Evaluating next-generation and traditional intensity measures in regional seismic risk assessment

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Abstract

Regional seismic risk assessments rely on a ground-motion intensity measure (IM) to link the level of shaking to damage and other consequences. However, a single IM does not necessarily provide the best representation of the seismic response across diverse building typologies within a regional portfolio. This limitation raises questions about the suitability of commonly adopted IMs and the implications of their selection for large-scale loss estimation. This study evaluates the performance of both traditional IMs, such as peak ground acceleration, PGA, and spectral acceleration, $Sa(T)$, and next-generation IMs, including filtered incremental velocity, $FIV3$, and average spectral acceleration, $Sa_{avg}(T)$, in predicting regional earthquake losses. Using the 2009 L'Aquila earthquake as a case study, the aggregated losses and the influence of different intra-IM spatial correlation models are compared. Additionally, the impact of cross-IM ground-motion fields (GMFs) generated through inter-IM spatial correlation models is assessed. The results show that the choice of IM strongly affects aggregated losses and traditional IMs generally have higher variability. Among the examined IMs, $FIV3(T)$ demonstrates the highest efficiency at the building-typology level, with negligible variation in aggregated losses across vibration periods. In contrast, $Sa_{avg}(T)$ exhibits sensitivity to the selected period, leading to wider variability in loss outcomes. The analysis of cross-IM GMFs further reveals notable effects for IMs with strongly period-dependent variability, particularly $Sa_{avg}(T)$. Overall, this study highlights the critical implications of IM selection for regional loss estimation and emphasises the need for careful consideration of spatial correlation models in seismic risk analyses. The findings advance the understanding of how traditional and next-generation IMs perform in portfolio-level assessments and demonstrate the importance of incorporating cross-IM ground-motion modelling when evaluating earthquake-induced losses.

Keywords: regional seismic risk, spatial correlation, ground motion fields, intensity measures

1- INTRODUCTION

Regional seismic risk assessment has become increasingly important because it supports estimates of earthquake impacts not only on single buildings, but on entire building portfolios and interconnected infrastructure systems. Unlike building-by-building studies, regional analyses must account for exposure distribution, uncertainty in structural response, and spatial variability and correlation of ground motions for this reason, the study is framed within the regional performance-based earthquake engineering (RPBEE) approach [1].

A central issue in seismic risk assessment is the choice of intensity measure (IM). Traditional IMs such as peak ground acceleration (PGA) and spectral acceleration at a single period, $Sa(T)$, are widely used, but they may be less efficient or less predictive of structural response and losses. To overcome these limitations, next-generation IMs such as average spectral acceleration $Sa_{avg}(T)$ and filtered incremental velocity $FIV3(T)$ have been proposed. These measures have shown improved efficiency and robustness in previous structural applications (e.g., [2], [3], [4], [5], [6]), but their influence on portfolio-scale loss and collapse estimate has still not been tested. Recent developments in spatial and inter-IM correlation models for next generation IMs (Monteiro et al. [7]) now enable their consistent application in regional-scale analyses, including the generation of cross-IM ground motion fields.

This study investigates how different IM choices affect regional seismic risk estimate for the reinforced concrete (RC) building stock of L'Aquila, Italy, under the 2009 $M_w = 6.3$ earthquake scenario. It compared traditional and next-generation IMs, examined the influence of spatial correlation models, and evaluated whether using one common IMs and cross-IM ground motion fields are preferable.

2- METHODOLOGY

The exposure model was derived from the GEM-based building stock for L'Aquila and restricted to residential RC buildings. The final portfolio includes 2,996 RC infilled-frame buildings, classified by code level, lateral load coefficient, and number of storeys. Only buildings from one to four storeys were considered, since more detailed information for taller buildings was unavailable. For structural modelling, representative 3D non-linear models, were first generated for each taxonomy using the Built Environment Data Framework's SimDesign service and OpenSees (Ozsarac et al., [8]). To reduce computational demand in the regional study, these 3D models were converted into equivalent single-degree-of-freedom (SDOF) systems through modal and pushover analyses. Mean capacity curves were derived by averaging the pushover curves of 100 randomly selected buildings per taxonomy. Based on these models, three period-grouping were adopted: $T = 0.4s$, $T = 0.55s$, and $T = 0.7s$.

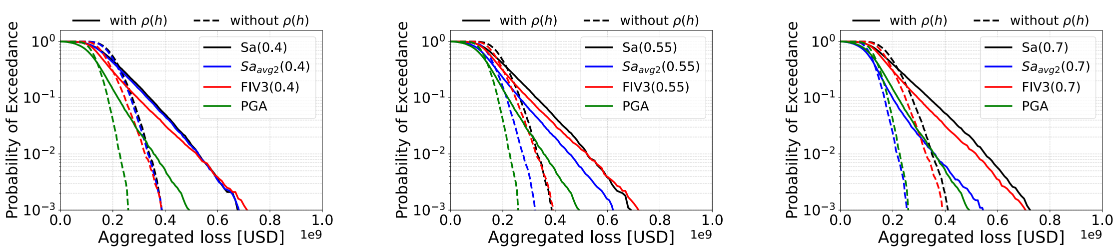
Hazard analysis was carried out using a single-site probabilistic seismic hazard analysis at the geometric centre of the portfolio. Hazard curves were developed for PGA, $Sa(T)$, $Sa_{avg}(T)$, and $FIV3(T)$, over 11 return periods. For each intensity level, 40 hazard-consistent records were selected using a conditional spectrum-based procedure using the Djura ground motion record selector [Shahnazaryan et al., [9]].

Fragility functions were derived specifically for this study using multiple stripe analysis (MSA). Non-linear time-history analyses were performed with hazard-consistent records for each taxonomy and IM. Four damage states were defined suing displacement thresholds linked to yield and ultimate displacements. These fragility functions formed the basis for estimating both repair losses and collapse counts.

Scenario-based assessment was then performed by simulating 10,000 ground motion fields (GMFs) for the 2009 L'Aquila earthquake. Spatial correlation of IMs was included using recent correlation models, specifically for next-generation IMs (e.g., Monteiro et al., [7]). Economic loss was estimated with a fragility-based damage-to-loss approach, in which, for each building and each simulation, a damage state is sampled probabilistically based on the fragility functions evaluated at the corresponding IM level. The realised damage state is then converted into economic loss using predefined damage ratios and replacement costs, and losses are aggregated across all buildings to obtain total portfolio loss. Repeating this process over all simulations yields a distribution of portfolio losses, from which loss exceedance probabilities are derived. In addition to standard intra-IM GMFs, the study also explored cross-IM GMFs to assess portfolios where different building groups are represented by different IMs or periods.

3- RESULTS

The study shows that IM selection can have a notable influence on regional loss estimates. Figure 1 shows that PGA generally produces the lowest predicted repair costs. This was attributed to the combination of its fragility characteristics and the distribution of PGA values in the simulated GMFs, which were concentrated at relatively low intensities where collapse probabilities remain small. By contrast, next-generation IMs, especially $Sa_{avg}(T)$, and $FIV3(T)$, often produce higher losses. Reasons for these difference stem from the specific case study used in addition to the ratio between demand and capacity when comparing the fragility functions and GMF demands.

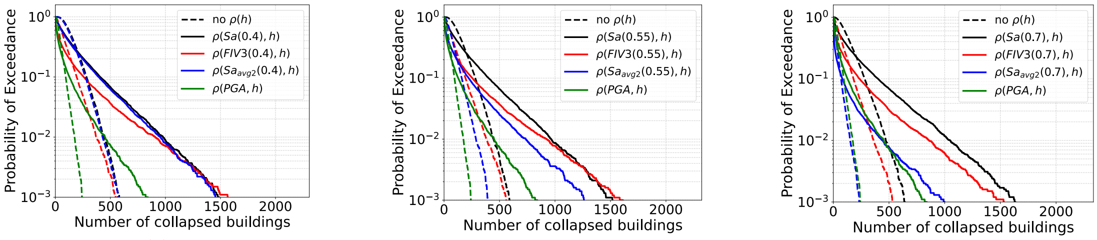


(a) (b) (c)

Figure 1- Comparison of the probability of exceeding a specified repair cost for the L'Aquila (2009) earthquake scenario, $M_w = 6.3$, using different IMs ($PGA, Sa(T)$, $Sa_{avg2}(T)$, and $FIV3(T)$) evaluated at periods (a) T=0.4s, (b) T)=0.55s, and (c) T=0.7s.

Spatial correlation consistently increased aggregated losses compared with analyses that neglected it, because correlated shaking increases the chance of simultaneous damage across multiple buildings. However, when comparing different intra-IM spatial correlation models, the overall portfolio loss curves remained quite similar. This suggests that for this case study, total regional losses are driven more by average site losses than by the specific form of the correlation model, except in cases of very low or absent correlation. The results also showed that fragility functions strongly control loss estimates. Simplified test demonstrated that changes in fragility median and dispersion can shift loss exceedance curves substantially, even when the simulated IM distributions are similar. This confirms the differences between IM-based loss estimated are not due only to hazard or GMF simulation, but also to the calibration and shape of the corresponding fragility functions.

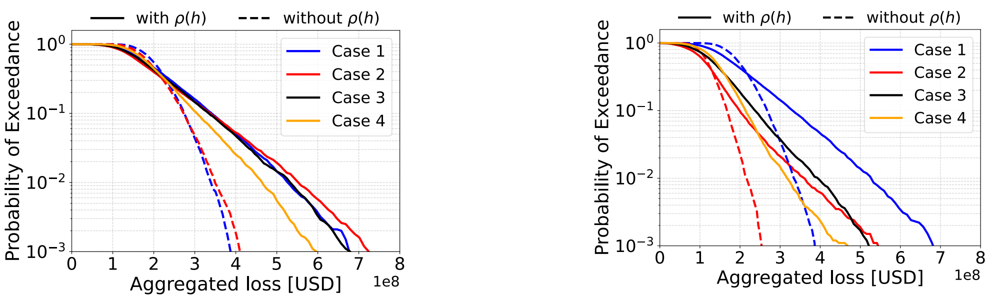
Regarding the sensitivity to the conditional period, $Sa_{avg2}(T)$ showed the largest variation in aggregated loss and collapse predictions across different periods. $FIV3(T)$, on the other hand, exhibited the lower period sensitivity and therefore the greatest robustness for collapse estimation. For collapse prediction, Figure 2 shows a comparison of different IMs in predicting collapse for the three vibration periods evaluated previously. For loss estimation the interpretation was more nuanced: although $Sa_{avg2}(T)$, was less stable overall across periods, it generally shows lower dispersion for lower damage states.



(a) (b) (c)

Figure 2- Comparison of the probability of exceeding a number of collapsed buildings for the L'Aquila (2009) earthquake scenario, Mw=6.3, using different IMs (PGA, $Sa(T)$, $Sa_{avg2}(T)$, and $FIV3(T)$), evaluated at periods (a) T=0.4s, (b)T=0.55s, and (c) T=0.7s.

Cross-IM analyses in Figure 3 show that different modelling approaches, including cross-IM spatial correlation, single period IMs, and aggregating of independent IM losses, produce notable differences for both $Sa(T)$ and $Sa_{avg2}(T)$. For instance, using $Sa_{avg2}(T)$ at $T = 0.4$ yields losses of approximately $\$2 \times 10^8$. Aggregating losses from $T = 0.4$ and $T = 0.7$ increases losses by about 5%, while fully accounting for cross IM spatial correlation increases losses by approximately 25%. Considering only T=0.7 leads to an increase of up to 65%. These results highlight the importance of full cross-IM modelling, which strongly depends on the IM sensitivity to period and portfolio composition, as also noted by Weatherill et al. [8].



(a) (b)

Figure 3- Probability of exceeding a given aggregated loss comparison for several cases for (a) $Sa(T)$ and (b) $Sa_{avg2}(T)$. Case 1 corresponds to T=0.4, Case 2 to T=0.7, Case 3 to cross-IM application, and Case 4 to aggregation of losses from T=0.4, and T=0.7.

4- CONCLUSIONS

The study shows that regional seismic risk estimates can be highly sensitive to the selected intensity measure, the associated fragility functions, and the way ground-motion variability is represented across the portfolio.

The results highlight that no single intensity measure is universally optimal for every purpose, which instead its suitability depends on whether the main objective is to estimate economic losses or collapse outcomes. The main conclusions are:

- The choice of IM has a strong impact on both aggregated repair losses and the predicted number of collapsed buildings, where traditional IMs, especially PGA, tend to predict lower losses and fewer collapses than next-generation IMs.
- The parameters of the fragility functions, particularly their median and dispersion, play a decisive role in shaping aggregated loss estimated.
- Differences among alternative intra-IM spatial correlation models have only a limited effect on total aggregated losses for this case study.
- $Sa_{avg2}(T)$ shows the greatest sensitivity to the selected conditional period, meaning that its loss and collapse predictions vary more across periods, and on the other hand, $FIV3(T)$ is the least sensitive to the period, being this way the most robust IM for collapse estimation.
- Although $Sa_{avg2}(T)$ is less stable across periods, it performs well for loss estimation in this portfolio because losses are dominated by lower damage states, for which this IM shows lower dispersion.
- The relevance of using cross-IM ground motion fields is notable and depends on how sensitive the selected IM is to period and on the composition of the building portfolio. So, for $Sa_{avg2}(T)$, it is more important showing considerable differences using cross-IM or aggregated loss approach.

Overall, the results support the use of next-generation IMs in regional seismic risk assessment, while also showing that the most appropriate IM should be selected according to the final assessment objective.

5- Acknowledgements

The ground motion record selections described here were performed using an academic licence of the Djura online ground motion record selector (www.djura.it).

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