Wellington Earthquake Scenarios and Seismic Design

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Executive Summary

This project brings together three strands of work relating to earthquake risk models as decision making tools: (1) a state-of-the-art synthesis of existing data and models for Wellington's seismic risk; (2) a transparent method for selecting a small number of representative earthquake scenarios for regional risk simulation; and (3) an evidence-based discussion of fatality risk tolerance thresholds that can inform building code provisions and broader policy.

Wellington is consistently identified as one of the most seismically exposed urban regions in Aotearoa New Zealand, with high contributions from both nearby active crustal faults and the Hikurangi subduction margin. Risk reduction decisions (retrofit prioritisation, emergency planning, investment in lifeline resilience, and land-use choices) often rely on deterministic scenarios because they are easier to communicate and easier to connect to 'what happens next'. At the same time, risk-based design and policy discussions increasingly require explicit targets for acceptable risk. Based on this, this project primarily contributes to the following:

- We propose a scenario selection framework that leverages disaggregation outputs and rupture catalogues from national probabilistic seismic hazard models. In the Wellington case study, this leads to two representative scenarios: a Mw 7.3 Wellington-Hutt Valley active-crustal earthquake and a Mw 8.1 Hikurangi subduction interface earthquake.
- We benchmark scenario-based ground motions against probabilistic estimates to make the 'representativeness' of scenarios explicit and provide median intensity maps for key measures (PGA and spectral accelerations).
- We compile and compare annual individual fatality risk (AIFR) thresholds used internationally for new and existing infrastructure, showing order-of-magnitude

differences across sectors and jurisdictions, and highlighting how thresholds are commonly tiered (acceptable, tolerable, unacceptable) under an internationally followed framework called *As Low As Reasonably Practical* (ALARP) approach.

Abstract

This final report synthesises three related research outputs that support risk-informed decision-making for Wellington, Aotearoa, New Zealand. First, we assemble a state-of-the-art review of data and models relevant to Wellington's seismic risk, spanning hazard characterisation, site and basin effects, exposure models, and fragility/vulnerability functions, and we identify critical gaps. Second, we introduce and demonstrate a framework for selecting deterministic earthquake scenarios that are representative of a region's seismicity by leveraging national seismic hazard models (PSHA), specifically disaggregation outputs and rupture catalogues. This framework is applied to Wellington using NSHM 2022 inputs and identifies two representative scenarios for regional risk simulation: a Mw 7.3 Wellington-Hutt Valley Fault, and a Mw 8.1 Hikurangi subduction interface. We generate scenario hazard maps for the two scenarios and benchmark hazard intensities against probabilistic hazard distributions to contextualise scenario severity. Third, we compile and compare international risk tolerance thresholds for infrastructure using annual individual fatality risk (AIFR) as a common life-safety metric, contrast thresholds for new versus existing assets, and provide a New Zealand context using model-based risk assessments and empirical fatality observations from other societal risks. Together, these outputs improve transparency in scenario selection, support coherent scenario-based risk communication, and provide an evidence base for explicit discussion of risk thresholds relevant to building code provisions.

Keywords

Earthquake, Quantifying hazards and risk, risk tolerance

Introduction

Wellington's exposure to earthquake hazards is shaped by a complex tectonic setting that includes nearby active crustal faults and the Hikurangi subduction margin. National-scale hazard updates (notably NSHM 2022) provide increasingly detailed characterisations of seismic sources and ground-motion uncertainty, but translating those probabilistic outputs into practical decisions remains challenging.
This project addresses a common bottleneck decision makers face in selecting a small number of credible, well-documented scenarios for communication, planning, and simulation. More often, scenario selection is judgment-based (e.g., historical event, perceived worst-case events, or convenience), and their consistency with national-scale models cannot be transparently established.
Another evolving discussion in risk-based design and regulatory circles is the explicit setting of acceptable life-safety risk. It is not trivial to determine what risk thresholds should be used for regulatory purposes and how they relate to the risks society tolerates elsewhere.
In view of the above, the following objectives were set for this project:
1) synthesise the current state-of-the-art data and models for Wellington seismic risk and identify critical gaps and research direction to enable robust modelling efforts that support decision making;
2) develop and demonstrate a transparent, repeatable framework for selecting representative earthquake scenarios using national hazard models; and
3) compile and contextualise international life-safety risk thresholds (using AIFR) to support explicit discussion of risk tolerance in building regulation.

Methodology

The following summarises the methodological components for each of the three objectives stated above. A more comprehensive discussion is included in the three research papers prepared for each objective.

Objective 1: State-of-the-art synthesis of data and models for Wellington’s seismic risk
Reviewed published and grey literature on Wellington seismic hazard, site/basin effects, exposure inventories, and fragility/vulnerability models.
- Organised evidence by the core risk ingredients: hazard, exposure, and vulnerability, and documented research gaps that materially affect risk estimates.

Objective 2: Representative scenario selection leveraging PSHA
- Selected an intended use-case (regional building risk simulation) and corresponding hazard level (design-level return period).

- Extracted seismic hazard disaggregation outputs from NSHM inputs for relevant intensity measures (e.g., SA at periods tied to building response).

- Identified dominant magnitude-distance-tectonic regime combinations and mapped them to specific rupture instances in the NSHM rupture catalogue.

- Where multiple rupture instances fit the same magnitude-distance bin, used rupture rate as a selection criterion, while maintaining the conceptual separation between PSHA (rates) and scenario hazard (intensities).

- Generated median ground-motion intensity maps for selected scenarios using the workflow consistent with the NSHM ground-motion logic tree, and benchmarked scenario intensities against probabilistic hazard distributions.

Objective 3: Risk tolerance synthesis using AIFR

- Compiled international risk thresholds for infrastructure and land-use policy that are expressed (or can be expressed) as annual individual fatality risk.

- Compared thresholds across asset classes and between new and existing infrastructure, and interpreted them through an ALARP-type framing (acceptable, tolerable, unacceptable).

- Provided New Zealand context by collating model-based AIFR assessments for selected hazards and settings and by summarising empirical fatality observations from other societal risks (health, transport, workplace).

- Provided a discussion on the treatment of risk and differentiating between various risk factors based on objective criteria such as voluntariness of risk, potential for mass impact, and societal risk perceptions.

Results and discussion

The following discussion is also organised in three separate paragraphs, each relating to the objectives stated earlier.

Objective 1: State-of-the-art synthesis of data and models for Wellington’s seismic risk

The review consolidates what is currently known about Wellington's hazard drivers (active crustal sources and the Hikurangi margin), the role of site and basin effects in shaping long-period demands, and the way exposure and vulnerability (building stock, non-structural components, and lifelines) translate shaking and ground failure into disruption. The recent updates to the NSHM provide valuable resources for hazard quantification and probabilistic hazard estimation for the region, including local site conditions. The work done for objective 2 provides additional frameworks to conduct scenario-based analysis. Building and infrastructure exposure is available, too, from previous efforts. However, there is work to be done to have consistent parametrisation of building and infrastructure exposure to enable robust regional risk estimates. Exposure data is available from multiple sources, and they are not necessarily consistent in how they represent building properties or attributes. Current work to develop exposure models using lidar-based imagery provides a promising avenue for comprehensive exposure data that can be updated over time to reflect infrastructure growth. Significant gaps, however, exist in fragility and vulnerability models that relate seismic hazard intensities to building performance and risk metrics. Although such models are available for various building types (e.g., mid- and high-rise reinforced concrete buildings), further work is needed to make them consistent and usable within a single risk quantification workflow. Some recent studies have developed robust numerical models that could be leveraged to develop fragility and vulnerability functions that represent local damage mechanisms for most buildings in Wellington. This gap also exists for infrastructure components such as bridges, power stations, pipes, etc. Another critical gap is accounting for damage and loss for cascading hazard events, such as landslides following an earthquake. Although robust models are available to estimate the likelihood of earthquake-induced landslides, there is no framework for estimating how that will impact the built environment. This work recommends using globally available fragility and vulnerability models as placeholders when locally grounded models are unavailable, but it also develops such models for Wellington to support a robust system-level seismic risk assessment.

Objective 2: Representative scenario selection leveraging PSHA

The framework developed in this effort has been applied to Wellington using NSHM-based disaggregation, yielding two scenarios intended to span the dominant source types relevant to regional risk. These scenarios are selected to estimate risk for the region's building portfolio. The two scenarios are: Mw 7.3 Wellington-Hutt Valley active-crustal earthquake (near-field, higher spatial variability of shaking) and Mw 8.1 Hikurangi subduction interface earthquake (broader regional footprint, comparatively more spatially uniform shaking)

For each scenario, we generated ground-motion intensity maps for PGA and spectral accelerations at key periods and compared scenario intensities to probabilistic hazard distributions to contextualise severity at the return period of interest. The benchmarking step is central to contextualising the scenario hazards to the NSHM estimates.

Objective 3: Risk tolerance synthesis using AIFR

The risk tolerance synthesis compiles AIFR thresholds used internationally for new and existing infrastructure and shows substantial variation across jurisdictions and asset classes. Where explicit distinctions are made, existing assets are commonly permitted thresholds roughly an order of magnitude higher than new assets, reflecting feasibility constraints in retrofit and upgrade. In parallel, the New Zealand context illustrates that model-based AIFR assessments for natural hazards and empirical fatality observations from health and transport occupy different magnitudes and serve different decision roles. The report emphasises the need to distinguish (a) thresholds as policy goals, (b) assessments as status-quo model estimates, and (c) observations as realised outcomes. This distinction reduces the risk of misinterpreting 'how risky things are' versus 'what risk is acceptable'. The discussion also emphasises the importance of differentiating earthquake risk from other sources (such as health or transport-related) based on the voluntariness of the risk, the potential for mass impact, and societal risk perception.

In summary, the outputs support a more coherent workflow for Wellington: select scenarios transparently from NSHM evidence, simulate impacts consistently across disciplines, and situate life-safety targets within an explicit risk tolerance discussion.

Conclusions

For risk models to effectively guide risk-reduction decisions at the local government level, consistency in data and modelling resolution and quality is required. This work has contributed to understanding the state of the art in both data and models across domains, thereby advancing the development of a robust risk model. Within that effort, key gaps have been identified, which can inform future research to enable effective, locally grounded, usable risk models. In addition, this work provides a clear framework for selecting representative scenarios leveraging the national seismic hazard model. This framework has been implemented in Wellington to select two deterministic scenarios, but it could also be used in other regions. Finally, this work also contributed to the ongoing discussion of risk thresholds for building code provisions and provided policymakers with an analysis to guide their decision-making.

Outputs and dissemination

Key outputs from this project include:
Manuscript 1: Earthquake Fatality Risk Tolerance: What risk thresholds should be used in setting building code provisions? (Submitted)

Manuscript 2: Framework for Selection of Representative Earthquake Scenarios for Regional Risk Simulation leveraging National Seismic Hazard Models. (In review)

Manuscript 3: Earthquake Risk in Wellington: A State-of-the-art Review of Data and Models (in preparation)
Scenario catalogue for Wellington (selected ruptures and documentation) and associated ground-motion intensity maps (PGA, SA at key periods)

Reproducible workflow notes for scenario selection and benchmarking to probabilistic hazard

Publications, communications and engagement

Peer-reviewed publications and manuscripts
Kakoty, P., Hulsey, A., Dunne, C., Brown, C., & Elwood, K. J. Earthquake Fatality Risk Tolerance: What risk thresholds should be used in setting building code provisions? (submitted).

Kakoty, P., Elwood, K. J., DiCaprio, C., & Bora, S. S. Framework for Selection of Representative Earthquake Scenarios for Regional Risk Simulation leveraging National Seismic Hazard Models (manuscript in review).

Kakoty, P. & Elwood, K. J. Earthquake Risk in Wellington: A State-of-the-art Review of Data and Models (working draft).

Engagement
1. Presentations at the 2025 NZ Society of Earthquake Engineering Annual Meeting in Auckland.
2. Presentation at the 13th International Conference on Structural Safety and Reliability (ICOSSAR) in Los Angeles, USA.
3. Poster presentation at the 2024 and 2025 QuakeCore Annual Meetings in Napier and Dunedin, respectively.
4. Participated in the Risk Tolerance Working Group meetings in Wellington.
5. Participated in the Japan-Taiwan-New Zealand Seismic Hazard Workshop in Yilan, Taiwan.