NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING

Framework for selection of representative earthquake scenarios for Wellington

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ABSTRACT

Earthquake scenarios are essential tools for assessing seismic risk and facilitating effective risk communication and developing risk reduction policies. Using a specific earthquake scenario allows for deterministic modelling of a rupture that is easier to understand and can provide context through comparison to similar past events. However, in regions like Wellington in New Zealand, where multiple active shallow crustal faults (e.g. the Wellington and Wairarapa faults) and a subduction zone (Hikurangi) contribute to seismic hazard, choosing deterministic scenarios to represent overall seismic risk is challenging. This paper outlines a systematic framework for selecting representative earthquake scenarios, while acknowledging the inherent subjectivity of the decision, and illustrate the implementation through a case study for Wellington that leverages seismic hazard disaggregation from the National Seismic Hazard Model. The selected scenarios presented in this paper will further be used for assessing seismic risk to residential buildings, as well as understand the impacts of cascading effects of secondary hazards such as landslides and liquefaction. This study serves as the foundation for a larger multidisciplinary effort aimed at developing a comprehensive scenario risk study for Wellington. The overarching goal is to synthesize multidisciplinary seismic risk insights for Wellington that can inform risk reduction strategies and enhances decision-making processes for resilience planning in Wellington.

1 INTRODUCTION

Within the seismic hazard and risk assessment literature, there has been extensive discussion and debate on probabilistic and deterministic methods. However, each of these approaches has its own strengths and applications. By definition, probabilistic methods account for all deterministic events with a finite probability of occurrence. In this context, deterministic approaches, which focus on single earthquake scenarios, ensure that these events are realistic, i.e. they have a finite probability of occurring. This underscores the complementary nature of the two methodologies: deterministic events can be validated using probabilistic analyses to confirm their feasibility, while probabilistic analyses can incorporate deterministic scenarios to ensure the inclusion of rational and realistic hypotheses (McGuire 2001).

The selection between deterministic and probabilistic approaches depends on several factors, including the context of the decisions to be made, the seismic environment, and the scope of the assessment (McGuire 2001). In scenarios where ground shaking is the major hazard and multiple faults contribute to this hazard, a probabilistic approach may be preferred. Such an approach could examine the multivariate shaking hazard at several locations simultaneously. Conversely, for systems like lifelines that cross active faults, a deterministic approach may be more appropriate. This would involve analysing the effects of fault displacements on the infrastructure system. The fundamental difference between probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA) lies in their treatment of earthquake occurrence rates and ground motion levels. As noted by Hanks & Cornell, (1994), the two approaches share more similarities than differences. However, a key distinction is that PSHA incorporates temporal dimensions, defining hazard as the mean rate of exceedance for a given ground-motion amplitude, whereas DSHA does not (Bommer 2002). In DSHA, the hazard is defined as the ground motion at the site resulting from the controlling earthquake.

In practice, deterministic scenarios can complement probabilistic frameworks by guiding the selection of specific events to evaluate the effectiveness of emergency response organizations and identify potential weaknesses. Such scenarios have been widely used for risk communication and planning mitigation strategies worldwide, including the HayWired scenario in California (Hudnut et al., 2018), the M9 Cascadia subduction zone scenario in the Pacific Northwest (Frankel et al., 2018), and the Alpine Fault Magnitude 8 (AF8) scenario in New Zealand (Orchiston et al., 2018). The study presented here is part of a broader effort to develop a multidisciplinary scenario study for Wellington, New Zealand bringing together the wide breadth of data collected in various studies over the past two decades. This initiative aims to enable a coordinated scenario study similar to HayWired and other similar efforts, which have proven valuable for risk communication, policy development, and urban planning. The first critical step in this effort is the identification of the most appropriate earthquake event to be considered in the scenario.

To address this need, this paper proposes a framework for identifying relevant and representative rupture scenarios using disaggregation information from probabilistic seismic hazard models. The framework is applied to Wellington, a region exposed to both active crustal and subduction faults, to develop a set of representative deterministic scenarios. The following sections outline the proposed framework, describe its implementation for Wellington, and present the selected deterministic scenarios, which will be used for further seismic hazard and risk assessments.

2 SCENARIO SELECTION FRAMEWORK

Probabilistic Seismic Hazard Analysis (PSHA) estimates the likelihood of various levels of earthquake-induced ground shaking at a specific location by considering contributions of all possible earthquake sources and their associated probabilities of rupture (Hanks & Cornell, 1994). This method accounts for uncertainties in earthquake size, location, and frequency, providing a comprehensive understanding of the expected seismic hazard estimates. The key steps in PSHA include identifying potential earthquake sources like fault lines or seismic sources, estimating the range of possible earthquake magnitudes for each source, calculating the distances from these sources to the site of interest, and evaluating the distribution of intensity of ground shaking from different magnitudes and distances. Finally, all this information is integrated to estimate the probability of exceeding various levels of ground shaking at the site. The results are often presented as hazard curves, which show the probabilities of exceeding different levels of ground motion intensity, incorporating contributions from all identified earthquake sources and their rupture rates(Baker et al., 2021).

Since these hazard curves account for all possible earthquake sources, they can help identify magnitude and distance combination that contribute most to a specific level of seismic hazard. The process of identifying magnitude and distance from PSHA is called seismic hazard disaggregation (Baker et al., 2021). Essentially, seismic hazard disaggregation of PSHA answers the question: which earthquake scenario (magnitude and distance combination) is most likely to cause ground motion intensity higher than a specified value? It is important to note that the specific value of ground motion intensity used for seismic hazard disaggregation depends on the intended application of this information, which will be discussed in more detail in the following sections. The framework developed in this paper uses seismic hazard disaggregation data to inform the selection of deterministic earthquake scenarios for regional seismic risk analysis.

Acknowledging the subjectivity in the decision to select specific deterministic earthquake scenarios, this framework provides a streamlined workflow to guide this decision-making process. The workflow, illustrated in Figure 1, begins with identifying the relevant site, site condition parameters, and ground motion intensity measures. Seismic hazard disaggregation is obtained for these given conditions, and magnitude-distance combinations that contribute highest to hazard are identified. These magnitude-distance combinations points to specific ruptures from the catalogue of ruptures underlying probabilistic seismic hazard model. Specific ruptures are then selected based on their rupture rate, potential of secondary hazards, and the local relevance of the rupture.

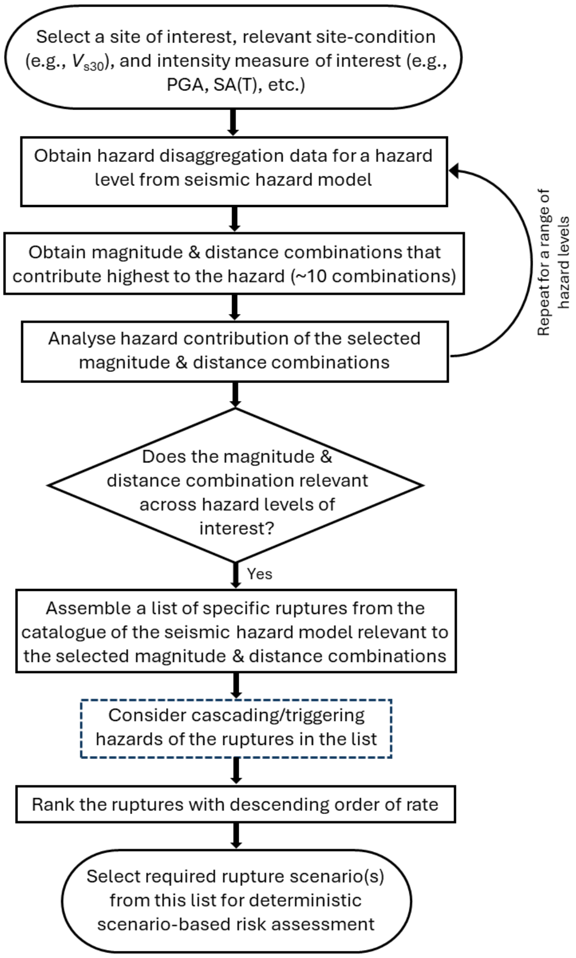


Figure 1 Workflow of selecting deterministic earthquake scenarios leveraging seismic hazard disaggregation data

3 SELECTION OF EARTHQUAKE SCENARIOS FOR WELLINGTON

This section describes an implementation of the proposed framework to select representative earthquake scenarios for Wellington, located in the southern tip of the north island of New Zealand. Wellington is exposed to multiple active shallow crustal faults such as Wellington-Hutt Valley fault, Wairarapa fault, etc. (Langridge et al., 2016). The Hikurangi subduction zone also lies underneath of this region. The current national seismic hazard model of NZ, released in 2022, estimates Wellington as one of the highest seismically active locations in New Zealand (Gerstenberger et al., 2024). The region's exposure to multiple earthquake sources from different tectonic regimes, combined with unique geological characteristics that may contribute to cascading or triggered hazards—such as fault displacement, landslides, liquefaction, and tsunamis—makes it challenging to define deterministic earthquake scenarios for regional risk reduction efforts. To address this, the proposed framework provides a structured workflow for selecting deterministic earthquake ruptures while acknowledging the inherent subjectivity of the decision-making process.

The case study presented here will be used to develop scenario-based seismic risk estimates for residential buildings in Wellington. Accordingly, a 475-year return period is chosen for hazard estimates, as it roughly corresponds to the design-level earthquake. Disaggregation from the national seismic hazard model is obtained for Wellington, with shear wave to top 30 meters of soil (V_{s30}) equal to 200 m/s, for three ground motion intensity measure of interest: spectral accelerations at *0.3s, 0.6s, and 1s*. Table 1 provides the average magnitude and distance from disaggregation results for spectral acceleration at 0.3s at 475-years. Since Wellington is exposed to multiple tectonic regimes, it is important to understand hazard contribution from each of the three unique tectonic regimes, i.e. active shallow crust, subduction interface, and subduction intraslab. As shown in Figure 2, hazard contribution from subduction interface source dominates among the earthquake source types. This observation is consistent across all hazard levels except for much lower return period (25-year), where all three source approximately contribute equally.

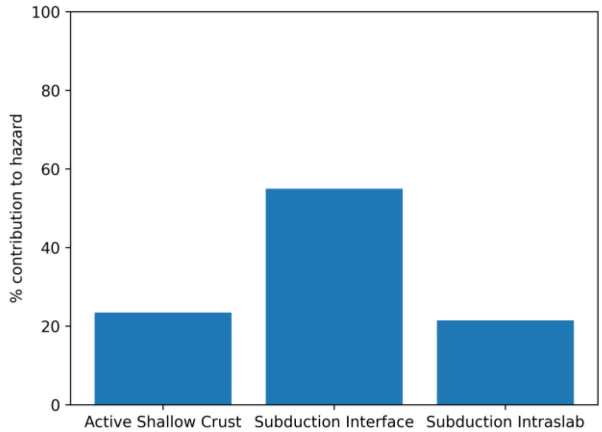


Figure 2. Disaggregation as per earthquake types for SA(0.3) at Wellington (Vs30 = 200 m/s) and corresponding to return period 475 years.

For each hazard level, seismic hazard disaggregation provides percentage contribution for magnitude and distance combination, as shown in Figure 3. Segregated for the three distinct tectonic regimes, this information enables identifying magnitude-distance combinations that contribute highest at this hazard levels. A total of 10 candidate magnitude and distance combinations are selected at each hazard level, and it is repeated for all the other hazard levels. A final list of magnitude distance combination is filtered to ensure that selected scenarios are relevant across all hazard levels. Figure 4 shows the relative contribution of selected five magnitude and distance combination across hazard levels with the magnitude, distance, and tectonic regime annotated in the figure. As shown in the figure, relative contribution of the same magnitude distance combination increases with increasing levels of hazard. This is because at lower hazard levels, there are a wider range of ruptures contribute to hazard and thereby reducing the relative contribution of the rupture that contribute the highest. Whereas, at higher hazard levels, a smaller proportion of magnitude and distance combination, typically higher magnitude and lower distances, dominate the hazard contribution thereby the relative contribution is higher for the same combinations.

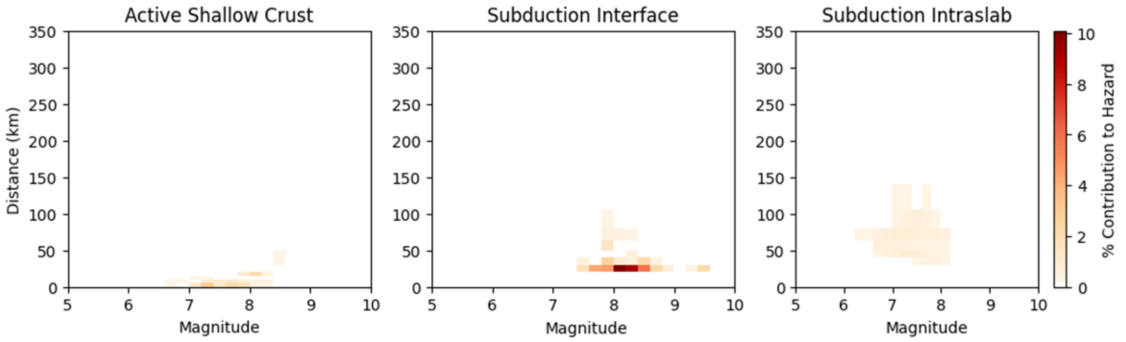


Figure 3. Disaggregation of ground motion intensity for spectral acceleration at 0.3s in Wellington (V_{s30} = 200 m/s) with respect to magnitude and distance for active shallow crustal, subduction interface, and subduction intraslab sources with annual probability (Figure source: GNS Science)

Table 1: Mean source from disaggregation results for peak ground acceleration with V_{s30} = 200 m/s in Wellington

Return Period	Mean Source		
	Magnitude	**Distance**	**Epsilon**
2475	8	30	1.9σ
975	7.9	31	1.6σ
475	7.8	33	1.4σ
~250	7.7	36	1.2σ
~100	7.5	43	1.0σ
50	7.2	50	1.0σ
25	6.9	59	0.9σ

The combinations of magnitude and distance shown in Figure 4 collectively represent the full probability distribution of resulting hazard values. The disaggregation from the NSHM also provides insights into contributions at different epsilon (ϵ) values, which indicate the deviation from the mean hazard estimate for a given magnitude-distance pair. An ϵ value close to 0 suggests that the corresponding hazard values are near the mean, whereas positive or negative ϵ values indicate that the hazard estimates fall in the tail ends of the distribution, either above or below the mean. Table 1 presents the ϵ values for the dominant sources at each return period. Since the goal of selecting a specific magnitude-distance combination is to ensure consistency with the hazard values probabilistically at the return period of interest, ϵ plays a crucial role in this process. A combination with the highest contribution to hazard and an ϵ value close to 0 is more likely to produce hazard estimates that is consistent with the expected hazard estimates from the NSHM at the return period of interest. Conversely, a combination with a high positive ϵ value is likely to correspond to a scenario that results in lower-than-expected hazard values. Figure 5 illustrates the relative contribution of a specific magnitude-distance combination, disaggregated by ϵ values. As shown in the figure, magnitude-distance combinations with higher positive ϵ values contribute less at lower return periods but have a greater relative impact at higher return periods. Therefore, analysing contributions across different ϵ levels helps identify rupture scenarios that are more likely to produce hazard estimates consistent with those from the NSHM for the return period of interest.

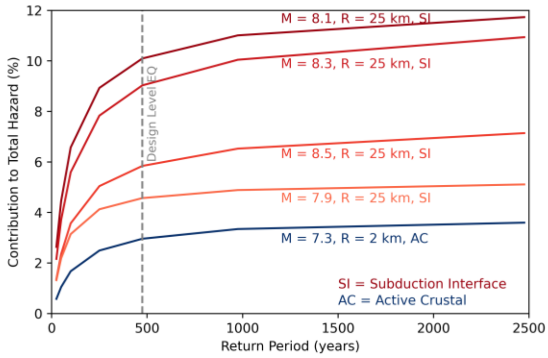


Figure 4. Contribution of five magnitude-distance combinations to peak ground acceleration (V_{s30} = 200 m/s) in Wellington, selected based on ascending order of their contribution to total hazard. The plots use varying shades of red to represent subduction interface sources, while the blue plot denotes active crustal sources. The design level earthquake is annotated for reference.

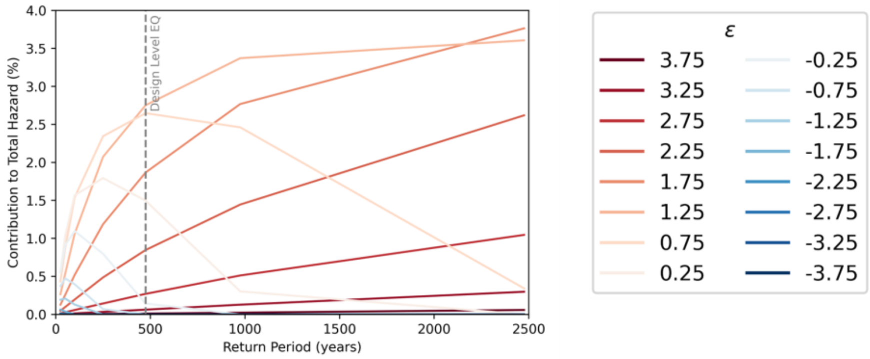
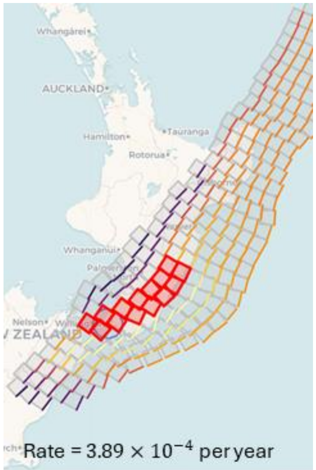


Figure 5. Contribution to total hazard of five one magnitude-distance combination (M= to peak ground acceleration (V_{s30} = 200 m/s) in Wellington disaggregated based on ϵ that indicates deviation from the expected hazard estimate. The plots use varying shades of red to represent subduction interface sources, while the blue plot denotes active crustal sources. The design level earthquake is annotated for reference.

Once a set of magnitude-distance pairs has been selected using the procedure described above, specific ruptures from the NSHM rupture catalogue are chosen to match the selected combinations. It is important to note that each magnitude-distance combination can correspond to multiple rupture scenarios in the NSHM, each with its own rupture rate. For example, a magnitude-distance combination of 7.3 and 2 km for an active crustal source results in six rupture instances on the Wellington-Hutt Valley fault, with rupture rates ranging from 1×10^{-6} per year to 1.33×10^{-4} per year. Among these, the rupture scenario with the highest rupture rate is selected to best represent the magnitude-distance combination. For active crustal sources, the selected rupture is shown in Figure 6, with a rupture rate of 1.33×10^{-6} per year. Similarly, for the Hikurangi subduction zone, a rupture scenario is chosen to represent the magnitude-distance combination of 8.1 and 25 km, with an associated rupture rate of 3.89×10^{-4} per year. Both selected rupture scenarios, illustrated in Figure 6, will be used in subsequent hazard and risk assessments. It is important to note that these ruptures are not directly relevant to the subsequent seismic hazard and risk assessment; instead, they serve solely as a criterion for selecting among multiple plausible rupture sources that align with the identified magnitude-distance combination. This distinction aligns with the fundamental difference between PSHA and DSHA in terms of their treatment of temporal units, as discussed earlier.

(a)



(b)

Figure 6. Selected rupture scenarios for Wellington from the catalogue of ruptures underlying New Zealand's National Seismic Hazard Model with their rates annotated and corresponding to (a) Wellington-Hutt valley fault (active crustal source) and (b) Hikurangi subduction zone. (Figure source: GNS Science)

4 CONCLUSION

Scenario-based seismic risk assessments play a crucial role in risk communication and the development of risk mitigation strategies. However, selecting representative deterministic earthquake scenarios has remained a challenge due to the lack of a structured framework. This paper addresses this gap by proposing a systematic approach that leverages seismic hazard disaggregation from probabilistic seismic hazard analysis (PSHA) models to inform the selection of deterministic scenarios.

The proposed framework was applied to Wellington, New Zealand, a seismically active region exposed to both active crustal faults and the Hikurangi subduction zone. Two representative earthquake scenarios were identified, one from each tectonic regime, that will enable meaningful seismic hazard and risk assessments. These scenarios will be benchmarked further against probabilistic hazard assessments to substantiate their relevance and applicability.

This study is part of a broader effort to develop a scenario-based seismic risk model for Wellington's residential buildings, incorporating cascading hazards such as landslides and liquefaction. The insights gained from this research will contribute to evidence-based risk reduction strategies, ultimately enhancing the region's resilience to future seismic events.

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