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A Sensitivity Analysis Framework to Quantify the Impact of Modelling Assumptions on Regional Seismic Risk Outputs

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ABSTRACT

Seismic risk modelling can be a powerful tool for decision-making as it provides an objective understanding of seismic risk in a region. Seismic risk modelling outputs such as casualties, building damage, population displacement, or building recovery time can inform actionable seismic policy development. For instance, the City of Vancouver is leveraging these metrics to quantify the potential risk reduction of various policy interventions and generate an objective policy basis. Nevertheless, these regional risk assessments require numerous assumptions and simplifications. Currently, the impact of these modelling assumptions on regional seismic risk outputs is not well understood. To address this knowledge gap, this study proposes a framework to quantify the impact of key modelling assumptions on regional seismic risk outputs using the City of Vancouver as a case study. While the sensitivity analysis groups risk modelling assumptions categorically into hazard, exposure and fragility, this paper focuses exclusively on the fragility component of the risk calculation and explores the resulting variability of risk outputs and the risk reduction potential of different policy interventions. The results of this analysis serve to identify the significance of key modelling assumptions to ensure a robust depiction of potential risk reduction is used when creating seismic policy options.

Keywords: Sensitivity Analysis, Regional Seismic Risk Modeling, Earthquake Mitigation, Decision Making

INTRODUCTION

The City of Vancouver is working to develop an objective policy basis by leveraging seismic risk assessment results to identify risk drivers, evaluate policy options to mitigate risk and quantify the impact of each intervention on risk reduction [1]. Regional seismic risk modelling requires a significant number of assumptions and simplifications pertaining to input variables related to the hazard, exposure and fragility of the City to obtain probabilistic risk results. This work uses Canada's First Public National Seismic Risk Model [2] to guide our baseline assumptions of the key elements of risk modelling. The City's seismic hazard is characterized by plausible deterministic earthquake scenarios with corresponding ground motion shaking estimates generated using ground motion models (GMMs) [2][3]. The exposure data groups Vancouver's 90,000 buildings into taxonomy designations defined by occupancy, building height, material, lateral system, and design level. Natural Resources Canada (NRCAN) worked jointly with the Global Earthquake Model (GEM) to develop taxonomy-based generalized fragility and vulnerability functions, consistent with Canadian construction practices, that translate ground motion shaking intensity into probability of damage or loss, respectively [2]. While these generalized fragility and vulnerability functions provide convenience when modelling risk at the regional scale, their intrinsic modelling uncertainty elicits questions regarding the suitability of regional seismic risk modeling to inform the development of earthquake mitigation policy. For instance, when buildings differ significantly from the predefined height ranges, have structural irregularities, dual lateral systems, or a range of design levels (due to retrofit interventions), the suitability of these simple models comes into question. In certain cases, some researchers forgo the use of taxonomy-based generalized fragility functions in preference of working extensively to derive building specific functions [4][5]. In Canada, the existing uncertainty of a taxonomy-based fragility function is compounded with unaddressed alterations to US-based HAZUS fragility data [2]. By means of a variance-based sensitivity analysis, we propose a framework to identify the impact of key fragility assumptions on the variability of the seismic risk outputs. The following sections of this extended abstract will further discuss the fragility assumptions required to perform regional seismic risk modelling, as well as the proposed framework to constrain the uncertainty in generalized fragility data. This analysis aims to increase the defensibility of these simple tools (i.e., fragility functions) to perform regional risk assessments by exploring their contribution to the seismic risk output variance. This work serves to inform risk modelers and decision makers alike of how to prioritize the evaluation of fragility functions to ensure more reliable and robust risk outputs.

REGIONAL SEISMIC RISK MODELLING

Regional seismic risk modelling is a powerful tool often used by policy makers to better understand a region's overall seismic risk. These models typically assess the seismic performance of individual buildings and their contribution to risk, under deterministic earthquake scenarios. Numerous risk metrics can be derived using HAZUS consequence functions to translate risk results into more informative metrics such as number of people injured or recovery time estimates [6]. This work considers risk under the same terms outlined in Hilt et al. [1], namely, number of casualties, number of people disrupted at daytime, number of people disrupted at nighttime, and number of buildings with extensive or complete damage. The primary focus of this study lies within the fragility component of the seismic risk calculations, specifically, in the use of fragility functions. As noted in Figure 1, a fragility function, as defined by HAZUS, classifies a building based on a subset of the taxonomy, building height, material, lateral system, and design level. These functions translate a given intensity measure or demand parameter into a probability of exceedance of a pre-defined damage state. In Figure 1 these values are spectral displacement and extensive damage respectively [1]. For each taxonomy subset, fragility functions consist of multiple functions, like the one shown in Figure 1, that describe whether a certain damage level is observed or exceeded, i.e., slight, moderate, extensive, and complete. These functions are typically expressed by means of lognormal probability distributions. Therefore, they are fully defined by the median and dispersion of each possible damage state.

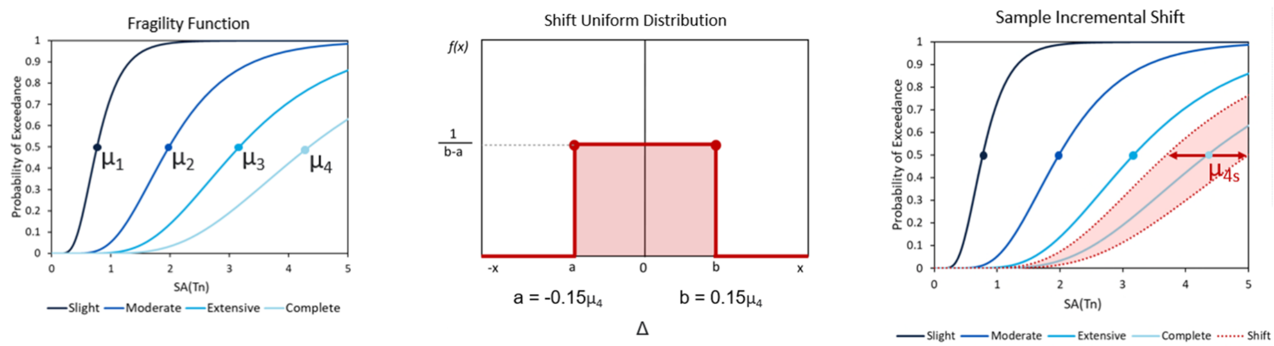
Figure 1. HAZUS Fragility Curve for C1M-HC (Concrete Moment Frame Mid-Rise Structure): Probability of Extensive Damage conditioned on Spectral Displacement [6]

In building Canada's First Public National Seismic Risk Model, the United States HAZUS fragility functions for all building typologies were adopted for modelling risk in Canada. To optimize these functions for risk modelling, NRCAN followed a methodology put forth by Ryu et al. [7] in which a new set of fragility functions that are conditioned on spectral acceleration were generated from the original HAZUS functions conditioned on spectral displacement (refer back to Figure 1). In the development of these revised fragility functions, some modifications were made to align the curves with Canadian construction practices, but these were limited to wood and masonry buildings [2] and the changes are not well documented. The use of primarily US-based fragility models, with some arbitrary adjustments, brings to question the suitability of these functions for use in Canada.

VARIANCE-BASED SENSITIVITY ANALYSIS FRAMEWORK

This work proposes a framework to understand the impact of uncertainty in fragility functions on regional seismic risk outputs. Uncertainty in each set of fragility functions is captured by shifts in the median values that characterize each damage state. To this end, we define a random variable to describe a possible shift in the assumed median value of each damage state in each fragility function. All other seismic risk model input assumptions related to the hazard and exposure are fixed to concentrate all potential contribution to output variability in the fragility assumptions. The impact of these possible shifts in the assumed median values is explored through a variance-based sensitivity analysis. In this analysis, specific building taxonomies (and their corresponding fragility functions) are selected based on defined criteria, and their impact on the variability of the previously mentioned seismic risk outputs is measured. The sensitivity is captured through the analysis of the first-order sensitivity coefficient and total effect sensitivity index of the following metrics: number of casualties, number of people disrupted, and the number of buildings with extensive or complete damage [1]. This work strives to investigate the impact of fragility functions on risk outputs that are leveraged to inform seismic policy. Therefore, these metrics are consistent with those used to identify the key drivers of risk within the City of Vancouver. The sensitivity coefficients will allow for the identification of fragility functions that carry significant impact on the variability of the selected output risk metrics.

The seismic risk model of the City of Vancouver has 78 possible fragility functions mapped to 90,000 buildings. To assess all fragility functions for sensitivity would be extremely expensive from a computational perspective. Therefore, this framework provides a set of criteria for objective selection of target fragilities, or input variables to the sensitivity analysis, that are anticipated to contribute most to the sensitivity coefficients. We propose targeting specific fragility functions based on the following criteria: (1) building density, (2) drivers of risk [1] and (3) building spread. Once selected, the fragility functions, or input variables, are analyzed for their sensitivity on risk outputs through individual shifts in their assumed median values. We define a uniform distribution to model the possible shift in the complete damage state median, or Δ_4, as illustrated in Figures 2a and 2b and tabulated in Equation 1. The distribution is defined by ±15% of the complete damage state to model a sufficient change in median as graphically shown in Figure 2c. Δ_4 is defined as a value sampled from the distribution in Equation 1.



(a) (b) (c)

Figure 2: Characterizing uncertainty in fragility functions: (a) baseline fragility function with damage state medians identified, (b) uniform distribution to characterize possible shifts the complete damage state median, and (c) graphical illustration of the range of potential shift to the complete damage state median.

The possible shift of the remaining damage state medians, or Δ_i, is computed using the product of the sampled potential shift for complete damage state, or Δ_4, and the relative ratio, RR_i, of the median of the damage state in question to the median of the complete damage state in the baseline (i.e., unmodified) fragility function, as outlined in Equation 2.

$$f(x) = \frac{1}{b-a} \; for \; a = -0.15\mu_4 \leq x \leq b = 0.15\mu_4 \tag{1}$$

$$\Delta_i = RR_i \cdot \Delta_4 \; where \; RR_i = \frac{\mu_i}{\mu_4} \; and \; i = 1,2,3 \tag{2}$$

The shifted fragility functions are then propagated through the regional seismic risk assessment to produce probabilities of damage for each building in the exposure dataset. These probabilities of damage are then used to calculate the relevant risk metrics using HAZUS consequence functions [6]. This process is then repeated for thousands of realizations using these revised fragility functions with new random samples at each iteration. Once all key outputs are calculated the risk metrics are then used to produce the following sensitivity indices: (1) the first-order sensitivity coefficient, which identifies a fragility function's marginal contribution to the output variance, and (2) the total effect sensitivity index, which captures a fragility function's marginal contribution and the contribution of its joint interaction, with other input variables, on the output variance [8]. The framework will provide both coefficients for each of the target input fragility functions analyzed for each of the four risk metrics. The results will serve to identify which fragility functions, and their interactions, have the greatest impact on the output variance of the risk metrics considered [8].

CONCLUSIONS

This study provides a framework to further our understanding of regional seismic risk models and promote assurance in the use of generalized fragility functions when leveraging risk results to inform decision making. While this paper is limited in scope to the study of fragility assumptions within regional risk calculations, future work should consider modelling the sensitivity of the entire input variable space including hazard and exposure assumptions. This will further our understanding of the impacts of interactions between different assumption types as well as study the relative difference in contribution to output variance between, hazard, exposure, and fragility assumptions.

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REFERENCES

[1] Hilt, M. P., Lambert, E. C., and Molina Hutt, C., "A Methodology to Leverage Seismic Risk Assessments to Inform Seismic Policy Development, the Case of the City of Vancouver," *Journal Paper*. In Preparation.

[2] Hobbs, T.E., Journeay, J.M., Rao, A.S., Martins, L., LeSueur, P., Kolaj, M., Simionato, M., Silva, V.,Pagani, M., Johnson, K., and Rotheram, D., 2022. Scientific basis of Canada's first public national seismic risk model; Geological Survey of Canada, Open File 8918, 57 p. https://doi.org/10.4095/330927

[3] Hobbs, T.E, Journeay, J.M., and Rotheram, D., "An earthquake scenario catalogue for Canada: A guide to using scenario hazard and risk results," Natural Resources Canada/CMSS/Information Management, 2021. Accessed: Dec. 18, 2022. [Online]. Available: http://dx.doi.org/10.4095/328364.

[4] Molina Hutt, C., (2017) Risk-based seismic performance assessment of existing tall steel framed buildings. Doctoral thesis (Ph.D), UCL (University College London). https://discovery.ucl.ac.uk/id/eprint/10040499/

[5] Almufti, I., Molina Hutt, C., Willford, M. and Deierlein, G. (2012). "Seismic Assessment of Typical 1970s Tall Steel Moment Frame Buildings in Downtown San Francisco." International Association of Earthquake Engineering. Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal, September 24-28. http://discovery.ucl.ac.uk/1384849/

[6] HAZUS, "Earthquake Advanced Engineering Building Module," HAZUS Multi-hazard Loss Estimation Methodology, Federal Emergency Management Agency, Washington, DC, 2014.

[7] Ryu, H., Luco, N., Baker, J., and Karaca E., "Converting HAZUS Capacity Curves to Seismic Hazard-Compatible Building Fragility Functions: Effect of Hysteretic Models," in *The 14th World Conference on Earthquake Engineering*, Oct. 2008

[8] Cremen, G. and Baker, J. W., "Variance-based sensitivity analyses and uncertainty quantification for FEMA P-58 consequence predictions," *Earthquake Engineering & Structural Dynamics*, 2020.

[9] Baker, J. W., Bradley, B. A., Stafford, P. J., "Seismic Hazard and Risk Analysis," Cambridge University Press, Cambridge, England, 2021.

[10] Kolaj, M., Halchuk, S., Adams, J., and Allen, T. I., "Trial Sixth Generation seismic-hazard model of Canada: seismic-hazard values for selected localities," Natural Resources Canada/CMSS/Information Management, 2020. Accessed: Dec. 18, 2022. [Online]. Available: http://dx.doi.org/10.4095/321473.

[11] Lambert, E. C. and Molina Hutt, C., "A Sensitivity Analysis to Quantify the Impact of Modeling Assumptions on Regional Seismic Risk Outputs," *Journal Paper*. In Preparation.

[12] Bast E. and Wong B., "Building Inventory Report Seismic Risk Assessment, City of Vancouver, September 2018," The University of British Columbia, Earthquake Engineering Research Facility, British Columbia, Canada, 2018