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HOW UNCERTAINTIES AND ASSUMPTIONS IN SEISMIC RISK ANALYSIS AFFECT THE DECISION-MAKER'S RISK PERCEPTION

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Abstract

Seismic risk analysis has been widely used by different decision-makers: private firms, insurers, reinsurers, and government officials to determine seismic insurance coverage and insurance premiums, prioritizing seismic reduction strategies, planning emergency response logistics, among others. However, the decision, and thus the risk analysis, is not the same for the different actors, as it depends on: 1) the final use of the risk results -as mentioned above-; 2) the characteristics of the assets: single building, homogeneous concentrated portfolio, heterogeneous concentrated portfolio, homogeneous disperse portfolio, heterogeneous portfolio; and 3) the consideration of different sources of uncertainty and their propagation. This study addresses several critical issues in seismic risk analysis at a local level and provides recommendations depending on the intended final use of the risk results based on the decision-maker. Sources of uncertainty in Hazard: ground motion correlations, Vulnerability: curve selection and consequence modeling, Exposure: type of portfolio (homogeneous/heterogeneous, concentrated/dispersed) and Risk: stochastic event set selection, are considered, and the results of each one presented and compared with each other.

Based on a case study in Medellin, Colombia for two different types of assets: concentrated heterogeneous portfolio and a dispersed portfolio, and three different decision-makers: Private firm, an insurance company, and local governments, the effects of including various sources of uncertainty are evaluated, and the variability in the results is analyzed taking into account the objective of each decision-maker. It is demonstrated that different assumptions in the loss modeling process and the inclusion of different sources of uncertainty can lead to considerably different risk results, biasing the decision. Understanding the results and their variability becomes extremely important, especially when the decision-maker is about to carry out mitigation strategies to reduce the seismic risk because neglecting these deviations can lead to decisions that, depending on the risk appetite, may not represent the optimal outcome. The analyses for the various cases are presented and the importance of informing the decision-maker about the assumptions and sources of uncertainty is commented upon.

Keywords: seismic risk analysis; uncertainty; decision-maker; mitigation strategies; effective risk communication.

1. Introduction

In the last decades, the development of catastrophe risk models has been experiencing a rising trend and they now represent the basis for risk decision-making for many stakeholders such as government officials, insurers, reinsurers, enterprises, and communities. However, there are still few analyses regarding the validation, calibration, and sensitivity of the results for models at different scales and, in many cases, the risk results are being communicated to decision-makers as absolute certain values, even when it is known that there is a great amount of uncertainty in the assumptions taken throughout the whole seismic risk modeling process. As stated in [1], even when the same calculation process is followed, the risk evaluators are still obligated to explicitly cite the adopted hypotheses, to avoid impeding unconsciously further possible refinements. Additionally, they should know better than anyone the limits of their models and the uncertainties involved in order to be able to effectively communicate them to the end-users [2].

In recent years more attention has been paid to this aspect and many studies [2] have tried to evidence the shortcomings and future trends in the modeling approach of seismic risk assessment. There is also another group of modelers that have illustrated, through cases of study, the significant variability in the losses when different scales, assumptions, and uncertainties are considered or neglected in the different stages of the risk analyses. Studies regarding this kind of analysis include [6].

However, this is still a topic mostly debated and treated in the academic environment. Seismic risk analyses in other contexts are being carried out disregarding many variables and uncertainties that may considerably vary the results, conditioning the decision-making outcome. Additionally, localized risk analyses, for specific cities or areas, are being conducted using global or regional vulnerability models and disregarding local hazard conditions and building practices, constraining the seismic risk results. As stated by [12], for the assessment of earthquake damage and losses at a local scale, models derived using a higher level of detail should be considered.

The following study addresses several of these issues in local seismic risk analyses and provides recommendations depending on the intended final use of the risk results based on the decision-maker. By considering a real portfolio in Medellin, it tries to illustrate the process that different actors may follow when conducting a seismic risk analysis and how the different assumptions, simplifications, and objectives may produce considerably different results. Sources of uncertainty such as the ground motion spatial correlations, vulnerability and/or fragility curve selection, the tectonic regime of the most relevant events for the site hazard, the consequence modeling and the type of portfolio, among others, are examined and the results of each one presented and compared with each other.

2. Methodology

The main idea of this study was to conduct different analyses resembling the process that a practitioner, with only accessibility to open-data software and databases, could follow. This could be the case of government officials or workers of disaster risk management offices, local insurance companies starting with the catastrophe risk business and practitioners that know about the subject but do not own the tools or resources to perform more detailed analyses. In this sense, open-source global and regional hazard, vulnerability and risk databases are the principal sources of information that can be consulted and used when performing seismic risk analyses.

To explore the different assumptions in the seismic risk modeling process two portfolios in Medellin, considering the hospital buildings in the city, are considered. The portfolios try to illustrate the cases of 1) a business owner (concentrated heterogeneous portfolio, such as the Medellin Clinic) and 2) the local health secretariat (whole portfolio of the city's hospitals). The location of the different buildings of the portfolio is presented in Fig 1, differentiating the location of the buildings that will be considered in the heterogeneous concentrated portfolio case (in green).

The portfolios were classified into four structural typologies representative of hospital buildings in Medellin: Low-rise reinforced concrete buildings (2-storeys), Mid-rise reinforced concrete buildings (5-storeys), High-rise reinforced concrete buildings (>8 storeys) and Low-rise confined masonry buildings (Fig 2). The SARA project hazard model for Colombia was used in the analysis, as it is until the moment the only fully publicly available model for the country. However, it must be said that, in order to be able to consider the correlation in the ground motions, some adjustments in the GMPE models were necessary, to allow this parameter to be computed. No analysis was made concerning the epistemic uncertainties of the hazard model. The main assumptions and sources of uncertainty that were considered and treated in the present study are illustrated in Table 1 and described in the following sections.

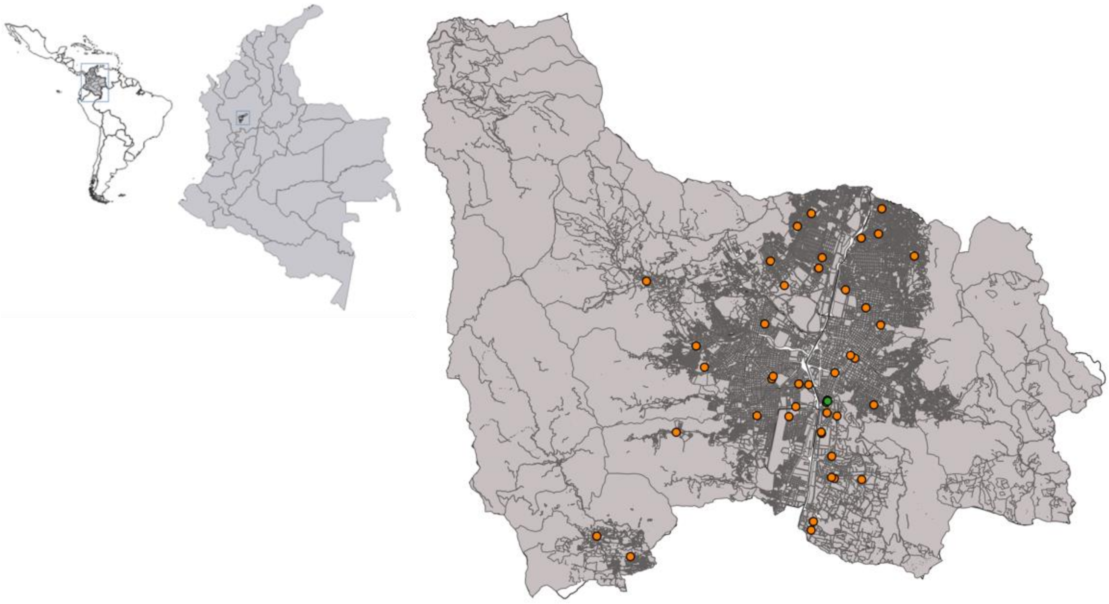


Fig. 1 – Localization of hospital portfolios of the case study in Medellín.

Fig. 2 – Structural typologies representative of the hospital buildings stock in Medellin.

Table 1 – Sources of uncertainty and possible assumptions in the risk modeling process analyzed.

Spatial Correlation	*Vulnerability/Fragility Selection*	*Tectonic Regime*	*Damage-to-loss model*
No correlation	From global database	Indifferent	SARA/GEM model
Jayaram & Baker	From regional database	Active Shallow	Hazus model
	Locally derived	Subduction	Bal et. Al [22]

The OpenQuake engine [13] was used to conduct the analyses reported in the following sections. In order to achieve convergence in the event-based risk analysis, a time frame of 100,000 years was assumed, after a sensitivity analysis over this variable was carried out as established in [4]. It is important to mention that for this specific publication, soil conditions and amplification factors were not included, even when it is well known their contribution in real site-specific applications and how crucial they are in the loss modeling process. For the different analyses, a response on rock (Soil type B) was assumed for the whole city.

In the following sections, a thorough description of the different assumptions is presented, with a brief summary of previous findings and recommendations of authors who have worked in each of the topics.

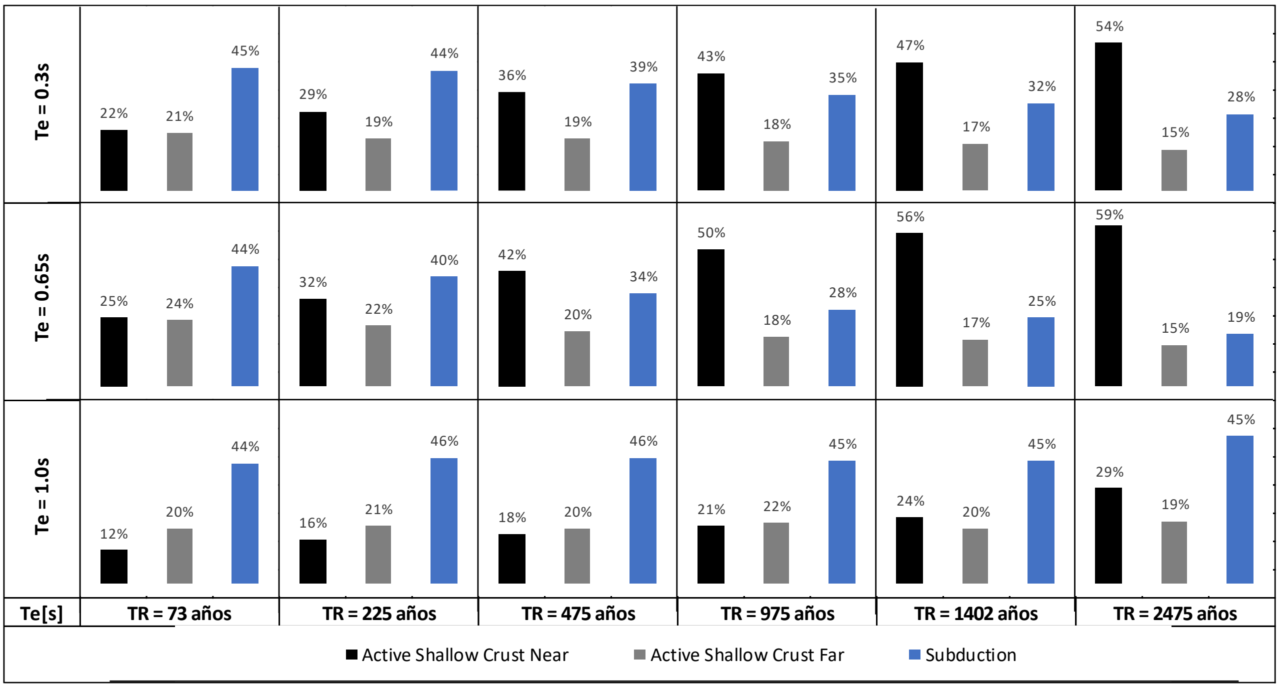
2.1 Ground motion spatial correlation

Modeling the spatial correlation of ground motion residuals, caused by contributions from source, path, and site, can provide valuable loss and hazard information, as well as a more realistic depiction of ground motion intensities [14]. Indeed, in terms of risk assessment of a portfolio of buildings, the accurate prediction of ground motion intensities at multiple sites is required especially when the sites are close to one another, because the wrong estimation of them could lead to an overestimation or underestimation of the final losses [15]. In this study, a spatial correlation of the intra-event variability was considered using the model of Jayaram and Baker [15] available in the OpenQuake Engine, to ensure that assets located close to each other will have similar ground motion levels. However, it should be mentioned that the impact of considering this spatial cross-correlation is limited or even negligible when the building portfolio is homogeneous or when it covers a large region [16].

2.2 Tectonic regime

In the past, it has been highlighted that failing to consider the characteristic properties of subduction events can very well lead to an underestimation of the seismic risk in regions where subduction sources represent a significant contribution in the expected seismic hazard. For this reason, a source contribution analysis was carried out for this study, for the three structural periods and six different return periods (Table 2).

Table 2 – Seismic-source contribution for different structural periods and return periods in Medellin.



Te[s]	TR = 73 años	TR = 225 años	TR = 475 años	TR = 975 años	TR = 1402 años	TR = 2475 años
Te = 0.3s	22% 21% 45%	29% 19% 44%	36% 19% 39%	43% 18% 35%	47% 17% 32%	54% 15% 28%
Te = 0.65s	25% 24% 44%	32% 22% 40%	42% 20% 34%	50% 18% 28%	56% 17% 25%	59% 15% 19%
Te = 1.0s	12% 20% 44%	16% 21% 46%	18% 20% 46%	21% 22% 45%	24% 20% 45%	29% 19% 45%

■ Active Shallow Crust Near ■ Active Shallow Crust Far ■ Subduction

According to the seismic hazard model and the site of analysis, two different tectonic regimes were considered: active shallow crust and subduction. It is important to note the considerable contribution of the subduction sources for the site under study for short return periods and for structures with long structural periods, as well as the differentiated contribution to hazard from near and far shallow crust sources.

2.3 Vulnerability/Fragility Selection & derivation

Fragility curves constitute one of the key elements of seismic risk assessment and at the same time an important source of uncertainty in the risk modeling process. Three primary sources of uncertainty are usually considered, 1) the definition of damage states, 2) the capacity of the element and 3) the earthquake input motion [2]. For the present study, only the third source would be analyzed and reported.

As previously stated, the open-source global and regional databases were the principal sources of information for the fragility curve selection. Three different groups of fragility functions were considered: those from the Global Earthquake Model database (global), those derived in the SARA project (regional) and three others which were derived specifically for this study (local). A brief description of the selected fragilities and their derivation methodologies is presented in the following sections.

2.3.1. Global Database: GEM Global – Active Shallow Crust and Subduction sets

The fragilities from the Global Earthquake Model [17] published in 2018, which were derived following the procedure reported in [18], were consulted. These are hosted at the GitHub repository (https://github.com/lmartins88/global_fragility_models.git). Considering the portfolio that is being studied, only typologies with high ductility were considered. For reinforced concrete (RC), infilled frames were chosen. The selected fragility curves from the database are 1) Low-rise RC buildings - frag_CR_LFINF-DUH_H2, 2) Mid-rise RC buildings - frag_CR_LFINF-DUH_H5, 3) High-rise RC buildings - frag_CR_LFINF-DUH_H8 and 4) Low-rise MCF buildings - frag_MCF_LWAL-DUH_H2.

2.3.2. Regional Database: SARA Project Database

In the case of the regional database, the curves derived for the SARA project following [12] were considered. The same typologies as in the preceding case were selected. It is important to note that, of all cases, SARA is the only database that does not differentiate the tectonic regime for the derivation of the fragility curves.

2.3.3. Derivation of local fragilities using NLTHA on SDOF

For the derivation of local fragility curves the Nonlinear time history analysis (NLTHA) on Single Degree of Freedom (SDOF) systems methodology used for the global model fragility derivation was followed, using the RMTK tool from the OpenQuake platform; a process that considers both building-to-building and record-to-record variability. With this procedure, the main objective was to study the impact of using site hazard-consistent ground motion selection in fragility curve derivation, as it represents one of the major sources of uncertainty in a seismic risk assessment. The same capacity curves used to derive the fragilities for the global earthquake model database [18] were used as inputs for the procedure. Other variables that were kept as in the global model include the damage model, the hysteretic behavior model, and the damping ratios.

For the record selection, considering the disaggregation analysis presented in [18] for Medellín, the mean hazard disaggregation parameters for the three structural periods of the structures (0.3s, 0.65s, and 1.0s) were computed for several return periods. Afterwards, following the procedure for ground motion selection explained in the previously mentioned study, which considers the conditional mean spectrum methodology proposed by [20], incorporating target mean and variance; and the [21] record selection routine, 25 different records for each IM were selected and scaled. Considering there were 15 different return periods ranging from 73 to 100,000 years, 375 pairs of ground motions records were properly selected, scaled and used in each NLTHA.

The comparison of some of the fragility models (global, regional and locally derived) is depicted in Fig. 3 and Fig. 4. Significant variability in the results for the different models can be seen for almost all limit states. However, it is worth noting that for structures with long periods (RC_H5 and H8), the derived curves show no significant differences between them, even when considering different tectonic regimes. For confined masonry, however, a great variability among curves for the same tectonic regime was obtained.

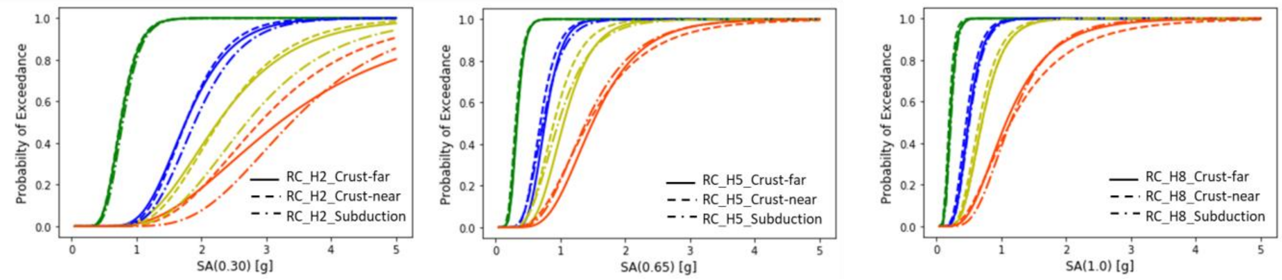


Fig. 3 – Fragility comparison among derived curves for RC_H2 (left) RC_H5 (center) and RC_H8 (right)

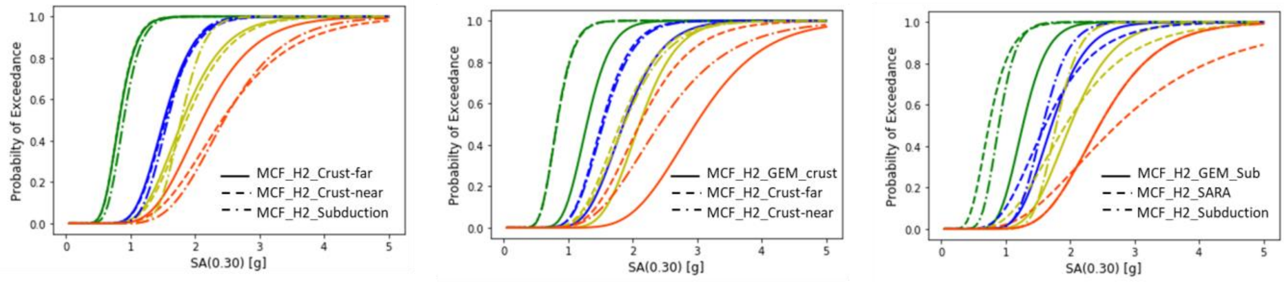


Fig. 4 – Fragility comparison for the confined masonry typology MCF_H2 among locally derived curves (left); shallow-crustal curves (center) and subduction curves (right).

2.4 Consequence Model

As stated in [8] the definition of the relationship between damage and loss is one of the highest sources of uncertainty within an analytical vulnerability assessment. In the mentioned study, several consequence models from the literature regarding RC buildings were compared with their own derived model, evidencing the high variability that can be found even for a specific building typology. As commented upon in [5] this is an area of research that has not been given enough attention and should be studied more deeply. Some of the aspects for future enhancement include the need for better recollection and consolidation of real damage data after seismic events, the importance of the compatibility between the damage model and the consequence model and the need for calibration of the models and results for specific locations.

However, even though the previous points present important areas that need further work, there is an interesting option that has not been fully considered: that of having the opportunity to include the decision-maker or final user as a participant of the risk modeling process, by using consequence models that represent the risk appetite, preferences or objectives of the final decision-maker. The first approach for this could be seen in the model developed by [22], where a loss ratio for extensive damage of 1.04 is assumed, to account for demolition, removal of debris and reconstruction of the structure. This based on law requirements in Turkey that establish that after an earthquake, only moderately damaged buildings are retrofitted, extensively and completely damaged buildings are demolished, and slightly damaged buildings are repaired.

In order to show the potential of this proposal, the objectives of 3 different stakeholders or decision-makers were included in the derivation of consequence models, being careful to ensure the compatibility of the assumed consequence model and the damage model used for the derivation of the fragility curves. The cases of 1) a risk-averse business owner who knows that after a moderate damage state he/she would need to replace the structure; 2) the insurance company that needs to calculate the premiums of its clients; and 3) the local government who wants to acquire a financial protection solution. The consequence models reported in [22], [23] and [24] are used respectively for each of the chosen decision-makers. The different consequence models are shown in Fig 5 and the comparison of the vulnerabilities using different consequence models for the confined masonry structural typology of the study is presented in Fig. 6.

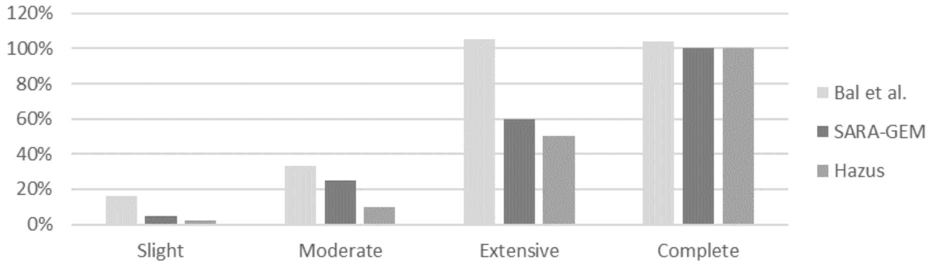


Fig. 5 – Consequence models used for risk analyses: Bal et al. [22], SARA-GEM [23] and Hazus [24]

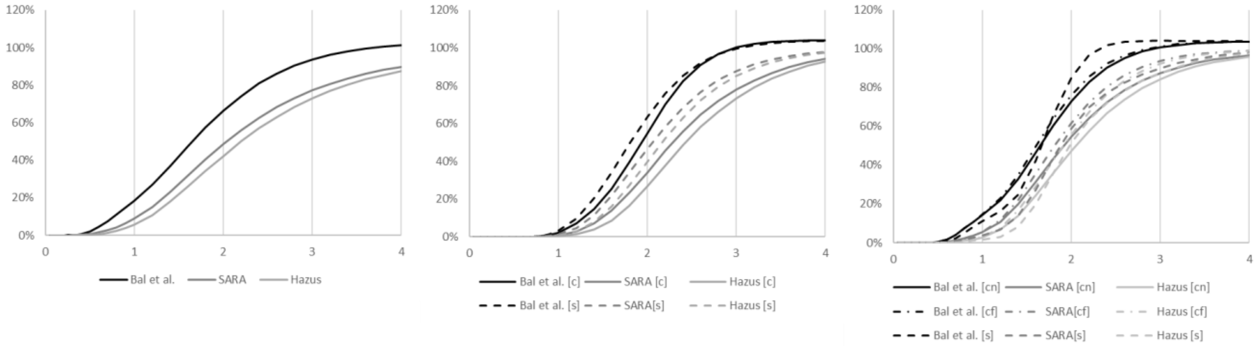


Fig. 6 –Vulnerability curve comparison considering different consequence models for typology MCF_H2 for regional (left); global (center) and local (right). [cx] = shallow crust (x=n: near; x=f: far) & [s] = subduction.

3. Results

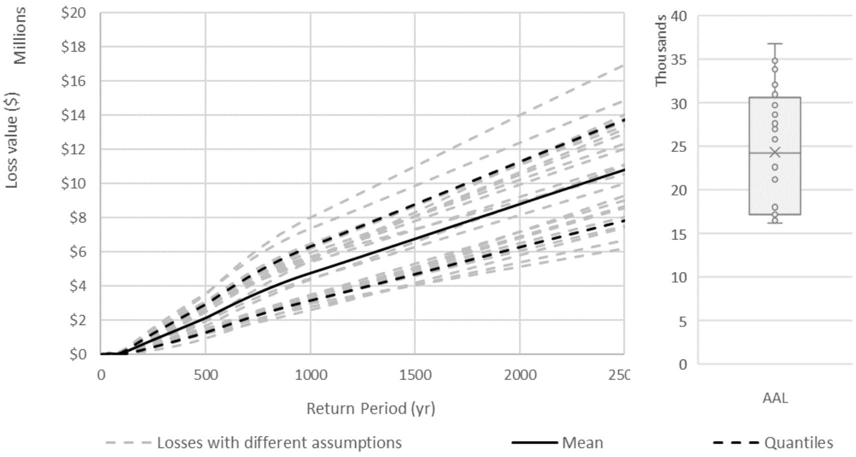


Fig. 7 – Dispersion in loss results with different assumptions for PML (left) and AAL (right) [US dollars]

Fig 7 depicts the complete picture of the results that were obtained from all the models that were used in this study. As it can be seen, there is a considerable variability in the results, with maximum values doubling minimum values for the case of the Average Annual Loss (AAL) and reporting loss ranges of US$ 10 million (3% of total portfolio) for a 2475 return period and of 5 US$ million (1.5% of total portfolio) for a 1000 return period for the Probable Maximum Loss (PML) curves. To illustrate the possible causes for this, analyses considering the different uncertainties mentioned in Table 1 were carried out.

Regarding the influence of spatial correlation, differences of 5 to 10% were obtained for the mean AAL for the analysis when considering and not considering spatial correlation for the cases using GEM and Hazus consequence models respectively, for the whole portfolio. PML reported similar behaviors. Finally, no significant difference was obtained for the mean and variability of the relative loss comparing the total and concentrated portfolio, meaning their behavior is the same when analyzing spatial correlation (Fig 8).

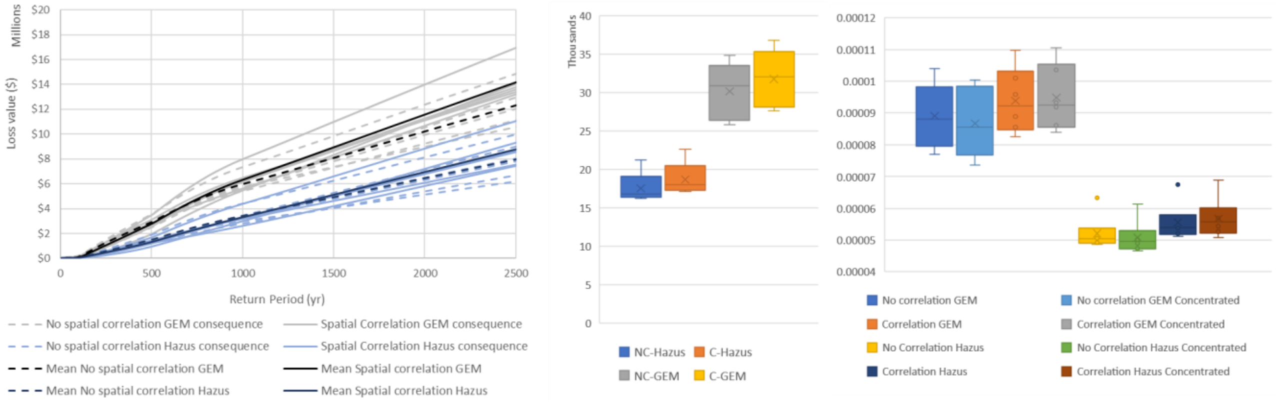


Fig. 8 – Effects of including or not spatial correlation for PML (left) and AAL (center) for the entire portfolio of hospitals and comparison with concentrated portfolio (right). [US dollars]

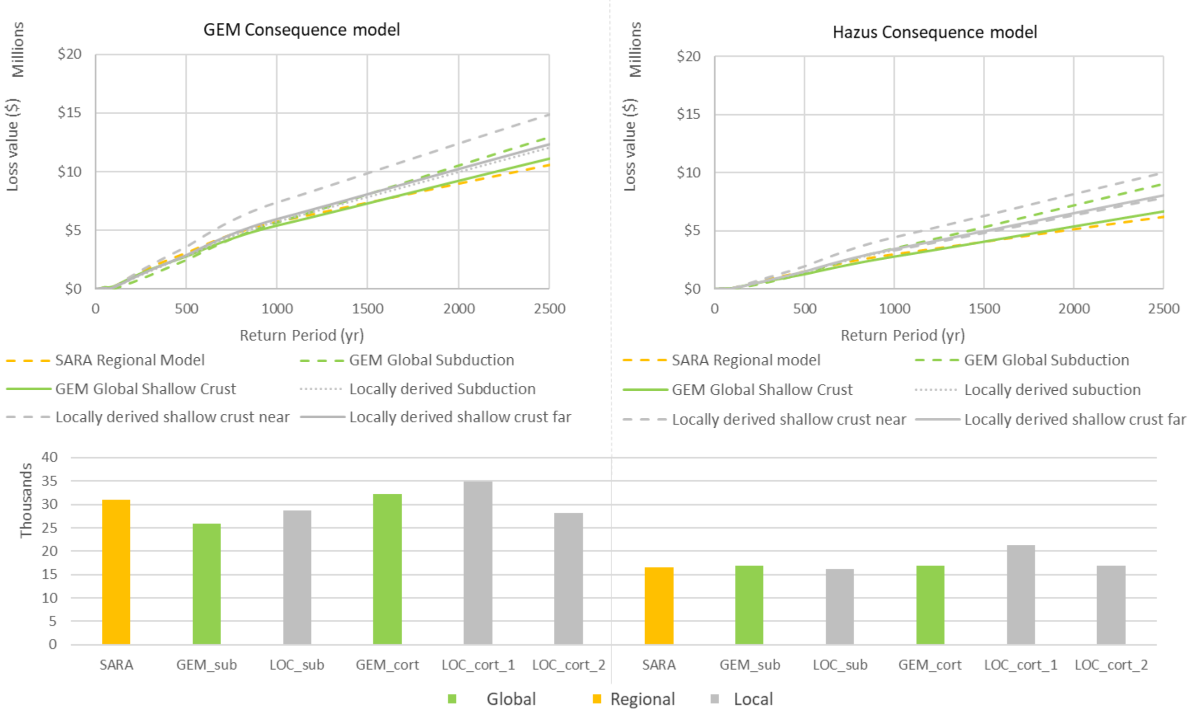


Fig. 9 – PML (top) and AAL (bottom) results for different types of fragilities (global, regional, local), differentiated by consequence model [US dollars]

In reference to the selection of fragility models, significant differences can be appreciated in the PML results, both for the models obtained using the GEM and Hazus consequence models (Fig 9). The losses using the three locally derived curves present the highest values for almost all return periods, while the use of SARA fragilities presents the lower bound for the losses in the portfolio. In this sense, the use of the regional model will most probably underestimate the PML for the portfolio. On the other hand, for the AAL, even when the differences are not as significant, it can be said that the derivation of local fragility curves considering the hazard of the region does give larger losses than using regional or global models.

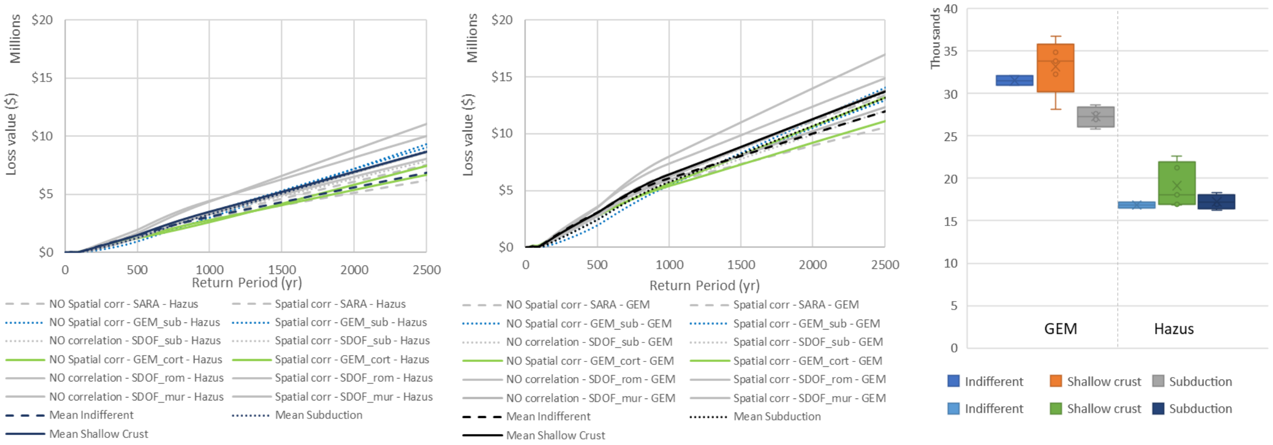


Fig. 10 – Effects of selecting GM's for specific tectonic regimes in the PML and AAL results [US dollars]

Now, considering the effect of the tectonic regime, it is important to notice the behavior reported for the AAL (Fig 10), where a large variability can be seen in the results obtained considering different shallow crust models, evidencing that taking into account near or far shallow crust sources in the record selection does condition the obtained results, with the fragility considering the near crust source giving significantly larger results than those of the global and regional models. It is also extremely important to note how the consideration of one or another consequence model present considerably different results regarding the AAL for each tectonic regime; in the Hazus case, the lower values for almost all tectonic regimes are the same, while for the GEM model the subduction regime results are considerably lower than the others.

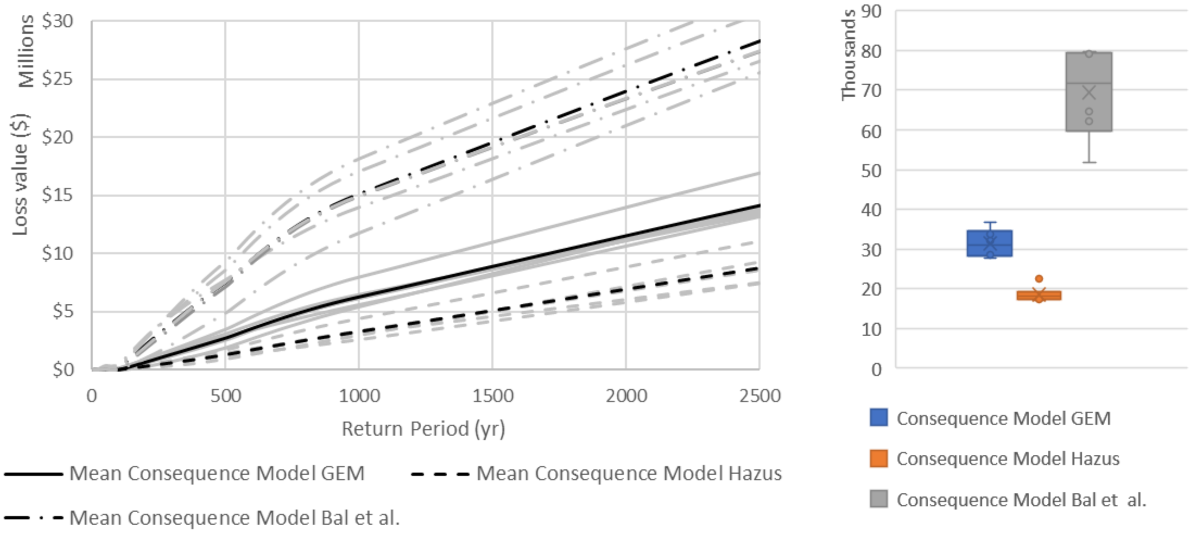


Fig. 11 – Effects of using different consequence models (for cases with spatial correlation). [US dollars]

Finally, it is worth to mention the significant differences that can be obtained when different consequence models are used (Fig 11). From all the studied variables, this is the one generating the highest variability in the results, which makes it an important source of model uncertainty, more so considering that till today it is extremely difficult to evaluate and calibrate this data realistically for every location. From the results, for both the AAL and the PML values, the ones using Bal et al. model almost double the results obtained using the GEM model, and this last one gives losses 1.5 times higher than those reported using Hazus. Even with these important differences between the results, the possibility of including the decision-maker point of view and decisions regarding the way of treating the different damages in the building should make it easier to choose one model over the other. Further research should be conducted to analyze this proposal, being cautious with the compatibility with the fragility damage model.

4. Analysis of results

Based on the previous results, it was possible to see the great differences in the outcomes that can be obtained when running seismic analysis considering different assumptions, uncertainties, and inputs. This is a very good reason to start communicating the assumptions and their related uncertainties to the final user, in order to avoid constraining or conditioning the decision-maker's choices.

Now, considering the decision-maker, the risk appetite and objective of the analysis are basic in the definition of inputs and assumptions in seismic risk analyses. Even for a similar objective (the definition of insurance premiums, deductibles costs, concentration risk, etc.), two different stakeholders may have totally different risk aversion levels and thus the results may vary as much as the ones presented in Fig 11. However, this is not seen as a bad thing, if the assumptions are discussed and shared with the end-user and the uncertainties are well treated and propagated throughout the whole analysis. As previously noted, the knowledge of the decision-maker about the consequence model used into the calculations is crucial in the reliability of the outcomes, especially if the goal of the analysis is clear; even more, if there is a known history of previous events in the area of study that could complement the models employed.

It is also worth mentioning that a lot of simplifications were made in different analyses, to illustrate what is being done by regular practitioners in many places in the world. Based on this, one may advise that a more thorough analysis should be mandatory as the scale of the analysis is reduced, because the simplification may very well be overestimating or underestimating the risk, depending on the case. However, it will also depend on the amount of time and resources that would be needed to improve the risk analyses. An optimal point should be investigated regarding the effectiveness and efficiency of doing a more thorough analysis, by doing sensitivity analyses over the results, in order to establish if it is worthy. With that being said, including hazard consistent records and structural variabilities (based on specific characteristics of the materials, construction practices and others of the specific zone) is considered extremely important in the modeling and the derivation of fragility curves for site-specific risk analysis.

5. Conclusions and future developments

Seismic risk analyses still pose great challenges for the risk modeler as many sources of uncertainty and variability should be identified, propagated and effectively communicated to the end-users. For those reasons, the delimitation of the scope or objective of the analyses is of great importance, as they will define the assumptions that can be made and the possible uncertainties that can be present in the risk analysis to be completed.

As it could be seen from the performed analyses, great variability was obtained based on the different assumptions taken throughout the whole risk modeling process, even when there was no consideration of uncertainty on the hazard component. The inclusion of different models or inputs, through the use of logic trees and others, may very well increase the variability in the results; however, as mentioned in many studies, this is an important future development to be included not only in the hazard component but in the vulnerability and exposure analyses too in order to account for the epistemic uncertainty in every stage.

Regarding other developments that should be considered on site-specific risk analysis, the inclusion of spatial correlation in the different GMPE models already available is basic, given it could be of importance in analyses for cities, localized sites or concentrated portfolios. In addition, future developments into the OQ Engine were identified due to the necessity to include the site effects in the analyses, not just from the GMPEs point of view but also from amplification factors obtained from the local soil conditions.

The calibration of capacity curves based on the specific building practices in the different regions should be developed and investigated to a greater extent, to improve risk results. For this, the use of structural monitoring, among other strategies, could be extremely beneficial to help characterize the local portfolios in a better way. For this particular case study, the derivation of capacity curves based on pushover analysis for representative local buildings will be looked into and compared with the earlier reported results.

On the other hand, considering the fragility derivation and based on the observed differences in results for different tectonic regimes, the need to develop local fragility and vulnerability models based on the site-specific hazard and ground motion selection and scaling is evident. These should consider different tectonic regimes and magnitude, distance, epsilon (M,R,ε) distributions from seismic hazard disaggregation for the specific sites. However, these analyses should not be made only for different tectonic regimes. There is also a need to differentiate even more the development of groups of fragility functions for crustal environments, as far-field and near-field events pose great differences in the derived curves and expected risk results.

Additionally, the need to have a thorough evaluation of real damage in structures after earthquakes, not only for collapsed buildings, in order to calibrate the damage state threshold criteria and the consequence modeling, is vital. Nevertheless, even nowadays, this type of analysis is limited and complex, and thus the use of consequence models that consider the end-user risk perception could be used as an alternative approach.

Finally, the active participation of the decision-maker in the risk assessment is a crucial point that needs to be stressed out, as it will lead to outcomes that agree with the risk perception of the stakeholders and final users. However, as of today, more collaborations between the different actors involved in the seismic risk evaluations should be promoted and several efforts must be done from different sectors to provide the tools and information needed to achieve more reliable results.

6. Copyrights

7. References

[1] Erto, P., Giorgio, M., & Iervolino, I. (2016). About knowledge and responsibility in probabilistic seismic risk management. Seismological Research Letters, 87(5), 1161-1166.

[2] Pitilakis, K. (2015). Earthquake risk assessment: certitudes, fallacies, uncertainties and the quest for soundness. In Perspectives on European earthquake engineering and seismology (pp. 59-95). Springer, Cham.

[3] Crowley, H., Colombi, M., & Silva, V. (2014). Epistemic uncertainty in fragility functions for European RC buildings. In SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk (pp. 95-109). Springer, Dordrecht.

[4] Silva, V. (2018). Critical issues on probabilistic earthquake loss assessment. Journal of Earthquake Engineering, 22(9), 1683-1709.

[5] Silva, V., Akkar, S., Baker, J., Bazzurro, P., Castro, J. M., Crowley, H.,...& Perrone, D. (2019). Current Challenges and Future Trends in Analytical Fragility and Vulnerability Modeling. Earthquake Spectra, 35(4), 1927-1952.

[6] Bazzurro, P., & Luco, N. (2007). Effects of different sources of uncertainty and correlation on earthquake-generated losses. Australian Journal of Civil Engineering, 4(1), 1-14.

[7] DeBock, D. J., & Liel, A. B. (2015). A comparative evaluation of probabilistic regional seismic loss assessment methods using scenario case studies. Journal of Earthquake Engineering, 19(6), 905-937.

[8] Martins, L., Silva, V., Marques, M., Crowley, H., & Delgado, R. (2016). Development and assessment of damage ‐ to ‐ loss models for moment ‐ frame reinforced concrete buildings. Earthquake Engineering & Structural Dynamics, 45(5), 797-817.

[9] Riga, E., Karatzetzou, A., Mara, A., & Pitilakis, K. (2017). Studying the uncertainties in the seismic risk assessment at urban scale applying the Capacity Spectrum Method: The case of Thessaloniki. Soil dynamics and earthquake engineering, 92, 9-24.

[10] Sousa, L., Silva, V., Marques, M., & Crowley, H. (2018). On the treatment of uncertainty in seismic vulnerability and portfolio risk assessment. Earthquake Engineering & Structural Dynamics, 47(1), 87-104.

[11] Silva, V. (2019). Uncertainty and correlation in seismic vulnerability functions of building classes. Earthquake Spectra, 35(4), 1515-1539.

[12] Villar-Vega, M., Silva, V., Crowley, H., Yepes, C., Tarque, N., Acevedo, A. B., ... & María, H. S. (2017). Development of a fragility model for the residential building stock in South America. Earthquake Spectra, 33(2), 581-604.

[13] Silva, V., Crowley, H., Pagani, M., Monelli, D., & Pinho, R. (2014). Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment. Natural Hazards, 72(3), 1409-1427.

[14] Verros, S. A., Wald, D. J., Worden, C. B., Hearne, M., & Ganesh, M. (2017). Computing spatial correlation of ground motion intensities for ShakeMap. Computers & Geosciences, 99, 145-154.

[15] Jayaram, N., & Baker, J. W. (2009). Correlation model for spatially distributed ground-motion intensities. Earthquake Engineering & Structural Dynamics, 38(15), 1687-1708.

[16] Weatherill, G. A., Silva, V., Crowley, H., & Bazzurro, P. (2015). Exploring the impact of spatial correlations and uncertainties for portfolio analysis in probabilistic seismic loss estimation. Bulletin of Earthquake Engineering, 13(4), 957-981.

[17] Silva, V., Amo-Oduro, D., Calderon, A., Costa, C., Dabbeek, J., Despotaki, V., ... & Viganò, D. (2020). Development of a global seismic risk model. Earthquake Spectra, 8755293019899953.

[18] Martins, L., & Silva, V. (2018, June). A global database of vulnerability models for seismic risk assessment. In the 16th European conference on earthquake engineering. Thessaloniki, Greece.

[19] Pérez, H. Hernández, A. Hoyos, M. Vides, R. (2020) Reduction in collapse safety of building structures located in epicentral areas in Colombia. World Conference of Earthquake Engineering.

[20] Baker, J. W. (2011). Conditional mean spectrum: Tool for ground-motion selection. Journal of Structural Engineering, 137(3), 322-331.

[21] Baker, J. W., & Lee, C. (2018). An improved algorithm for selecting ground motions to match a conditional spectrum. Journal of Earthquake Engineering, 22(4), 708-723.

[22] Bal, İ. E., Crowley, H., Pinho, R., & Gülay, F. G. (2008). Detailed assessment of structural characteristics of Turkish RC building stock for loss assessment models. Soil Dynamics and Earthquake Engineering, 28(10-11), 914-932.

[23] Yepes-Estrada, C., & Silva, V. (2017). Probabilistic seismic risk assessment of the residential building stock in South America. Paper No. 2050. In Proceeding of the 16th World Conference on Earthquake Engineering (pp.9-13).

[24] FEMA. HAZUS-MH MR5, technical manual, Department of Homeland Security—Federal Emergency Management Agency, 2014.