude and distance, the intensity has lognormal distribution, the probability $\mathrm{Prob}(A > a|M, R_i)$ is calculated as follows:

$$\mathrm{Prob}\ (A > a|M, R_i) = \varphi\left(\frac{1}{\sigma_{lna}} \ln \frac{E(A|M,R_i)}{a}\right) \qquad (9)$$

in which φ denotes the standard normal distribution, $E(A|M, R_i)$ the average value of the logarithm of the intensity (given by the corresponding attenuation law), and σ_{lna} its corresponding standard deviation. The seismic hazard is then expressed in terms of the rate of exceedance of given values of seismic intensity. The seismic intensity a is measured by the ordinates of the response spectrum of pseudo accelerations for 5% of the critical damping and the natural period of vibration *T* of the building of interest. Based on the information provided by Committee AIS-300 (see Fig. 2a), the probability P_{Amax1} that the maximum annual acceleration A_{max1} exceeds pre-established PGA values in one year, *i.e.*, for $N = 1$, may be readily estimated. As an example, Fig. 2b shows a plot of the probabilities determined from Fig. 2a for 0.02g intervals for the city of Cúcuta.



(a)

(b)

Figure 2. Probability of occurrence of PGA values due to seismic events in Cúcuta. (a) Expected value of the rate of exceedance in Cucuta [1/year]; (b) Probability of annual exceedance of PGA values.

The probability densities for 0.02g intervals were obtained for the seven cities considered in the study through differentiation of the probability of annual exceedance of PGA levels, shown in Fig. 2b for illustration purposes for Cúcuta. The first two statistical moments, *i.e.*, the expected value and the variance of the annual PGA, were next estimated using Eqs. (10) and (11) respectively.

$$E(PGA) = \sum_{i=1}^{n_B} d_i a_i \tag{10}$$

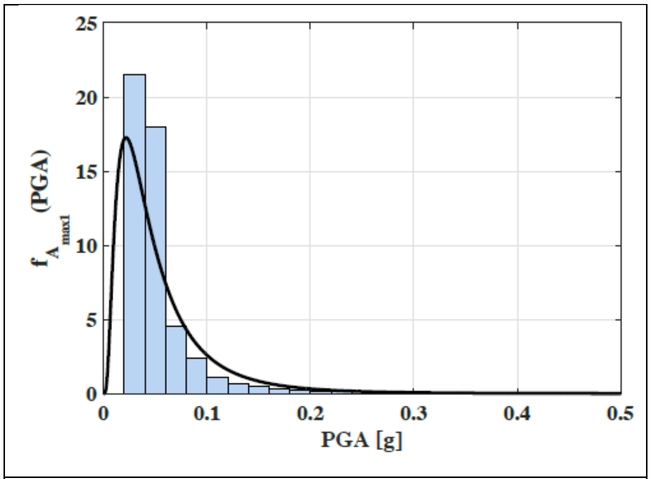
$$Var(PGA) = \sum_{i=1}^{n_B} (E(PGA) - d_i)^2 \, a_i \tag{11}$$

in which d_i is the distance between the origin and the barycenter of the *i-th* column with area a_i of the frequency diagram consisting of n_B columns, as indicated in Table 1.

Table 1. Statistical moments of maximum annual acceleration $\boldsymbol{A_{max1}}$.

City	Expected value E(*PGA*)[g]	Variance *Var*(*PGA*)[g²]
Armenia	0.0513	7.33E-4
Bogotá	0.0406	6.62E-4
Bucaramanga	0.0445	5.32E-4
Cali	0.0535	7.51E-4
Cúcuta	0.0545	25.0E-4
Manizales	0.0517	7.62E-4
Medellín	0.0480	6.18E-4

Four probability density functions (Lognormal, Weibull, Gumbel, and Normal) were evaluated to determine the goodness of fit to the set of PGA observations, searching for a distribution that presented the best performance for the ensemble. The parameters of the various density functions for the seven cities considered were determined using the method of statistical moments, with the first two moments presented in Table 1. For the city of Cúcuta, it was concluded that the maximum annual acceleration is best modeled by the Lognormal distribution, as illustrated in Fig. 3a. Weibull, Gumbel, and Normal distributions for Cúcuta are illustrated in Figs. 3b, 3c, and 3d, respectively. The same procedure was performed for the other six cities.



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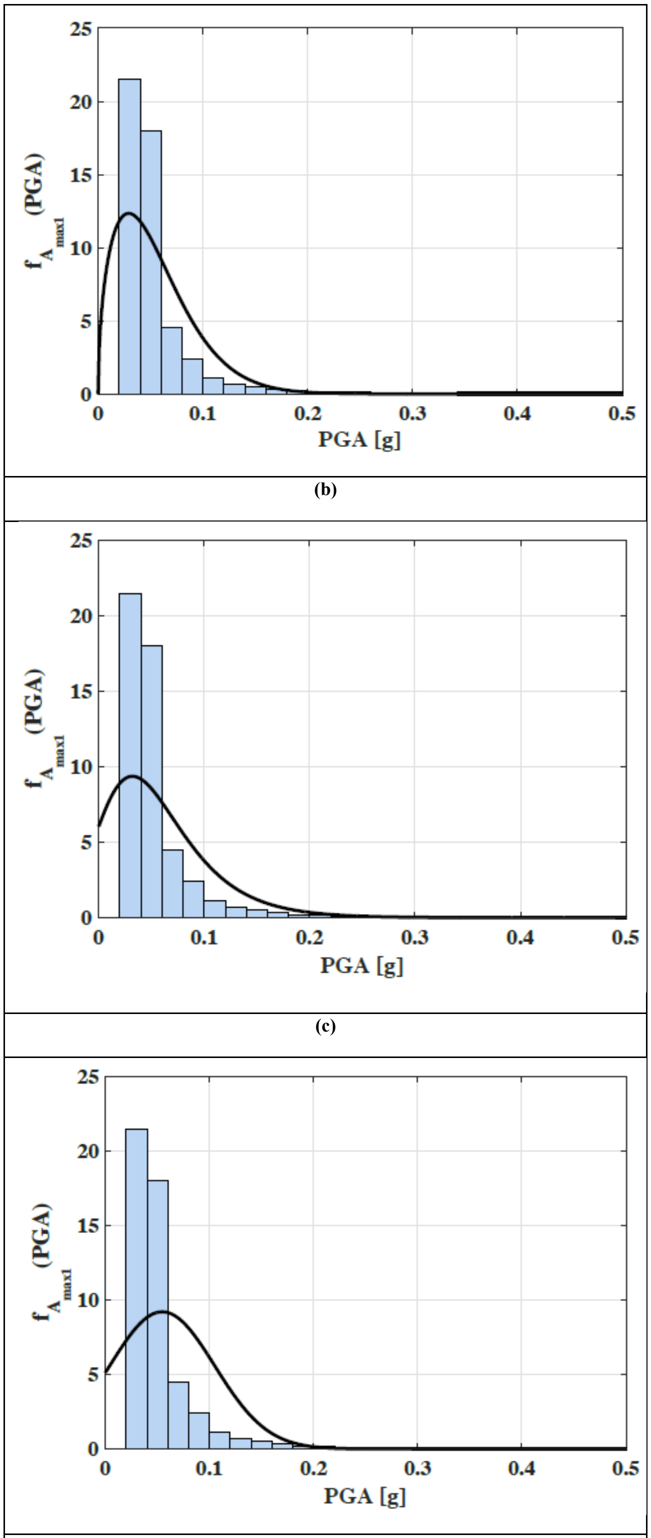


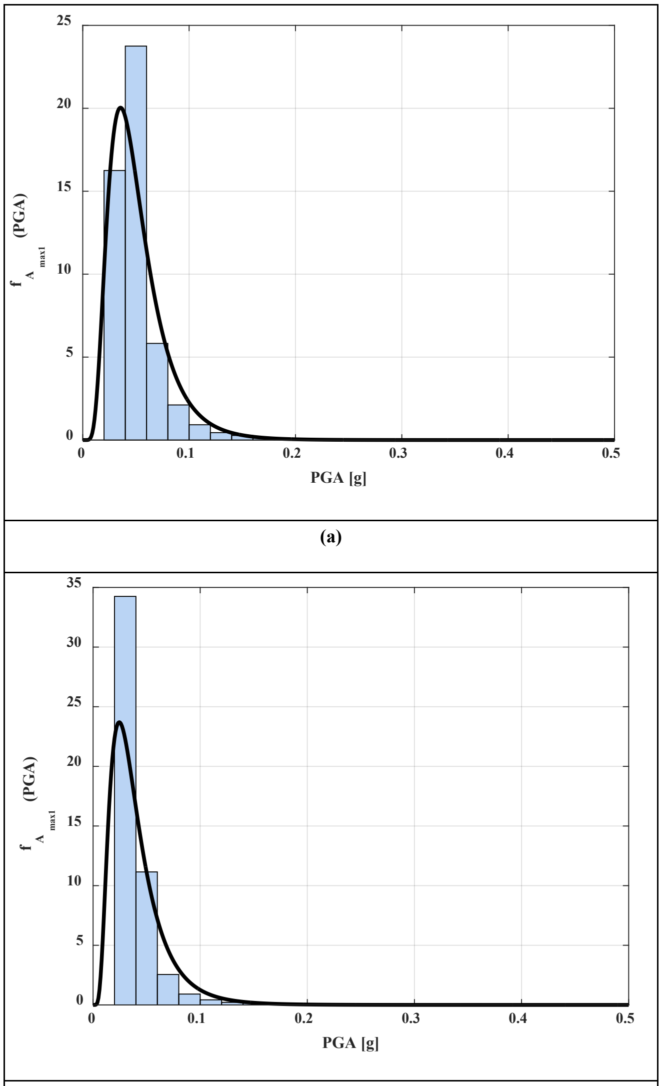
(b)

(c)

(d)

Figure 3. Probability density function fits to PGA records in the city of Cúcuta. (a) Lognormal probability density function; (b) Weibull probability density function; (c) Gumbel probability density function; (d) Normal probability density function.

In all cases, the Lognormal function presented the best fit to the data (see Figure 4), which suggests that the maximum annual acceleration A_{max1} in these Colombian cities may be assumed to be a lognormally distributed random variable.



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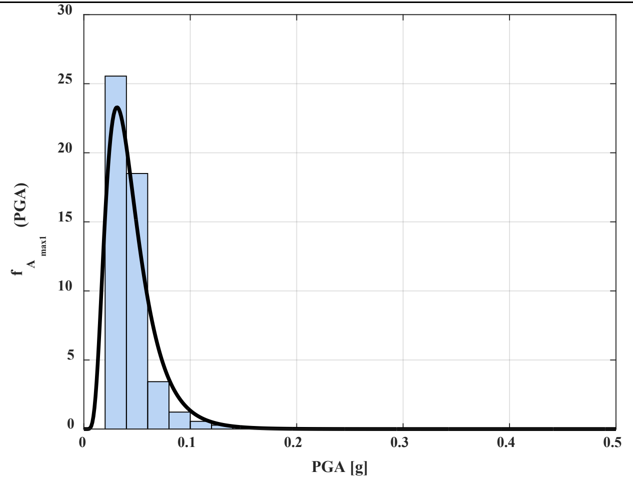

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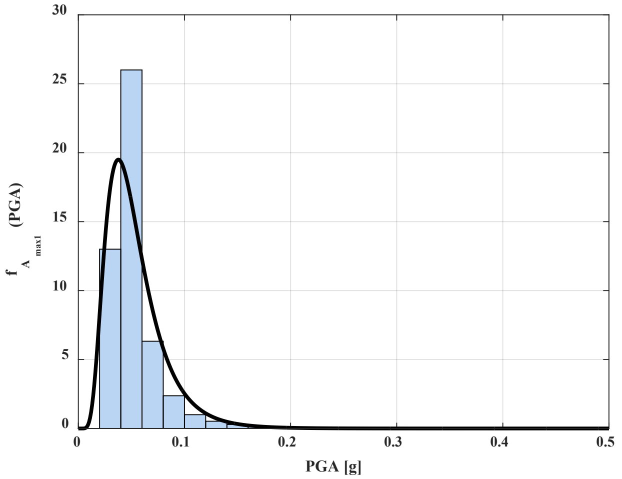

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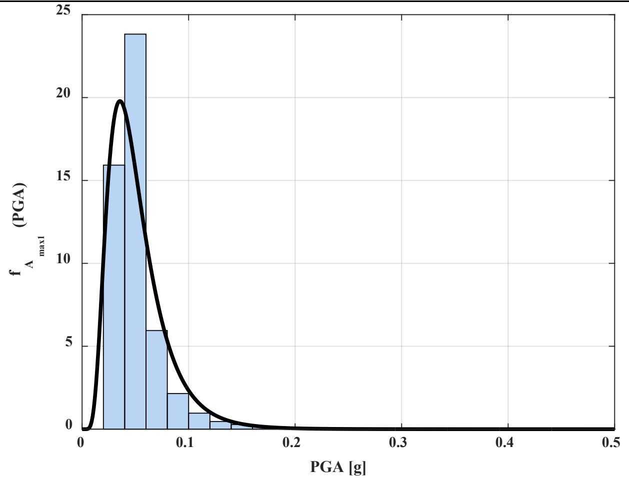

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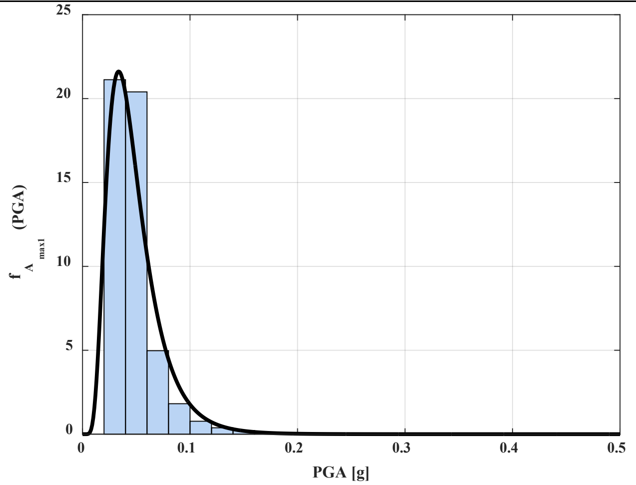


(f)

Figure 4. Plots of Lognormal pdf and corresponding $\boldsymbol{A_{max1}}$ histograms for remaining cities. (a) Armenia; (b) Bogotá; (c) Bucaramanga; (d) Cali; (e) Manizales; (f) Medellín.

Thus, the parameters of the lognormal density function for each location may be determined by means of Eqs. (12) and (13), employing the moments presented in Table 1. The lognormal function is shown in Eq. (14).

$$\lambda_{PGA} = E(\ln PGA) = \ln\big(E(PGA)\big) - \tfrac{1}{2}{\zeta_{PGA}}^2 \qquad (12)$$

$${\zeta_{PGA}}^2 = Var(\ln PGA) = \ln\left[1 + \left(\tfrac{\sigma(PGA)}{E(PGA)}\right)^2\right] \qquad (13)$$

$$f_{A_{max1}}(PGA) = \tfrac{1}{\sqrt{2\pi\zeta_{PGA}}}\, exp\left[-\tfrac{1}{2}\left(\tfrac{\ln PGA - \lambda_{PGA}}{\zeta_{PGA}}\right)^2\right] \qquad (14)$$

Assessment of first two moments of the PGA in fifty years periods

The largest value of the PGA in predefined time periods at locations of interest is a random variable of relevance in seismic hazard analysis and design. An $N = 50$ years is often adopted in seismic codes as a mean recurrence period for design purposes. Hence, the probability density function of the PGA for $N = 50$ years, f_{max50}, was determined for the seven Colombian cities considered in the present study, on the basis of the pdf of the annual PGA. It is known in the Theory of Extreme Values that the maximum value of N independent samples of a lognormal random variable tends, as $N \rightarrow \infty$, to a type I (Gumbel) probability density function (Ang and Tang, 1990).

The authors are not aware of the existence of analytical expressions for the pdf of the maximum value of arbitrary N independent samples of a lognormal function, so histograms for the seven Colombian cities were obtained by numerical simulation. For such purpose, series of s samples of the peak value observed in $N = 50$ years with the lognormal parent distribution, which led to simulated values of the mean $E(PGA)$ and standard deviation $\sigma(PGA)$ of f_{max50}. Table 2 presents the results of the simulation for s ranging from 60 to 200, to provide an indication of the rate of convergence.

Table 2. Mean and standard deviation of $\boldsymbol{f_{max50}}$ for different samples sizes.

City	Mean and Std. Dev. [g]	s = 60	s = 80	s = 100	s = 200
Armenia	E(*PGA*)	0.1471	0.1465	0.1460	0.1427
	σ(*PGA*)	0.0347	0.0323	0.0331	0.0315
Bogotá	E(*PGA*)	0.1366	0.1365	0.1360	0.1324
	σ(*PGA*)	0.0388	0.0356	0.0364	0.0339
Bucaramanga	E(*PGA*)	0.1257	0.1254	0.1248	0.1222
	σ(*PGA*)	0.0302	0.0269	0.0279	0.0260
Cali	E(*PGA*)	0.1495	0.1483	0.1482	0.1456
	σ(*PGA*)	0.0348	0.0311	0.0331	0.0314
Cúcuta	E(*PGA*)	0.2620	0.2587	0.2575	0.2523
	σ(*PGA*)	0.0999	0.0955	0.1006	0.0904
Manizales	E(*PGA*)	0.1495	0.1494	0.1487	0.1455
	σ(*PGA*)	0.0359	0.0324	0.0339	0.0320
Medellín	E(*PGA*)	0.1353	0.1343	0.1341	0.1319
	σ(*PGA*)	0.0311	0.0293	0.0291	0.0276

Introducing the statistical moments for s = 200 indicated in Table 2 in Eqs. (15) and (16), the parameters of a Type I (Gumbel) distribution may be determined for each location. The adopted distribution for $N = 50$, given by Eq. (17), is identical to the asymptotic type I distribution.

$$\alpha_{50} = \frac{\sigma(PGA)\sqrt{6}}{\pi} \tag{15}$$

$$\gamma_{50} = E(PGA) - 0.5772\alpha_{50} \tag{16}$$

$$f_{max50}(PGA) = \frac{1}{\alpha_{50}} exp\left[-\left[\frac{PGA-\gamma_{50}}{\alpha_{50}}\right]\right] exp\left[-exp\left[-\left[\frac{PGA-\gamma_{50}}{\alpha_{50}}\right]\right]\right] \tag{17}$$

The parameters α_{50} and γ_{50} for the seven Colombian cities considered in the present study are presented in Table 3. Figures 5 and 6 show that the type I (Gumbel) asymptotic distribution is a satisfactory model for the maximum PGA in 50 years in all cases. It should be observed, in addition, that the pdf for larger time periods ($N > 50$) may be obtained analytically from Eq. (17) if desired. It must be underlined again, as discussed in detail in the Introduction, that the short length of the series of observations, renders the use of the lognormal parent distribution questionable for $N \gg 50$.

Table 3. Parameters of Type I distributions of the PGA in fifty years.

City	α_{50}	γ_{50}
Armenia	0.0233	0.1302
Bogotá	0.0264	0.1172
Bucaramanga	0.0196	0.1112
Cali	0.0234	0.1322
Cúcuta	0.0705	0.2116
Manizales	0.0240	0.1320
Medellín	0.0216	0.1190

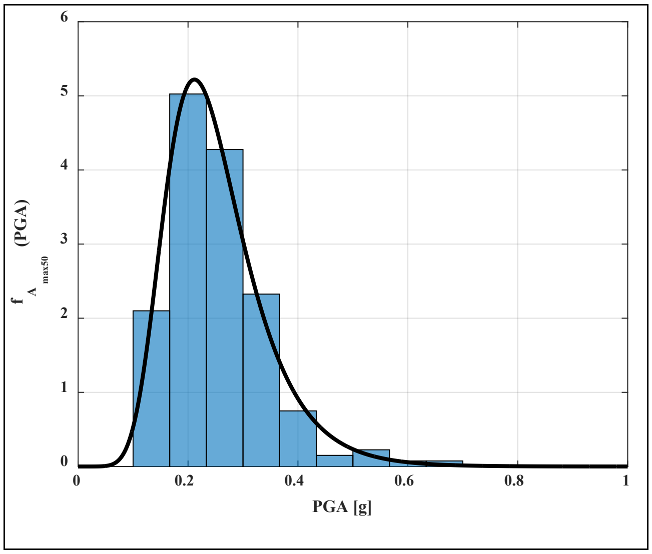
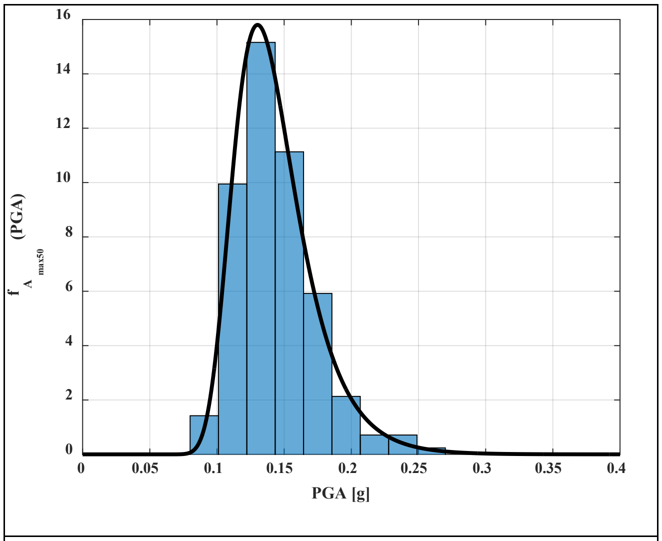


Figure 5. Type I (Gumbel) probability density function fit to simulated maximum acceleration in fifty years in Cúcuta.



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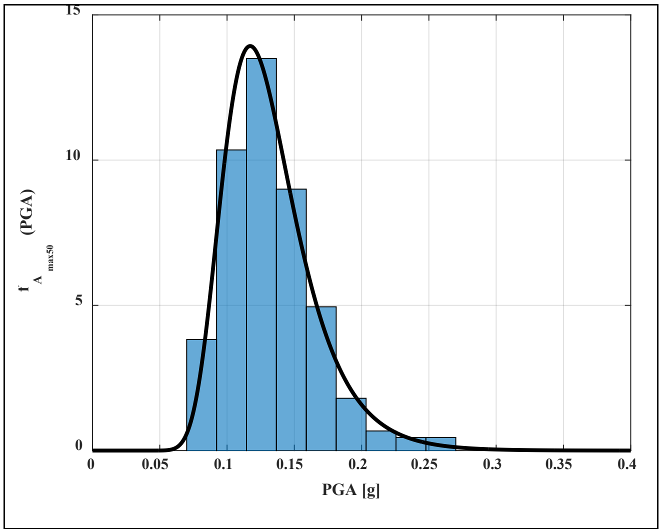

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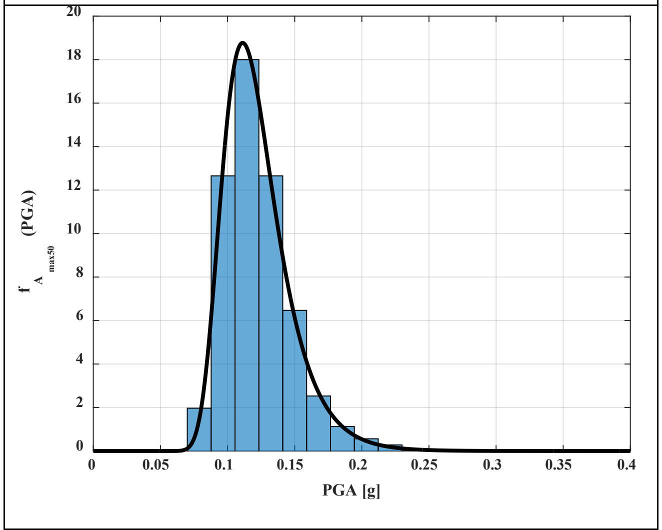

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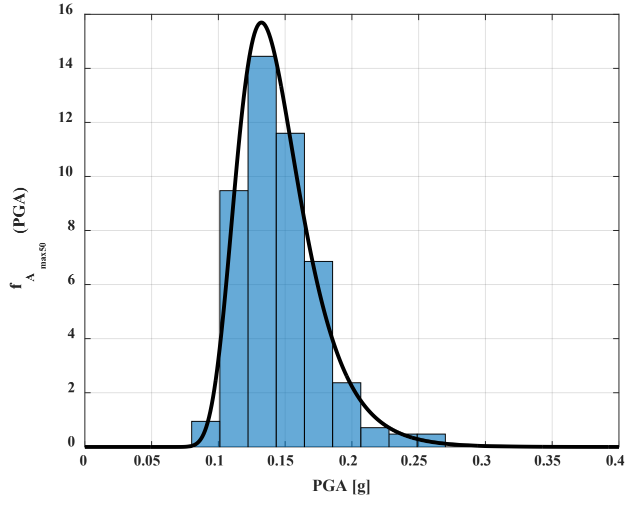

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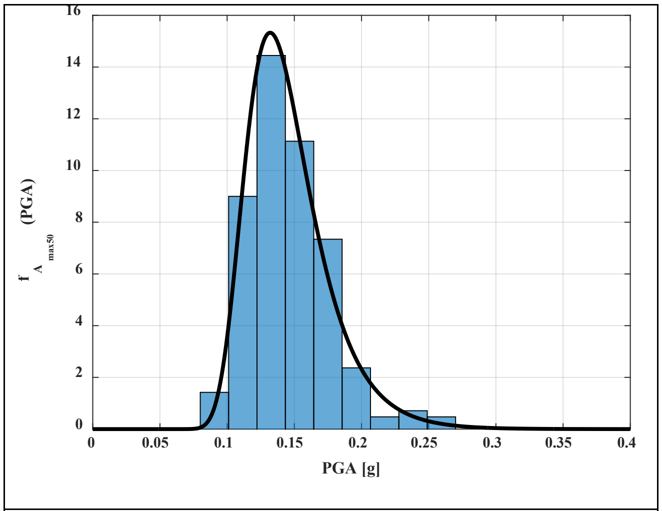

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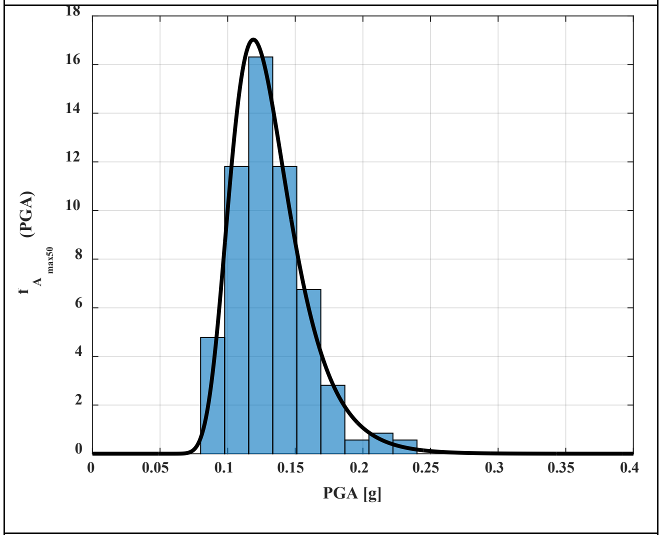

(f)

Figure 6. Type I (Gumbel) probability density function fitted to the maximum acceleration in fifty years. (a) Armenia; (b) Bogotá; (c) Bucaramanga; (d) Cali; (e) Manizales; (f) Medellín.

Table 4 presents in the first column acceleration values characterized by a 10% probability of being exceeded in a fifty years period, at each city listed in Table 1, obtained analytically using Eq. (17) as well as values prescribed by AIS-300 (2009) in the second and third columns. The latter indicates the effective peak horizontal acceleration for design (A_a) and the acceleration coefficient that represents the effective horizontal peak velocity for design (A_v) for the same hazard level. According to AIS-300 (2009), both parameters (A_a and A_v) are associated with the design earthquake that is established, so the hazard level has a probability of exceedance of 10% in 50 years. Thus, to calculate A_a, the maximum acceleration of the ground (vibration period of 0 seconds) is calculated for a return period of 475 years, a factor that affects the area of short vibration periods, that is, those that are sensitive to acceleration. The value A_v is calculated by taking the value of the acceleration for a period of vibration equal to 1 second divided by a constant equal to 1.2. This value defines the seismic coefficient for design structures with intermediate and high vibration periods, that is, those that are sensitive to velocity.

Table 4. Acceleration in terms of g with 10% exceedance probability in fifty years.

Type I	A_a	A_v	City
0.183	0.25	0.25	Armenia
0.177	0.15	0.20	Bogotá
0.155	0.25	0.25	Bucaramanga
0.185	0.25	0.25	Cali
0.370	0.35	0.25	Cúcuta
0.186	0.25	0.25	Manizales
0.168	0.15	0.20	Medellín

It may be observed that the acceleration levels obtained in this paper, for a 10% probability of being exceeded in 50 years, are globally compatible with those indicated by AIS-300 (2009). The mean value for the seven cities according to the proposed approach is 0.20g, while the mean A_a value according to AIS-300 (2009) is 0.205g, although some large positive or negative differences occur at specific locations. These differences may suggest that the present approach is somewhat more precise than AIS-300 (2009). It should also be underlined that the present model allowed the application of a methodology for an optimized design, based on reliability, of friction damping devices, as described by Ontiveros-Pérez et al. (2019), for a typical reinforced concrete building in the city of Cúcuta.

Conclusions

The paper describes an approach to assess seismic hazards in seven Colombian cities employing data furnished by the Association of Seismic Engineering (AIS-300 Code). The proposed scheme is based on estimates of the probability density function (pdf) of the maximum annual peak ground acceleration (PGA) at locations of interest, which were adopted as parent distributions for the ensuing developments. The probability density functions next determined by means of random simulations are compatible with previous seismic hazard assessments for those locations. Those functions are considered useful tools for engineering design, mainly in reliability analysis and optimization procedures of conventional engineering buildings and structures at the indicated seven Colombian cities.

In fact, since the results are based on existing records of the PGA observed during seismic events, they cannot be expected to account for the seismic risk resulting from large, very low frequency of occurrence events, as might be required for the design of nuclear power stations or large dams, for which purpose the specification of a design PGA would obviously be insufficient. For standard constructions, on the other hand, most building codes base their seismic requirements on simplified schemes, which often depend on a design PGA. The PGA observed at any recording station is influenced by soil conditions at the site and in neighboring areas (which are necessarily crossed by incoming seismic waves), but it is reasonable to admit that predictions based on existing PGA data at any given site may be used to predict the seismic risk around the recording site. The previous assumption is valid when the soil profile at the site is typical of the surrounded area and is clearly superior to other schemes in which the seismic risk is quantified for regions that cover thousands of square kilometers, which largely exceed the areas of the Colombian cities examined in the analysis.

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References

Acevedo, A.B., J.D. Jaramillo, C. Yepes, V. Silva, F.A. Osorio, and M. Villar, 2017. "Evaluation of the seismic risk of the unreinforced masonry building stock in Antioquia, Colombia". Natural Hazards, 86(1), pp.31-54. doi: 10.1007/s11069-016-2647-8

Acevedo, A.B., C. Yepes, D. González, V. Silva, M. Mora, M. Arcila, and G. Posada, 2020. "Seismic risk assessment for the residential buildings of the major three cities in Colombia: Bogotá, Medellín, and Cali". Earthquake Spectra, 36(1), pp. 298-320. doi: 10.1177/8755293020942537

Ang, A. H-S., and W. H. Tang, 1990. "Probability Concepts in Engineering Planning and Design", Volume II, ISBN 0-171-03201-8.

Cardona O, Ordaz M, Reinoso E, Yamín L, Barbat A (2010) Comprehensive Approach to Probabilistic Risk Assessment (CAPRA). International initiative for disaster risk management effectiveness. Procedures of the 14th European conference on earthquake engineering, Ohrid, Macedonia.

Cardona O, Ordaz M, Reinoso E, Yamín L, Barbat A (2012) CAPRA – Comprehensive Approach to Probabilistic Risk Assessment: International Initiative for Risk Management Effectiveness. Procedures of the 15th World Conference on Earthquake Engineering. Lisbon, Portugal.

Carreño, M.L., O.D. Cardona, and A.H. Barbat, 2007. "Urban Seismic Risk Evaluation: A Holistic Approach", Natural Hazards, 40(1), pp. 137-172. doi: 10.1007/s11069-006-0008-8

Comité AIS-300: Amenaza Sísmica (2009) "Estudio General de Amenaza Sísmica de Colombia 2009", Asociación Colombiana de Ingeniería Sísmica-AIS.

Esteva, L. (1976): "Seismicity" , Chapter 7, in Seismic Risk in Engineering Decisions, Edited by C. Lomnitz and E. Rosenbluth, Elsevier Scientific Publications, London.

Haldar, A., and S. Mahadevan, 2000. "Probability, Reliability, and Statistical Methods in Engineering Design", John Wiley & Sons, New York, ISBN 0-471-33119-8.

Ojeda, A., and J. Havskov. 2001. "Crustal structure and local seismicity in Colombia", Journal of Seismology, 5, 575-593. doi: 10.1023/A:1012053206408

Ojeda, A., S. Martinez, M. Bermudez, and K. Atakan. 2002. "The new accelerograph network for Santa Fe De Bogota, Colombia and implications for microzonation", Soil Dynamics and Earthquake Engineering, 22, 791-797. doi: 10.1016/S0267-7261(02)00100-8

Ontiveros-Pérez, S.P., L.F.F. Miguel, and J. D. Riera. 2019. "Reliability-based optimum design of passive friction dampers in buildings in seismic regions", Engineering Structures, 190, 276-284. doi: 10.1016/j.engstruct.2019.04.021

Ordaz, M., Aguilar, A., Arboleda, J. 2007 "CRISIS, Program of computing seismic hazard", México: Instituto de Ingeniería, Universidad Nacional Auténoma de México.

Ordaz, M., Martinelli, F., D'Amico, V., and Meletti, C. CRISIS2008: A flexible tool to perform probabilistic seismic hazard assessment, Seismological Research Letters, vol. 84(3), p. 495–504, 2013.

Pulido, N. (2003). "Seismotectonics of the northern Andes (Colombia) and the development of seismic networks", Bulletin of the International Institute of Seismology and Earthquake Engineering, 2003 Special Edition 69-76.

Riera, J.D., and I. Iturrioz. 2013. "Performance of the Gutenberg-Richter Law in numerical and laboratory experiments", Transactions SMiRT 22, International Conference on Structural Mechanics in Reactor Technology, August 2013, San Francisco, USA.

Riera, J.D., and I. Iturrioz. 2015. "Considerations on the diffuse seismicity assumption and the validity of G-R law in Stable Continental Regions (SCR)", Revista Sul-americana de Engenharia Estrutural 12 (2) (2015) 7–25, https://doi.org/10.5335/rsee.v12i2.4544.

Salgado, M.A., G.A. Bernal, L.E. Yamín, and O.D. Cardona. 2010. "Evaluación de la amenaza sísmica de Colombia. Actualización y uso en las nuevas normas colombianas de diseño sismo resistente NSR-10", Revista de Ingeniería, (32), 28-37.

Salgado-Gálvez, M.A., D. Zuloaga-Romero, G.A. Bernal, M.G. Mora, and O.D. Cardona. 2014. "Fully probabilistic seismic risk assessment considering local site effects for the portfolio of buildings in Medellín, Colombia", Bulletin of earthquake engineering, 12(2), 671-695. doi: 10.1007/s10518-013-9550-4

Salgado-Gálvez, M.A., G.A. Bernal, A.H. Barbat, M.L. Carreño, and O.D. Cardona, (2016a). "Probabilistic estimation of annual lost economic production due to premature deaths because of earthquakes", Human and Ecological Risk Assessment: An International, 22(2), pp. 543-557. doi: 10.1080/10807039.2015.1095072

Salgado-Gálvez, M.A., D.Z. Romero, C.A. Velásquez, M.L. Carreño, O.D. Cardona, and A.H. Barbat. (2016b). "Urban seismic risk index for Medellín, Colombia, based on probabilistic loss and casualties estimations". Natural Hazards, 80(3), pp.1995-2021. doi: 10.1007/s11069-015-2056-4

Salgado-Gálvez, M.A., D. Zuloaga, S. Henao, G.A. Bernal, and O.D. Cardona. 2018. "Probabilistic assessment of annual repair rates in pipelines and of direct economic losses in water and sewage networks: application to Manizales, Colombia". Natural Hazards, 93(1), pp.5-24. doi: 10.1007/s11069-017-2987-z

Scholz, C.H. (2002). "The Mechanics of Earthquakes and Faulting", 2nd. Edition, Cambridge Univ. Press.

Wesnousky, S.G. (1994): "The Gutenberg-Richter or characteristic earthquake distribution, which is it?", Bulletin of the Seismological Society of America-BSSA, 84 (6), 1940-1959.