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VALIDATING PROBABILISTIC EARTHQUAKE RISK MODELS: TESTS THAT TELL YOU IF YOU'RE WRONG, BUT NOT IF YOU'RE RIGHT

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Extended Abstract

Probabilistic earthquake risk models have a multitude of applications, ranging from the identification of regions where risk reduction measures are required, to the development of financial mechanisms to transfer the risk from the public sector to the international market of reinsurance. The recent release of the Global Risk Model (Silva et al. 2019) by the Global Earthquake Model (GEM) Foundation and its partners offers a unique opportunity to further evaluate relevant risk metrics (e.g. average annualised losses, probable maximum losses), and consequently improve the existing global model. The assessment of probabilistic seismic hazard and risk is characterized by large epistemic and aleatory uncertainties, which introduce a strong variability in the resulting losses. Thus, it is fundamental to verify, validate and calibrate the different components of the seismic risk model to increase its reliability and accuracy. However, this validation process is extremely challenging due to lack of data and the dynamic nature of earthquake risk.

On the probabilistic seismic hazard assessment component, there are a number of tests that are frequently explored to verify the reliability and (to some extent) the accuracy of the model. These include the verification of the seismicity generated by the seismogenic model against instrumental earthquake catalogues, evaluation of thousands of past macroseismic observations or ground motion recordings to empirically compute hazard exceedance curves, the systematic comparison between various seismic hazard models (Pagani et al. 2016), and the verification of the applicability of ground motion prediction equations through the use of strong motion databases. Despite the critical importance in verifying and validating the seismic hazard component, it is not sufficient to guarantee that the associated earthquake losses will be reliable and realistic.

Damage and loss databases are usually less reliable for destructive events that happened more than four decades ago, and even when some data exist, factors like population growth, inflation, enforcement of design regulations or political unrest might have caused drastic transformations in the built environment. It is thus necessary to perform a multitude of tests to verify the reliability and accuracy of the exposure and vulnerability components of probabilistic risk models. In general, these verifications represent sanity checks that identify weaknesses in the model, but might not sufficiently prove the accuracy of any particular component. Throughout the development of the GEM global seismic risk model, various components were subjected to verification and validation exercises. As a first step, the various components were shared with experts from dozens of countries, who provided comments and suggestions through web-surveys, technical meetings and workshops. Some of the locations where these events took place include Addis Ababa, Pavia, Bishkek, Gandhinagar, Kathmandu, Lima, Medellin, Vancouver, Golden, San Jose, Santo Domingo and Porto. These meetings and reviews usually allowed the identification of building classes that were missing in the exposure model, the adjustment of the replacement costs (usually according to the development pattern: rural, urban and large cities) and a critical review of the fragility and vulnerability functions (in particular if some vulnerability classes seem to be too conservative or optimistic).

The fragility and vulnerability functions were tested using damage and loss data from 123 past events between 1980 and 2017. In this process, USGS *ShakeMaps* were used with the global exposure dataset and the global fragility and vulnerability functions to estimate the

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number of collapsed buildings and direct economic losses, respectively. The framework employed for these calculations is described in Silva and Horspool (2019). A comparison between the estimated and observed losses (adjusted to 2017) is depicted in Figure 1.

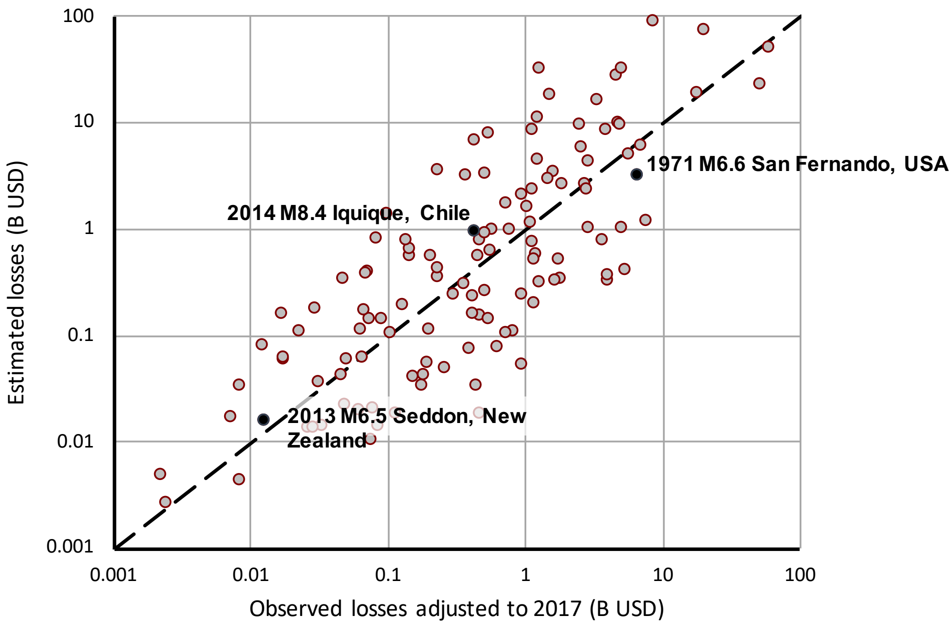

Figure 1. Comparison between estimated and observed losses for 123 past events.

Although a fair agreement between the estimated and observed losses was obtained (with limited bias), there is clearly a large dispersion in the results. Reasons for this variability are thoroughly explained in Villar and Silva (2017) and Silva et al. (2019), and can be summarized as:

- The exposure dataset used for the estimation of the damage or loss is most likely different from what actually existed at the time of the event. These discrepancies could be due to the use of housing census or cadastral data that have been collected after the event (and thus it accounts for the buildings that have been replaced or repaired/retrofitted), or many years before the event (and thus it does not contain all of the infrastructure that has been built afterwards).
- The datasets which are used to develop the exposure component are frequently incomplete, flawed and are not fit-for-purpose. Some of these datasets include locally collected data, housing census surveys, technical reports and cadastral datasets, which often do not have information such as the year of construction or the lateral load resisting system. Consequently, the assignment of the vulnerability classes will be biased and affected by epistemic uncertainty.
- The damage and loss surveys performed after the occurrence of earthquakes are, unfortunately, affected by a strong subjectivity. The lack of training and experience of the surveyors can affect the final counting, as well as the allocation of each building into a damage state. The collapses occurring in remote areas might not be taken into account, and the loss claims tend to be above the repairing costs if an insurance policy is in place. For some events (e.g. Armenia 1999, Athens 1999), structural collapse, partial collapse or buildings to be demolished have been assigned to specific categories, while in others everything has been deemed as complete damage, despite the fact that the repair costs and likelihood of mortality are significantly different. Finally, it is possible that structures that were damaged in previous seismic events (or even due to other causes besides ground shaking) are accounted as affected buildings.
- Fragility and/or vulnerability models are often not available for all of the building typologies found in a given region. As a consequence, functions developed for other regions (or even other building classes) are applied, which will naturally introduce a

bias in the risk results. Moreover, fragility and vulnerability functions are probabilistic models, which are not meant to provide the *true* damage or loss values, but instead the *expected* (most likely) results, with an associated aleatory uncertainty.
- One of the most reliable sources of ground shaking maps from past events is undoubtedly the USGS *ShakeMap* system. However, its efficiency and accuracy are highly conditioned on the availability of strong motion data from local recording stations. Thus, the lack of instrumentally captured data prevents the reduction of the uncertainty and bias in the shaking input, which can lead to an over- or underestimation of ground motion fields. Another feature that can lead to significant variations between the estimated and the observed ground motion (and consequently in the damage) is the possible occurrence of directivity effects. Without a dense network of seismic stations, the ground shaking will have to be computed using GMPEs, which might not sufficiently incorporate this phenomenon.

In addition to the verification of the performance of the fragility and vulnerability functions against past events, it is also possible to assess their reliability within a probabilistic framework. In this context, the annual probability of moderate and complete damage is calculated for a number of locations around the world, ranging from low (but not negligible) seismic hazard (e.g. Barcelona, Perth) to very high seismic hazard (Oakland, Istanbul). By considering all of the building classes in a single location, it is possible to compare directly the vulnerability between all building classes. This procedure allows identifying vulnerability functions which might be over or under-predicting the expected losses (e.g. a vulnerability function that is leading to an annual collapse probability for ductile concrete that is above the collapse probability for adobe or unreinforced masonry structures). This is obviously a relative (and rather qualitative) comparison, and still does not guarantee that the set of functions are performing adequately. The annual probabilities of moderate and/or complete damage can also be evaluated based on past damage observations. For example, annual probabilities of collapse above 1% are difficult to justify, even if damage databases for relatively small countries with several past events are considered (e.g. Costa Rica, Italy, Ecuador). Likewise, for buildings designed according to modern regulations (e.g. Eurocode 8), annual probabilities of moderate damage should not exceed 10^{-4}, and the probability of collapse should not be greater than 10^{-5} (e.g. Silva et al. 2015). The inverse line of thought can also be explored. Vulnerable building classes such as unreinforced masonry or earthen construction in seismically active regions should not have an annual probability of collapse below 10^{-3}, according to some of the damage observations reported in the global earthquake consequences database (https://platform.openquake.org/ecd). It is important to note that a simple comparison between all functions is also possible through a loss ratio versus intensity measure plot, but the use of different intensity measures (e.g. peak ground acceleration, spectral acceleration at different periods of vibration, average spectral acceleration) often hinders this comparison. Although all of these verifications do not explicitly allow concluding whether a vulnerability/fragility model is adequate, they can support modelers in the identification of the components (e.g. set of ground motion records, damage criterion, definition/calibration of the numerical models) that might need improvement.

The results from the global seismic risk model were also compared with the estimates provided by other initiatives, in particular the UNISDR Global Assessment Report (GAR 2015). The former risk estimates provide average annualized losses and loss exceedance curves for six building occupancies (GAR 2015). A comparison between the aggregated *AAL* covering the residential, commercial and industrial building stocks from GAR and this study is presented in Figure 2.

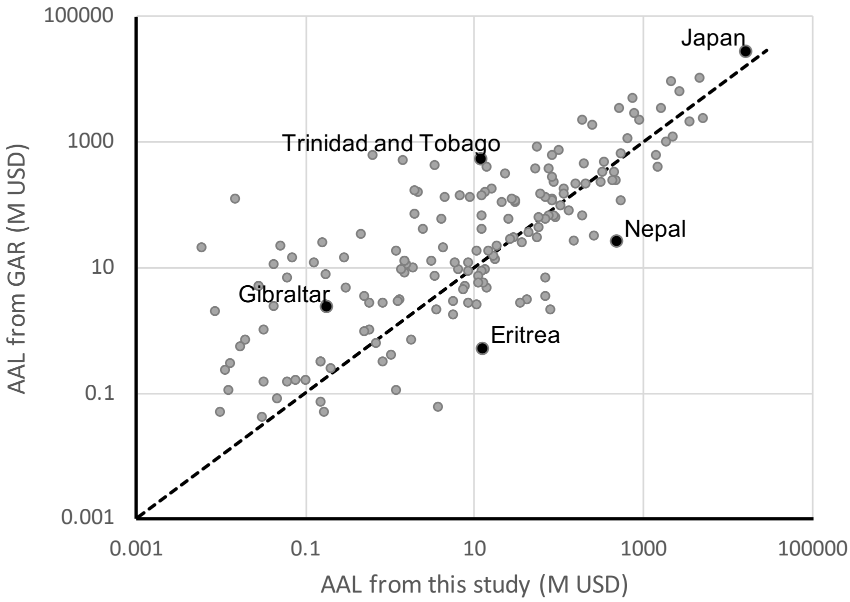

Figure 1. Figure caption here.

Figure 10. Average annual loss ratio (in percentage) for the top 15 countries.

Although there is a general agreement between the *AAL* estimates from both studies, the results from this study are on average below the ones presented by GAR by a factor of 2. At the global scale, GAR indicates an AAL of approximately 100 billion USD, while this study puts that to less than half, at 45 billion USD. The identification of the causes for these discrepancies is a rather complex process since the methodology followed by the GAR was considerably different. Although (with the exception of a few countries) current loss databases do no have sufficient events to empirically derive a national average annual loss, it is fair to assume that at a global scale, an approximate annual loss can be derived. According to the NatCatService of MunichRe (MunichRe 2019), the last four decades of seismic events indicate an average annual loss in the order of 40 billion USD. This value is below the annual loss indicated by GEM or GAR, but it should be noted that not all of the past seismic events have been included in this database. Smaller events that generated limited losses are often not included. However, it should also be noted that GEM and GAR did not consider potential losses due to landslides, liquefaction and tsunamis, while the NatCatService account for these losses. Overall, it does seem like recent efforts to estimate global seismic risk are overestimating the expected earthquake losses.

Concluding remarks

Earthquake risk assessment is fundamental for a number of disaster risk management measures, including the development of financial instruments to transfer risk to the private sector, allocation of funding for the implementation of risk reduction policies, or the development of large-scale retrofitting/strengthening campaigns. The calculation of earthquake risk metrics such as annualized average losses (AAL) or exceedance probability (EP) curves require complex seismic hazard, exposure and vulnerability models. Each one of these components is affected by large aleatory and epistemic uncertainties, which must be constrained. The validation of the input models requires large databases of strong motion recordings, building information and loss/damage data. However, the existing databases (open or proprietary) are far from being statistically sufficient to verify and calibrate all of the components involved in the assessment of probabilistic seismic risk. Moreover, even with the improvement of the geographical coverage and time range of the existing databases, earthquake risk changes rapidly over time due to the increase in the population or the evolution of the building practices, which renders exposure or loss data with more than three decades practically obsolete. This study summarised a number of tests which allow performing sanity checks and identifying which components might benefit from additional improvements. This study also discussed some of the current challenges in verifying and validating existing models. At the global scale, the global seismic risk model of the GEM Foundation is leading to an average annual loss which is comparable with one of the most complete and reliable loss databases, but further investigation is still necessary to validate the seismic risk at the national and subnational scales.

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