PROBABILISTIC SEISMIC RISK ASSESSMENT OF THE RESIDENTIAL BUILDING STOCK IN SOUTH AMERICA

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Abstract

This paper presents a probabilistic seismic risk assessment for the residential building stock in South American countries prone to earthquakes: Argentina, Bolivia, Chile, Colombia, Ecuador, Peru and Venezuela. Average annual economic loss maps, mean loss exceedance curves per country, and statistics that reveal which building classes are most vulnerable to earthquakes are some of the examined results. An event-based simulation approach was employed for the calculation of the economic losses and physical damage of buildings, considering a wide spectrum of uncertainties. A comprehensive logic tree was used in order to incorporate the epistemic uncertainty in the selection of the ground motion prediction equations (GMPEs) in accordance with the existing tectonic regimes; and for the vulnerability model, sets of fragility curves developed for each building class specified in the exposure model account for both the record-to-record and building-to-building variability. The results obtained in this study are a crucial step towards the reduction of seismic risk, as they are essential for understanding how earthquake threat is distributed across South America.

Keywords: South America; probabilistic seismic risk; residential buildings, earthquake losses, earthquake damage

1. Introduction

South America is located in a seismically active region, particularly the areas near the subduction zone in the Pacific coast. The Andean countries – Argentina, Bolivia, Chile, Colombia, Ecuador, Peru and Venezuela – have experienced multiple strong earthquakes that have caused significant number of casualties, economic losses and damage to the physical infrastructure. The distribution of population in the Andean countries is characterized by a large urban concentration, with approximately 80% of the inhabitants located in regions with moderate or high seismicity (i.e. peak ground acceleration, PGA, on rock larger than 0.1g) [1]. The residential building stock in some regions comprises a large number of vulnerable structures due to informal construction and lack of endorsement of modern seismic regulations. Seismic risk assessment may represent an important tool for understanding and reducing the impact of earthquakes, and supporting the development of policies for the sustainable development of the region.

The probabilistic approach employed for calculating the economic losses and physical damage of buildings considers a wide spectrum of uncertainties. In the hazard model, logic trees are used in order to incorporate the epistemic uncertainty from a number of parameters in the source model, as well as different ground motion prediction equations (GMPEs) in accordance with the existing tectonic regimes. In the vulnerability model, fragility curves developed for each building type specified in the exposure model account for both the record-to-record and building-to-building variability; whereas the uncertainties in the economic and human losses at different intensity levels are considered by specifying a mean and associated coefficients of variation of the loss ratio.

As part of the South America Risk Assessment (SARA) project led by the Global Earthquake Model (GEM) [2], extensive research on regional seismic hazard modelling, characterization of the residential building portfolio, and evaluation of the physical vulnerability of structures in the region has been undertaken. These three components constitute the basic input for the probabilistic seismic risk assessment in the region using the *OpenQuake-engine* [3, 4]. All of the datasets and models developed as part of the project can be found in the online platform dedicated to SARA (https://sara.openquake.org/).

The results obtained through this comprehensive assessment are presented for the main residential building classes prevalent in the region: unreinforced and confined masonry structures, reinforced concrete buildings (infilled frames, bared frames and dual/wall systems), and adobe/earthen houses. Average annual economic loss maps for South America, mean loss exceedance curves per country, and statistics that reveal the building classes that are most vulnerable to earthquakes are also presented. This information is essential for understanding how the risk is distributed across South America and thus how it can be effectively managed. Formulation of risk mitigation plans, increasing risk awareness, development of seismic code provisions for design of safer structures, and retrofitting strategies for the most vulnerable types of construction are some of the applications of the results obtained in this study.

2. Input models

2.1. Seismic hazard model

The probabilistic seismic hazard analysis (PSHA) model developed as part of the SARA project was utilized in the present study [5]. This model includes all the possible active seismic sources in South America and describes them in terms of geometry, magnitude-frequency distribution, occurrence rates and rage of possible magnitudes. Advanced and original methods for earthquake modelling were implemented: the shallow seismicity is modeled using an integrated model of distributed seismicity (area-source for both, active shallow crust and stable continental regions) and crustal fault sources; the subduction interface seismicity is modeled as large fault sources with a 3D geometry, and the subduction in-slab seismicity is modeled as 3D volumes of ruptures describing the spatial distribution of events within this area. Four tectonic regimes were considered: subduction interface, subduction intraslab, active shallow crust and stable shallow crust. The epistemic uncertainty coming from the selection of GMPEs for each tectonic region was considered using a logic tree. Fig. 1 presents the mean hazard map for South America corresponding to the 10% probability of exceedance in 50 years. Site conditions were considered through the average shear-velocity down to 30 m (vs30). Considering that the present study focused on a regional assessment, a simplified model [6] based on the topographic slope was assumed.

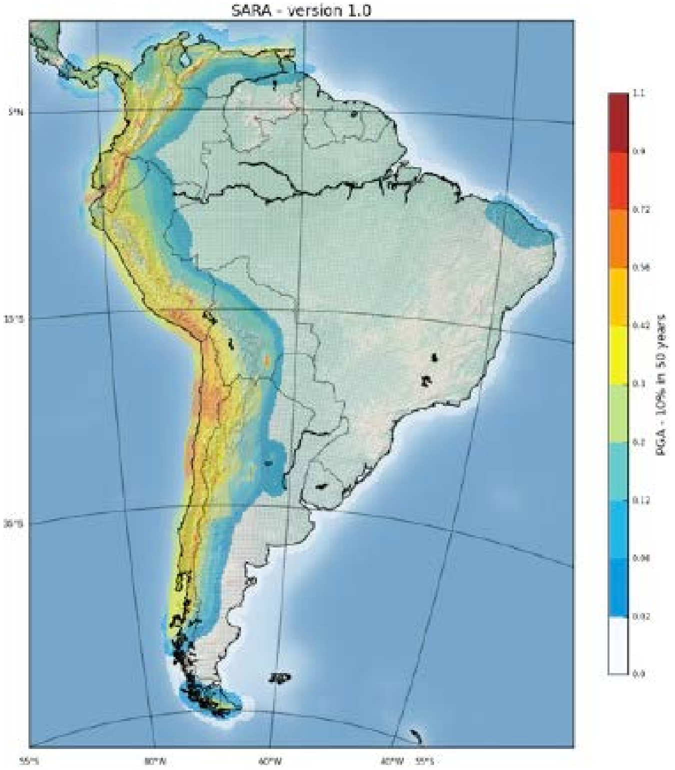

Fig. 1 – Mean South American hazard map (PGA [g] for 10% probability of exceedance in 50 years) [5]

2.2. Exposure model

The present study utilizes the uniform exposure model for the residential building stock in the Andean countries presented by Yepes-Estrada *et al.* 2015 [1]. The model comprises information about the number of dwellings and buildings classified into forty building classes, the average built-up area per dwelling, the average number of dwellings per building, the average structural replacement cost, and the average number of occupants per building. The methodology utilized in the estimation of dwelling and building fractions is based on housing census surveys and expert judgment. The most important features for classifying the building stock according to the expected seismic response were: the predominant material of the exterior walls, the material of the floor, the type of dwelling, and the type of area (urban or rural). The building stock is estimated by combining the number of dwellings available in the databases with mapping schemes that classify dwelling fractions based on the selected features.

The definition of the building classes was performed using the GEM building taxonomy [7], a uniform and comprehensive classification system developed to characterize buildings according to a number of attributes. Forty building classes were defined taking into account the predominant construction material, the lateral load resisting system, the ductility level, and the range of the number of storeys. Table 1 presents a summary of the distribution of building classes across countries, and the main five typologies for each country are highlighted in light grey. Table 2 summarizes the model at national level.

The aforementioned information is available at different geographical scales, from the national level up to the third administrative level, which includes a total of 6,303 locations in the region. Additional information regarding the exposure model is available in the *SARA wiki* (https://sara.openquake.org/risk:exposure).

Table 1 – Summary of residential dwelling classes in accordance with census data [1]

GEM Taxonomy	Argentina	Bolivia	Chile	Colombia	Ecuador	Peru	Venezuela
CR+PC/LWAL/H:1,3			1.3%	0.3%			
CR/LDUAL/DUC/H:4,7	1.9%	0.2%		0.1%		1.0%	
CR/LDUAL/DUC/H:8,19	1.3%					0.3%	
CR/LFINF/DNO/H:1,3	11.8%			3.5%	4.1%	1.6%	13.9%
CR/LFINF/DUC/H:1,3	3.1%				0.6%	1.6%	1.8%
CR/LFINF/DUC/H:4,7	0.8%			2.3%	0.4%		
CR/LFLS/DNO/H:1,3		0.4%			7.8%		
CR/LFLS/DUC/H:1,3		0.4%			0.7%		
CR/LFLS/DUC/H:4,7					0.8%		
CR/LFM/DNO/H:1,3	4.7%			3.5%	4.0%		6.4%
CR/LFM/DUC/H:1,3	1.6%				0.6%		1.1%
CR/LFM/DUC/H:4,7	0.3%			2.3%	0.4%		
CR/LWAL/DNO/H:1,3	0.6%		4.1%				
CR/LWAL/DNO/H:4,7	0.5%		2.7%			0.2%	
CR/LWAL/DUC/H:1,3			2.6%				
CR/LWAL/DUC/H:4,7	0.5%		2.1%	1.5%		0.2%	0.5%
CR/LWAL/DUC/H:8,19			1.7%			0.2%	
ER+ETR/H:1		10.5%	0.2%	1.6%	1.7%	8.0%	0.7%
ER+ETR/H:1,2		8.0%	1.0%	2.3%	1.1%	1.6%	0.8%
MCF/DNO/H:1	9.7%	1.2%	3.6%	2.9%	4.1%	2.6%	
MCF/DNO/H:1,3	13.5%	16.5%	12.2%	9.7%	19.4%	7.2%	14.6%
MCF/DUC/H:1,3	6.5%	3.7%	6.5%	5.7%	1.2%	8.1%	0.7%
MR/DNO/H:1,3	0.9%		11.1%				
MR/DUC/H:1,3	0.9%		3.6%	2.3%		0.3%	
MUR+ADO/H:1	1.4%	10.5%	0.3%	0.8%	1.8%	18.6%	0.4%
MUR+ADO/H:1,2	0.4%	8.2%	4.0%	1.2%	1.0%	6.6%	5.9%
MUR+STDRE/H:1,2	1.2%	0.5%	0.3%	1.6%		0.9%	
MUR+STRUB/H:1,2	1.2%	0.5%		1.3%		1.3%	
MUR/H:1	9.8%	6.7%	0.1%	4.5%	8.0%	8.9%	0.5%
MUR/H:1,3	21.5%	22.3%	7.7%	35.6%	26.5%	13.7%	36.0%
S/LFM/H:4,7	0.1%						7.5%
UNK	1.6%	6.0%	2.8%	3.6%	1.0%	5.1%	7.6%
W+WBB/H:1				0.8%	5.3%	2.3%	
W+WHE/H:1,3	0.4%	0.1%				0.4%	
W+WLI/H:1	1.4%	0.6%	2.7%	0.3%	0.3%	2.4%	
W+WLI/H:1,3	0.2%	0.4%	20.7%	2.7%	2.1%		0.2%
W+WS/H:1	1.5%	2.2%	1.8%	1.3%	1.6%	4.8%	
W+WS/H:1,2			7.2%	4.1%	2.1%		
W+WWD/H:1	0.6%	0.9%		1.6%	3.6%		0.7%
W+WWD/H:1,2				2.3%		2.4%	0.8%
TOTAL Dwellings	**13,814,471**	**2,803,982**	**3,899,448**	**9,742,956**	**3,748,919**	**6,400,131**	**6,929,968**

Table 2 – Summary of building inventory [1]

Country	Number of Dwellings (Thousands)		Number of Buildings (Thousands)		Replacement cost [USD billion]		Population (Thousands)	
	Urban	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**
Argentina	12,473	1,341	7,106	1,137	579	39	36,467	3,650
Bolivia	1,826	978	1,314	924	19	6	6,789	3,271
Chile	3,360	540	1,761	394	211	29	13,090	2,026
Colombia	7,489	2,254	4,277	1,944	260	47	31,283	9,892
Ecuador	2,391	1,357	1,416	1,113	56	20	9,091	5,393
Peru	4,790	1,611	3,780	1,343	88	25	20,810	6,602
Venezuela	6,112	818	3,277	622	161	14	24,183	3,045
Total	**38,441 (81%)**	**8,899 (19%)**	**22,931 (75%)**	**7,477 (25%)**	**1,374 (88%)**	**180 (12%)**	**141,713 (81%)**	**33,879 (19%)**

Fig. 2 presents the distribution of dwellings in the region, as well as total estimates. The building stock in the Andean region is characterized by high urban concentration, where more than 30% of the population and structures are located in the capital cities, which (with the exception of Buenos Aires and La Paz) have intermediate to high seismic hazard. The most representative building classes are masonry construction (55%), reinforced concrete buildings (17%), earth/adobe houses (13%), and wooden structures (8%).

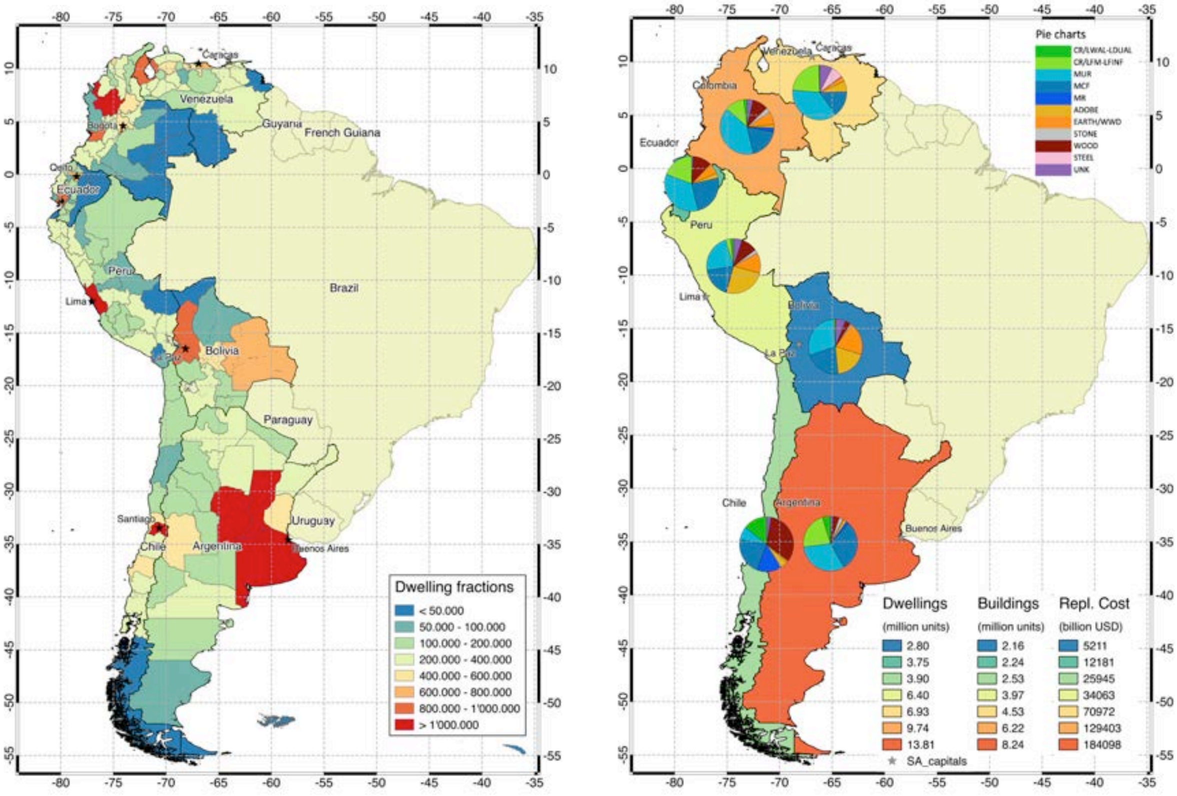

Fig. 2 – Distribution of the residential dwellings in South America (left), and total number of dwelling, buildings and replacement cost in the Andean countries with pie charts indicating dwelling fractions (right) [1]

2.3. Fragility and vulnerability model

Despite the existence of several fragility and vulnerability models for South America, it is not possible to employ them in a large-scale regional model due to numerous limitations. For example, these models have been developed using different methodologies and assumptions (e.g. structural modelling, damage criteria, number and type of damage states), and the existing models do not cover all the residential building classes presented in the previous section. Any direct comparison or combination of existing models across countries is not adequate and it is of limited validity [8]. Therefore, the present study uses the fragility model proposed by Villar *et al.* 2016 [8], which was developed for large-scale risk analysis in the region. Fragility functions, that establish the probability of exceeding a level of damage conditional on ground shaking intensity, were generated for the most representative residential building classes in South America.

A total of 54 fragility functions were developed using non-linear dynamic analyses, and considering a wide spectrum of sources of variability such as the building-to-building or the record-to-record uncertainties. For each building class, the seismic performance of 150 single-degree-of-freedom oscillators when subjected to a set of 300 ground motion records using non-linear time history analyses was estimated, and the resulting damage distribution was used to derive a set of fragility functions. The assumptions, methodology and main results are thoroughly described [8]. As an example, Fig. 3 illustrates the resulting fragility functions for a three-stories non-ductile reinforced concrete (RC) infilled frame, and a one-story adobe house.

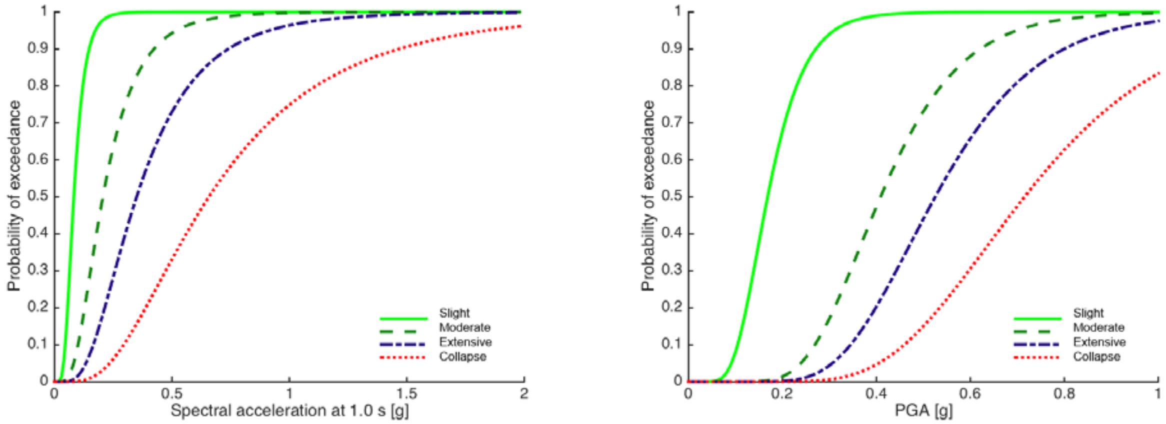

Fig. 3 – Fragility functions for three-stories non-ductile RC infilled frame, LFINF/DNO/H:3 (left), and one-story unreinforced adobe house, MUR+ADO/H:1 (right) [8]

The fragility functions were developed considering four damage states: slight, moderate, extensive and collapse; and three intensity measures types: PGA, spectral acceleration (Sa) at 0.3 seconds, and Sa at 1.0 second. These three intensity measure types allowed a good correlation between the damage distribution and the ground shaking [8].

The selected fragility model provides sets of fragility functions that represent the probability of exceeding a level of damage conditional on ground shaking intensity. However, the purpose of the present study focus on the economic impact of earthquakes in South America, and therefore it is necessary to transform this model into a vulnerability model that represents the mean loss ratio and corresponding coefficient of variation conditional on ground shaking intensity. To this end, a simplified model describing the damage ratio (cost of repair to cost of replacement) for each damage state was assumed: 0.05, 0.25, 0.6, and 1.0 for slight, moderate, extensive, and collapse damage states, 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. Fig. 4 illustrates the resulting vulnerability curves for a three-stories non-ductile reinforced concrete (RC) infilled frame, and a one-story adobe house.

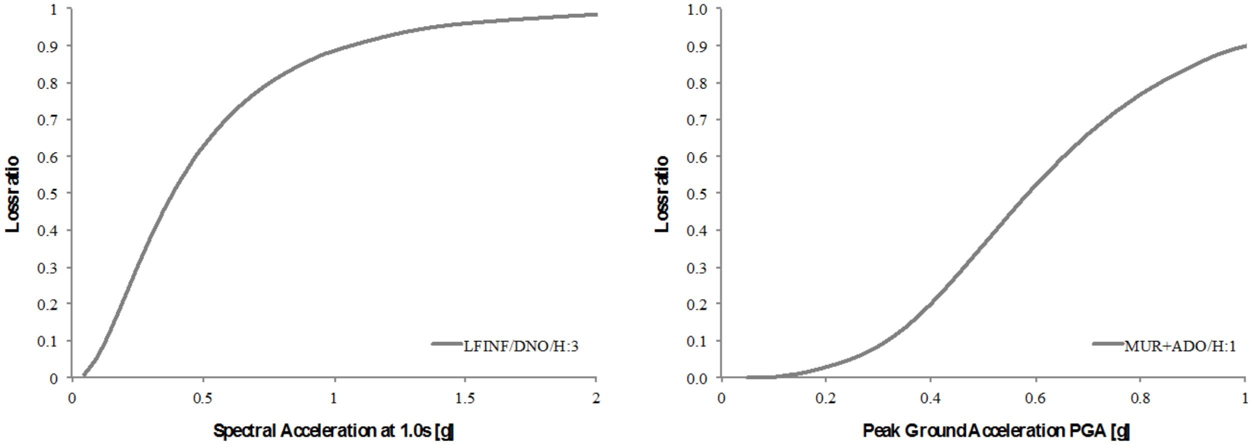

Fig. 4 – Vulnerability curves for three-stories non-ductile RC infilled frame, LFINF/DNO/H:3 (left), and one-story unreinforced adobe house, MUR+ADO/H:1 (right)

3. Seismic risk assessment

Probabilistic seismic risk assessment is fundamental for understanding the potential for human and economic losses in a region. The present study utilizes the input models described in the previous section (probabilistic seismic hazard, exposure and vulnerability) and combines them using the *OpenQuake-engine* to calculate numerous risk metrics: average annual losses, loss exceedance curves, risk maps for different return periods and loss curves at various spatial resolutions.

An event-based Monte Carlo simulation approach was followed for the calculation of risk metrics [8]. For the present study, 20,000 synthetic catalogues, or stochastic event sets (SES), representative of the seismicity of the region over a period of one year were generated for each country. In this context, a SES represents possible earthquake ruptures that can be generated 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 taking into account the inter- and intra-event variability suggested in the GMPE. In addition, the uncertainties coming from the selection of GMPEs are included through the use of logic trees for the different tectonic region types.

One of the most common loss statistics generated in risk assessment is the average annual (or annualized) loss (AAL), because it allows a direct comparison of the expected losses in different areas. For each asset, the average losses are estimated considering all events generated over the specified time period (one year, for the present study) and the corresponding vulnerability functions.

Regarding the spatial distribution of losses in South America, Fig. 5 presents the distribution of mean AAL at the first administrative level in the seven studied countries (left), as well as the mean AAL in Colombia at municipality level (top-right). These types of results allow the identification of the regions with the highest potential economic losses within a country, and thus where risk reduction activities should be prioritized. The AAL can also be aggregated at different geographical levels. For example, Fig. 5 (bottom-right) presents the mean average annual loss ratio (AALR, ratio between the total mean AAL with the total exposed value) for each country. The results indicate that Ecuador and Chile are the countries with larger AALR, 0.44% and 0.21%, while Argentina is the country with the lowest value, 0.02%.

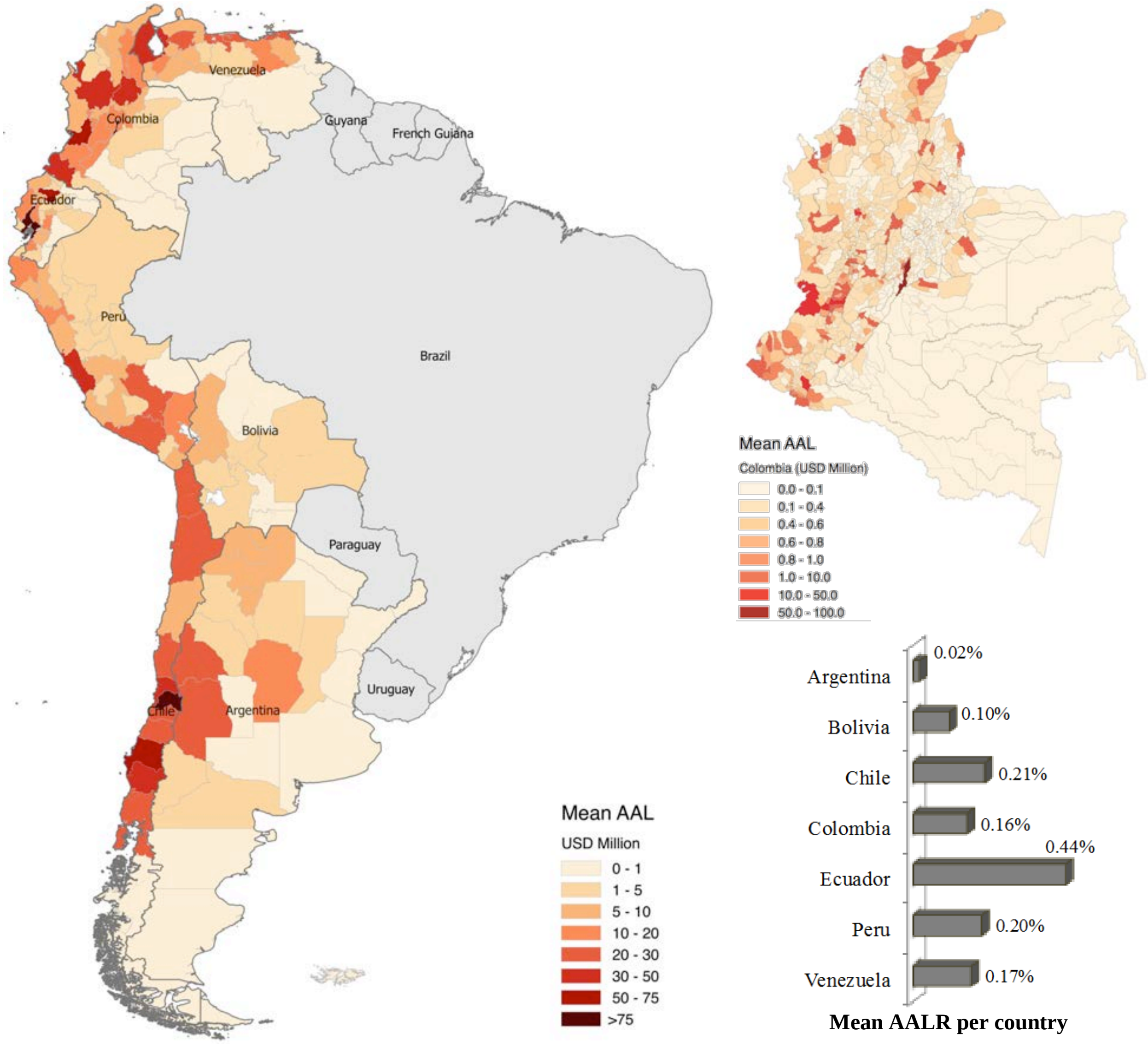

Fig. 5 – Distribution of mean average annual losses (AAL) in South America (left), mean average annual losses in Colombia at municipality level (top-right), and mean average annual loss ratio (AALR) per country (bottom-right)

Average annual losses can also be investigated per building class. As an example, Fig. 6 presents the losses per material of construction of the lateral load resisting system. It is clear that the largest contribution of economic losses is coming from masonry and reinforced concrete construction.

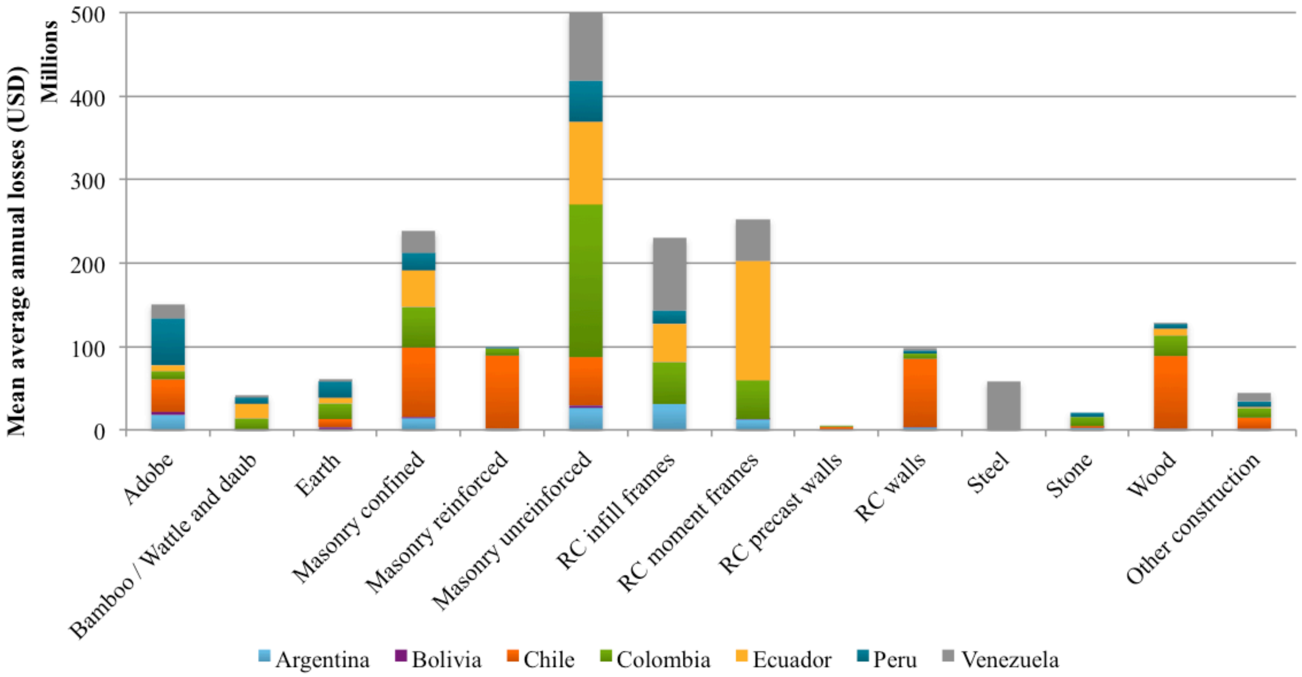

Fig. 6 – Mean average annual losses (AAL) in South America per construction material

An additional statistic widely used in risk assessment is the loss exceedance curve, also known as probable maximum loss (PML) curve. In this case, economic losses are associated to a given probability of exceedance or return period. Fig. 7 presents the loss exceedance curves for each country, where the largest absolute economic losses were estimated for Colombia and Chile for all return periods. In addition, Fig. 7 highlights the return periods for 75, 200, and 500 years, corresponding to the 50%, 20% and 10% probability of exceedance in 50 years, respectively.

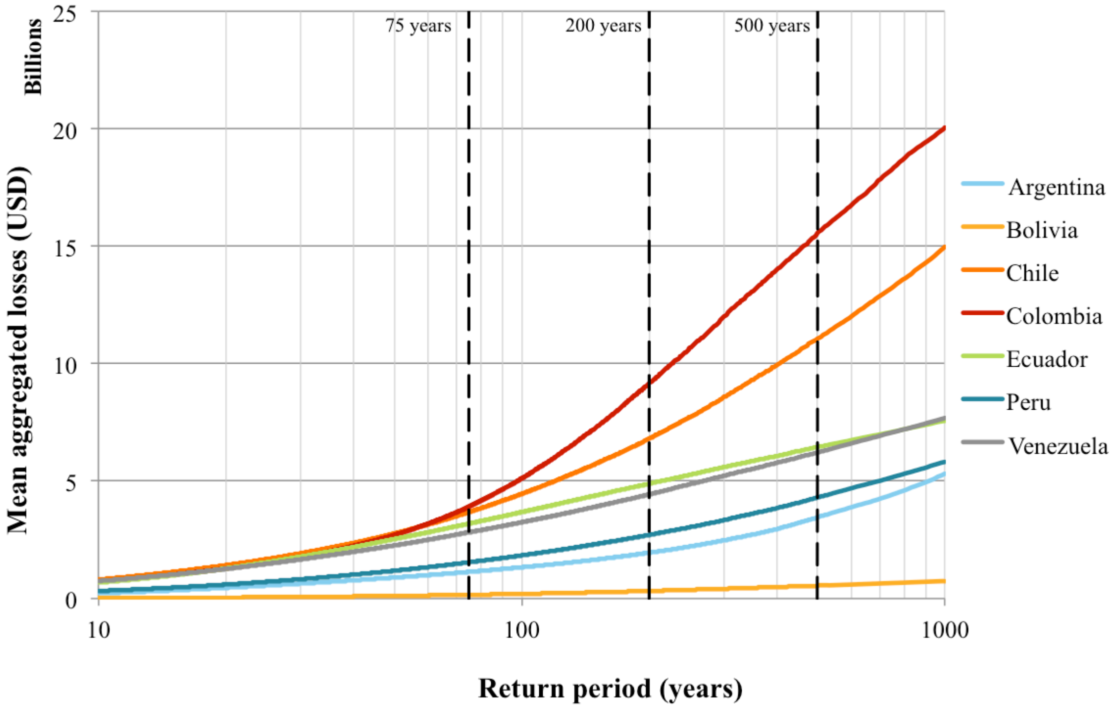

Fig. 7 – Mean loss exceedance curves (left), and mean average annual loss ratios (right) for the Andean countries

As previously indicated in Section 2.1, the hazard model incorporated epistemic uncertainties in the selection of the GMPEs through the use of a logic tree. The hazard model incorporated 36 possible branches in the GMPE logic tree that were propagated to the risk calculation, thus obtaining risk estimates for each branch. However, for the sake of clarity, the results presented in the manuscript have been summarized considering only the mean values, and additional statistics are available for the reader in the *SARA wiki*. As an example, the variability in the results in the loss exceedance curve can be observed in Fig. 8 for Colombia, where grey curves represent the possible realizations and the black curve represents the weighted mean exceedance curve.

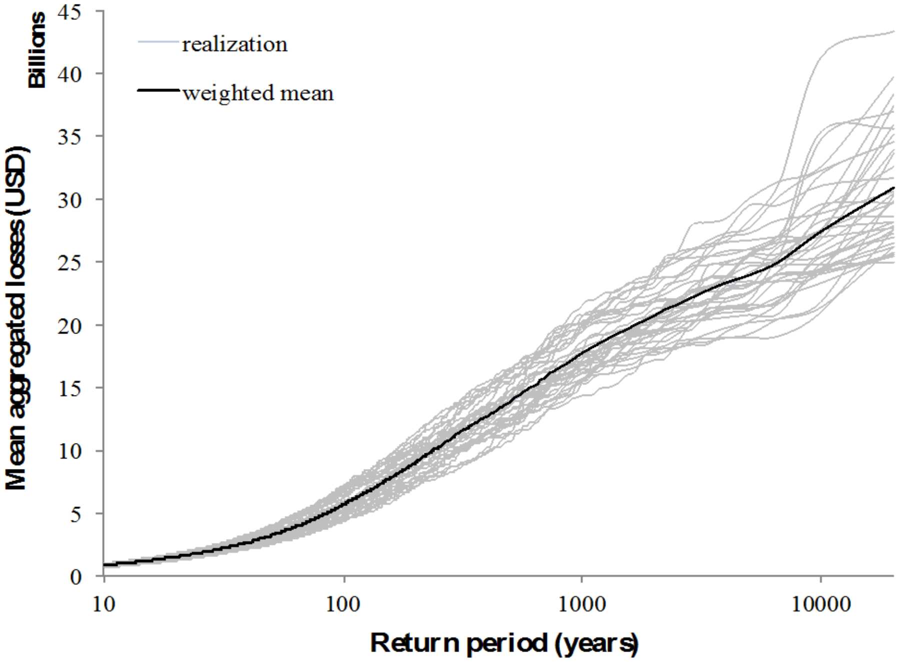

Fig. 8 – Loss exceedance curves for Colombia considering all branches in the GMPE logic tree

Finally, to present in more detail the results of the study for a specific country, Fig. 9 illustrates on the left an example of the AAL for the 10 municipalities with higher economic losses in Colombia (left); where the losses coming from Bogota, Antioquia and Valle del Cauca, the largest urban concentrations, account for 45% of the total AAL in the country. Furthermore, Fig. 9 depicts on the right the fraction of losses per building class for those municipalities, where it can be observed that the largest contribution of losses is coming from masonry structures; that includes unreinforced, confined and reinforced masonry.

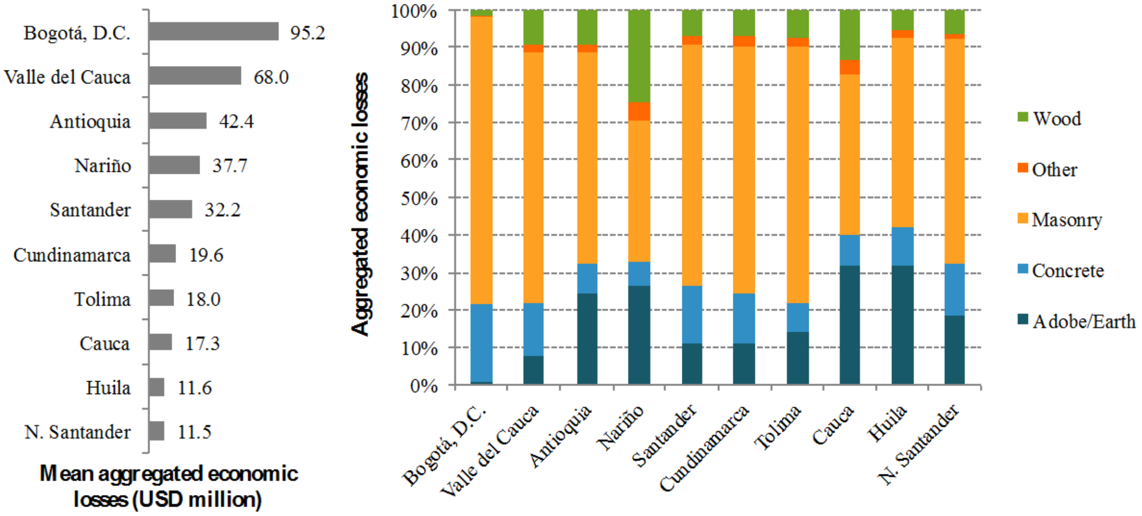

Fig. 9 – mean AAL for the 10 municipalities with highest economic losses in Colombia (left), and fraction of losses per building class (right)

The risk metrics presented in this section have been summarized in an earthquake risk profile for each country, in order to support decision makers in the development of large-scale risk reduction measures. All of the datasets and models employed in the probabilistic risk analyses can be found in the *SARA wiki*, together with the earthquake risk profiles for each country.

4. Conclusions

A comprehensive probabilistic risk assessment for the residential building stock in South America was presented. The study was developed in a collaborative framework; models, datasets, and results are open and publicly available through the *SARA wiki*. The manuscript describes the required input models, as well as methodology and obtained results. Numerous risk metrics were estimated at various spatial resolutions: average annual losses, loss exceedance curves, and distribution of losses per building class.

The results indicate that the building classes that present largest economical losses in the region are unreinforced masonry and reinforced concrete moment frames with and without infill panels. Regarding mean average annual losses, Chile and Colombia are the countries with largest losses (more than USD 450 million), while Ecuador is the country with the largest average annual loss ratio, 0.44% of the total exposed value. Argentina and Bolivia have the lowest losses in the region.

Understanding the potential of economic losses through risk assessment studies is the first step towards reducing seismic risk in a region. This type of analysis contributes to the development of disaster risk reduction (DRR) strategies, creation of pre- and post-disaster emergency plans, promotion of risk awareness campaigns, and development of mechanisms to transfer the financial risk to the private sector.

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References

[1] Yepes-Estrada C, Silva V, Valcárcel J, Acevedo A, Hube M, Coronel G (2015): A Uniform Residential Building Inventory for South America. Earthquake Spectra, under review.

[2] Global Earthquake Model (GEM) Foundation, 2015. South America, available at http://www.globalquakemodel.org/what/regions/south-america/ (last accessed 15 May 2015).

[3] Pagani, M., Monelli, D., Weatherill, G., Danciu, L., Crowley, H., Silva, V., Henshaw, P., Butler, L., Nastasi, M., Panzeri, L., Simionato, M., Vigano, D. (2014) "OpenQuake-Engine: An Open Hazard (and Risk) Software for the Global Earthquake Model", Seismological Research Letters, 85(3):692-702.

[4] Silva, V., Crowley, H., Pagani, M., Modelli, D., Pinho, R. (2013a). Development of the OpenQuake Engine, the Global Earthquake Model's Open-Source Software for Seismic Risk Assessment. Natural Hazards, 72(3): 1409-1427.

[5] Garcia, J., Weatherill, G., Pagani, M., Rodriguez L., Poggi, V., and the SARA hazard team, 2017. Building an open seismic hazard model for South America: the SARA-PSHA model. Proceedings 16th World Conference On Earthquake Engineering, 9-13 January 2017, Santiago, Chile.

[6] Allen, T. I., and Wald, D. J. (2007). Topographic Slope as a Proxy for Seismic Site Conditions (Vs30) and Amplification around the Globe, U.S. Geological Survey, Open File Report 2007-1357, 69 pp.

[7] Brzev S, Scawthorn C, Charleson AW, Allen L, Greene M, Jaiswal K, Silva V (2013): GEM Building Taxonomy Version 2.0, GEM Technical Report 2013-02 V1.0.0, GEM Foundation, Pavia, Italy, doi: 10.13117/GEM.EXP-MOD.TR2013.02.

[8] Villar-Vega, M., Silva, V., Crowley, H., Yepes-Estrada, C., Tarque, N., Acevedo, A.B., and Matias, H., 2016. Development of a Fragility Model for the Residential Building Stock in South America. Earthquake Spectra, under review.

[9] GEM (2016). The OpenQuake-engine User Manual. Global Earthquake Model (GEM) Technical Report 2016-03. doi: 10.13117/GEM.OPENQUAKE.MAN.ENGINE.1.9/01, 189 pages.