
Probabilistic approach to estimating regional building damage from an earthquake and its cascading hazards

S.R. Uma, D. Burbidge, Y. Mahmood, K. Jones, A. Griffin, & J. Roger

Earth Sciences New Zealand, Lower Hutt, New Zealand.

J. Moratalla

Formerly GNS Science, Lower Hutt, New Zealand.

ABSTRACT

Earthquakes often trigger cascading hazards. Subduction zones, in particular, are capable of generating extremely large earthquakes that can trigger multiple cascading hazards, including liquefaction, lateral spreading, landslides and tsunamis, along with extreme levels of ground shaking. Buildings exposed to this series of hazards are potentially subject to greater levels of damage, resulting in increasingly compromised functionality. For disaster-response planning purposes, it is important to understand the extent of potential consequences by considering a full range of hazards and various sources of uncertainties. In this paper, we present a probabilistic approach to quantify the impacts from an earthquake and its cascading hazards as building damage metrics that aim to understand both economic and societal impacts.

Due to the uncertain nature of earthquakes and the response of buildings to them, the proposed framework tracks uncertainties through Monte Carlo simulations to create hundreds of possible damage realisations for every building in the affected region. At each building site, the hazard intensities represented by the ground shaking and the cascading hazards are modelled probabilistically, and the performance of each building is assessed using fragility/vulnerability functions. The method is demonstrated using the building portfolio of Napier, Aotearoa New Zealand, to calculate the impact following a M_w 8.4 Hikurangi subduction interface earthquake. The performance metrics used here include: (i) mean damage ratios distributed across the region from all the collective hazards caused by the earthquake; and (ii) the relative contributions to higher damage states (e.g. non-occupiable buildings) by hazard type.

1 INTRODUCTION

Aotearoa New Zealand (NZ) faces risks from various types of natural hazards, and earthquake-induced disasters are well-known historically. Earthquakes often trigger cascading hazards of different types depending on the geological setting of the affected region. Examples include: (i) the 2010–2011 Canterbury Earthquake Sequence with ground shaking-induced liquefaction, lateral spreading and landslides (Hughes et al., 2015); and (ii) the 2016 Kaikōura earthquake-shaking-induced landslides, tsunami, landslide dams and flood plain subsidence (Robinson and Rosser, 2017). Such earthquakes demonstrate the importance of addressing multi-hazard problems, with a need to model the cascading hazards conditioned on the triggering intensities of the primary hazard (the ground shaking). The buildings in a region exposed to these primary and cascading hazards experience varying degrees of damage severities influenced by the respective hazard types and intensities at their sites and by their own physical vulnerabilities. Acknowledging the uncertain nature of hazards and building responses to these, there is a need for a probabilistic approach that can dynamically correlate hazard intensities and their uncertainties across cascading perils and building responses within a simulation-based framework to provide quantitative and useful metrics of building-damage distributions.

A general approach to incorporate cascading effects of earthquakes is to focus on one or two earthquake scenarios and associated cascading hazards. Previous studies (Power et al., 2018; Burbidge et al., 2019) have adopted deterministic or expert judgement approaches. The work by Goda (2020) calculated time-dependent probabilistic risk estimates by considering ground shaking and tsunami hazards and their respective fragility functions but did not cover their cascading hazards, such as liquefaction and landslides. Moratalla and Uma (2023) developed a probabilistic framework that captured uncertainties and variabilities of ground-motion shaking and cascading hazards, including liquefaction, lateral spreading and landslides across a region. Through a case study, their work demonstrated its application potential on the regionally distributed road network in Napier, NZ to derive probabilistic estimates of inaccessibility for a potential Mw 8.4 earthquake-source scenario from Hikurangi Subduction Zone (HSZ). In the interest of generating other risk metrics, such as annualised probabilistic loss or risk exceedance curves for the assets exposed, the framework has been further developed to include stochastic event-based risk assessment methods to cover the impacts from a range of potential earthquakes from HSZ (Moratalla et al., 2026), including cascading earthquake hazards and tsunami.

1.1 Objectives and scope of the present study

The objective of the present study is to estimate damage distribution of building stock of a region for a single earthquake scenario and its cascading hazards. In addition to the previously developed earthquake-triggered cascading hazard models (for liquefaction, lateral spreading and landslides) in Moratalla and Uma (2023), the current work includes a tsunami hazard model (for earthquake rupture and not other source mechanisms) developed using the framework proposed in Moratalla et al. (2026). The scope of this study thus comprises:

1. Presenting a robust methodology that is built on the work of Moratalla and Uma (2023) and Moratalla et al. (2026), which uses a simulation-based probabilistic framework for the scenario earthquake to derive desired metrics of building-damage distribution in a region.
2. Illustrating the methodology for a case study area, Napier in the Hawke's Bay region, NZ, for a Mw 8.4 earthquake-source scenario in HSZ and its triggered cascading hazards. In this study we will fix the magnitude and location of the event, but will account for the uncertainty in the resulting ground motion, liquefaction, landslides and tsunami and the effect of that to the damage to Napier's residential building stock following the earthquake. This particular scenario was chosen to be consistent with the one previously used in Moratalla and Uma (2023).

2 METHODOLOGY

The proposed methodology includes a probabilistic approach, adopting Monte Carlo simulations with models for hazards (primary earthquake ground-shaking and cascading hazards) and building-damage functions and the models that represent uncertainties through probabilistic distributions. For a given earthquake scenario, the estimation of cascading hazard intensities are conditioned based on the earthquake ground-shaking intensity at the building site. Building-damage functions are fragility functions with specified intensity measure of the hazard, representing discrete levels of damage as damage states (DS). For this study, it was necessary to use harmonised damage states across all types of hazards, so we have applied the one developed by Moratalla et al. (2026) with unified five-level classification – DS1 as ‘Slight’, DS2 as ‘Moderate’, DS3 as ‘Severe’, DS4 as ‘Extensive’ and DS5 as ‘Complete or Collapsed/Washed away’ – to signify the impact from tsunami hazard. These are used to arrive at a single damage state and corresponding damage ratio for a building. This can be done by either assuming that the final DS is the maximum DS across all perils or by combining the losses from the moderate damage states up until they reach the maximum loss (to prevent double counting). The workflow is depicted in Figure 1.

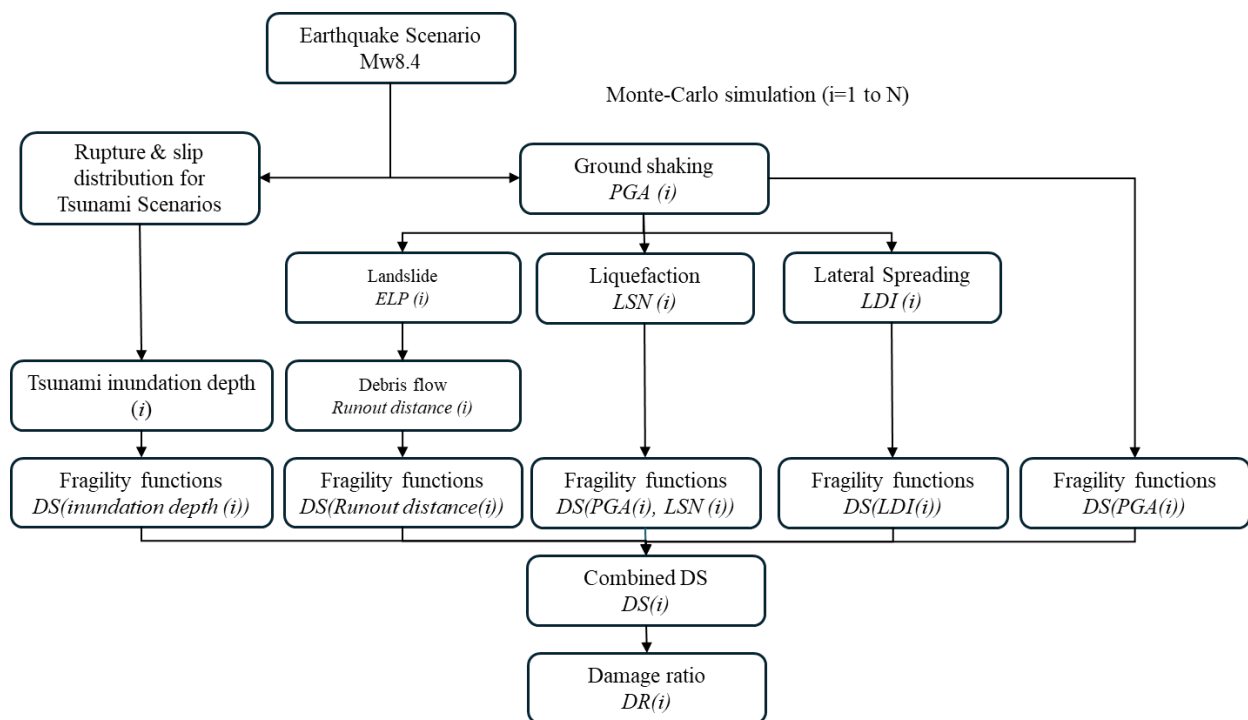


Figure 1: Methodology workflow for earthquake scenario-based cascading-hazard damage calculations (adapted from Moratalla et al., 2026).

For a given Monte Carlo simulation, we then randomly select a specific value within the probabilistic distribution of the appropriate hazard intensities or damage-state/damage-ratio functions for one realisation of the damage. We then repeat the Monte Carlo simulation repeatedly until we achieve statistical stability in our results.

3 ILLUSTRATIVE STUDY

To illustrate the methodology through a case study area, we have selected Napier city in the Hawke’s Bay region of the east coast of NZ. As the city is situated directly above the HSZ interface, it is exposed to earthquake shaking and tsunami hazards. Geotechnical investigations within the city have shown areas with liquefaction potential (Rosser and Dellow, 2017), and the presence of waterways (rivers and streams) show likelihood of lateral spreading triggered by earthquakes. Some parts of the city have hillslopes

(e.g. Bluff Hill) and previous studies have developed methods to estimate probabilities of earthquake-induced landslides (Brideau et al., 2021; Massey et al., 2021). The city has about 38,000 residential buildings (Scheele et al., 2023) and provides a good sample size to derive damage states and mean damage ratios representing regional building damage distribution. The following sections explain various models within the workflow and inputs required.

3.1 Ground-motion hazard modelling

For the chosen M_w 8.4 earthquake scenario, the ground-motion intensities are calculated using Peak Ground Acceleration (PGA) as the intensity measure. PGAs are modelled using Ground-Motion Prediction Equations (GMPE) recommended in OpenQuake (GEM). GMPEs consider factors such as the distance to the earthquake source, the earthquake magnitude, the tectonic regime and the site effects represented by mean shear wave velocity, or V_{s30} . The sources of uncertainties associated with ‘between events’ and ‘within the event’ were included for each ground-motion realisation during Monte Carlo simulations. The uncertainties in ground-motion intensities from GMPEs are defined through their respective lognormal probability distribution functions.

3.2 Tsunami hazard inundation modelling

The methodology we use to simulate the possible tsunami caused by the scenario earthquake is described in Moratalla et al. (2026). Briefly, variable slip distributions are first calculated on a rectangular finite fault source template located at the surface with a rupture geometry derived from Strasser et al. (2010) and the OpenQuake sources described in section 3.1 (GEM, 2019). We then vertically project these sub-faults vertically directly onto a subduction zone interface model based on Williams et al. (2013). The slip variations are then re-scaled to produce the seismic moment needed for an M_w 8.4 earthquake with a rigidity 40 GPa (4.5×10^{21} N.m). For each slip distribution, we then modelled the initial crustal deformation, tsunami propagation and resulting inundation into Napier using COMCOT (Cornell Multi-grid Coupled Tsunami model; Wang, 2008). The propagation is then simulated over 10 hours at the Mean High Water Spring tidal level (MHWS; mean sea level + 0.92 m in Napier). The Digital Elevation Model (DEM) used for the present study is the same one used in a previous tsunami inundation study for Napier (Fraser et al., 2014). Land-cover features, such as buildings, are deliberately removed from DEM data and replaced with corresponding equivalent roughness values for different types of land cover to simplify the computation (Wang et al., 2017). Figure 2 shows some example slip distributions for potential M_w 8.4 ruptures and their resulting tsunami inundations.

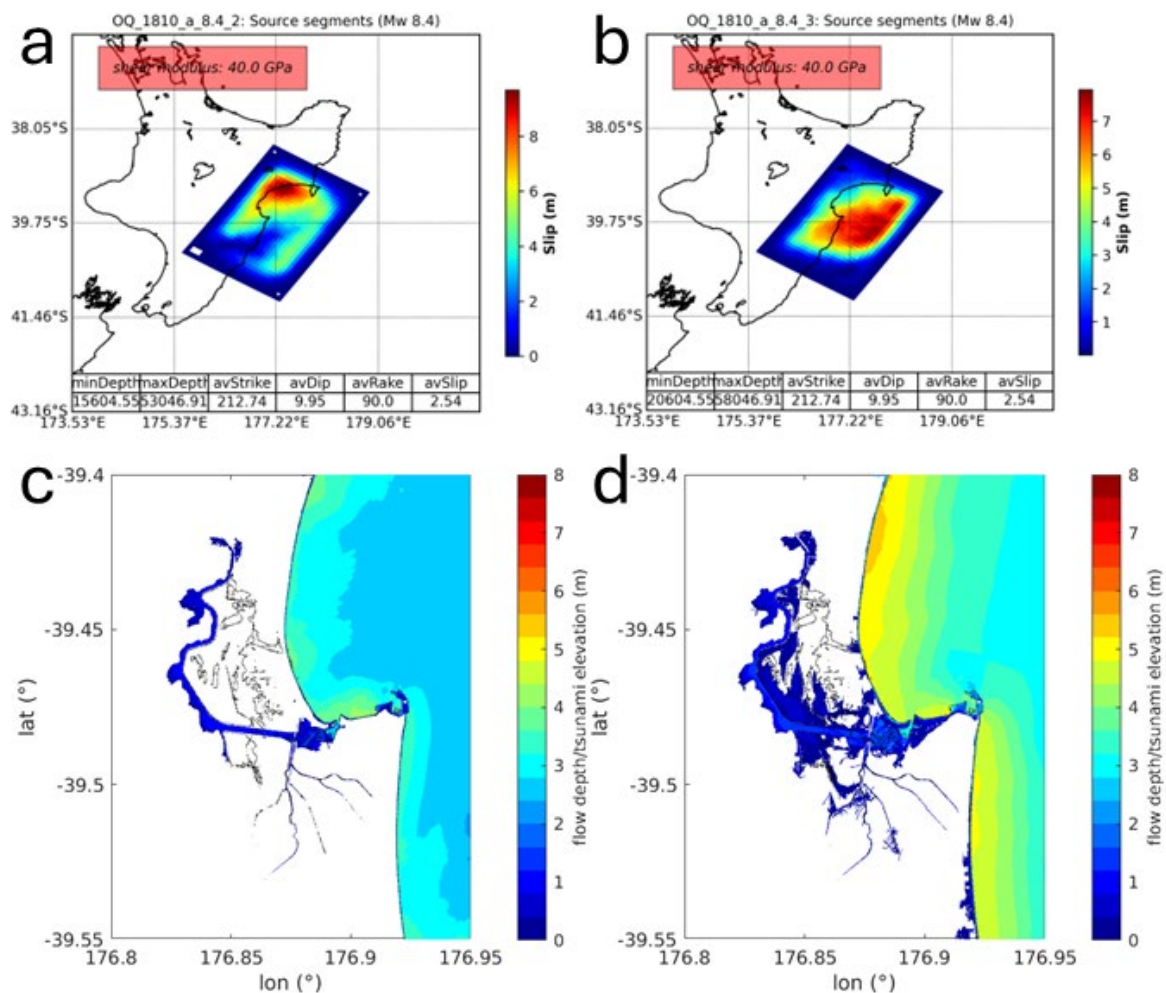


Figure 2: Examples of earthquake slip distribution variations (a, b) and resulting maximum tsunami flow depth maps (c, d) for Napier corresponding to a Mw 8.4 earthquake on the HSZ interface.

3.3 Liquefaction hazard modelling

Napier is identified with land areas susceptible to liquefaction. The study of Rosser and Dellow (2017) mapped six different liquefaction-susceptibility zones in the Napier area based on geomorphological and sedimentological information. Material variability in each zone was studied using borehole information. Within each zone, the CPT (cone penetration test) data were used to calculate potential vertical settlement (Zhang et al., 2002) within the upper 10 m depth from ground level, as well as the liquefaction severity number (LSN; Tonkin & Taylor, 2013). These values were fitted into normal distribution to enable modelling the spatial variability of LSN in that zone. Recent work by Griffin (2024) offered confidence in using the information provided by 2017 maps by analysing 17 CPT data across four of the zones. The resulting liquefaction zones are presented in Moratalla et al. (2026).

3.4 Lateral spreading

Lateral spreading is associated with the lateral displacement of the ground, and the extent of displacement can be estimated using the method proposed by Zhang et al. (2004) and is described by the Lateral Displacement Index (LDI). A further correction on LDI is applied to account for the ground slope towards a free face (for example, with a water body) measured from the building site. To model lateral displacements, higher-resolution modelling was applied to include the effects of distance and slope with respect to the free face of the waterbody (Griffin, 2024).

3.5 Landslides

An Earthquake-Induced Landslide (EIL) forecast tool (Massey et al., 2021) was used to generate the probability of a landslide being present over a grid cell within the Napier area for different levels of earthquake ground-shaking intensities. Landslide source regions were defined using empirical relationships between slope, local slope relief and landslide occurrence derived from the Kaikōura earthquake landslide inventory (Jones et al., 2024), to represent potential landslide locations. For each source region, we determined the probability of Maximum Credible Volume Class (MCVS) using the frequency-area distribution (see Moratalla et al., 2026 for details). Landslide runout was modelled using an empirical model of Fahrböschung angle, defined as the angle between the landslide source and the landslide deposit (Brideau et al., 2021). The extent of the landslide debris-inundation zones was estimated using probability of exceedance for a given volume class (100%, 84%, 50% and 16%). The EIL tool, volume class and runout probabilities were then mapped to buildings located within the debris-inundation zone to assign a damage state.

3.6 Building exposure modelling

For this study, we considered the residential building stock of Napier as the exposure model. The data were obtained from the national building inventory developed by Scheele et al. (2023) and presented a total of 38,344 buildings for the analysis. The inventory database provides information on building locations and parameters relevant for identifying appropriate fragility/vulnerability functions, such as number of storeys, construction material and year of construction.

3.7 Damage functions modelling

Two versions of damage functions are used in this study: one relates to the severity of damage sustained by the building, referred to as ‘fragility functions’, and the other uses ‘vulnerability functions’ to calculate the damage ratio, which is the ratio of repair cost to replacement cost for a specified damage state. Fragility functions are generally expressed as cumulative probability functions relating to the probability of exceeding a given damage state for varying intensity parameters. We have referred to HAZUS 2.1 to determine the fragility functions for shaking and permanent ground-displacement-related damage. For tsunamis, we have used the fragility functions derived by Suppasri et al., (2013). For liquefaction, we have used shaking fragility functions with suitable modification factors to represent the worsening effects from soil behaviour on building performance. Under landslide impact, the buildings are assigned with three levels of damage depending on the extent of interception of a runout polygon with a building footprint. As mentioned in Section 2, we have applied harmonised damage-state methodology to arrive at a single damage state that can be reasonably related to a damage ratio (expressed as ratio of repair cost to replacement value of the building), and we refer to the range of damage ratios as suggested by HAZUS. As these are based on HAZUS, which are more relevant to earthquake-related damage and repair cost ratios, these may not be truly representative of repair costs for other hazard types, an area to be addressed by future research.

4 RESULTS AND DISCUSSIONS

By carrying out 1000 Monte-Carlo simulations, we generated estimates of building-damage distribution for the Mw 8.4 earthquake scenario and related cascading hazards for Napier. The mean damage ratios (MDRs) resulting from the combined effects of all earthquake-induced hazards were widely distributed across the study region. To capture this distribution, the study area was subdivided into a regular grid with a spatial resolution of 300 m. Within each grid cell, the MDR was computed by aggregating the damage ratios of all buildings located in that subdivision. This approach enables a consistent regional comparison of damage intensity and highlights spatial patterns in earthquake-related impacts across the study area (Figure 3).

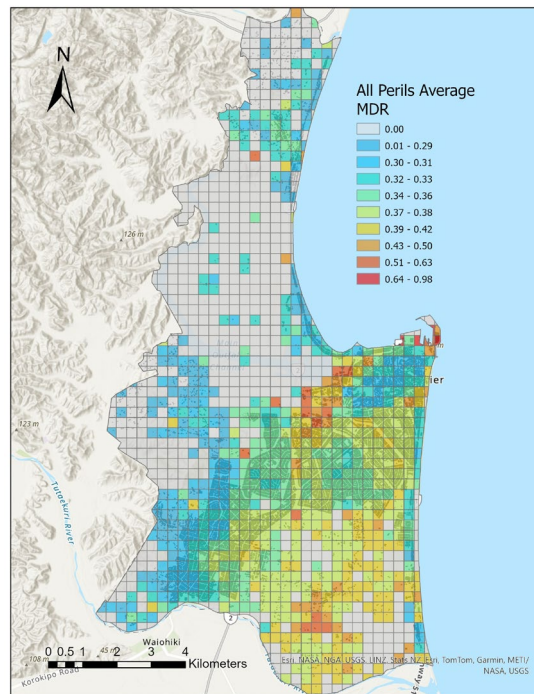


Figure 3: Mean damage ratios distributed across the region from all collective hazards caused by the earthquake.

The buildings in the study area experience differing levels of exposure to multiple hazards. While all buildings (38,344) are subjected to earthquake-induced ground shaking, the proportions of buildings exposed to and damaged by other perils are comparatively lower. Table 1 compares the contributions of different hazards to the ‘Extensive’ and ‘Collapse’ damage states (DS4& DS5), revealing clear differences in exposure, severity and spatial influence. These damage states would be of interest to end users, such as emergency managers for preparedness and response planning (e.g. life safety and temporary accommodation). Liquefaction is the most widespread cascading hazard, causing the most widespread damage. It affects 88.4% of buildings, with 50.6% of exposed structures reaching extensive or collapse damage states, highlighting liquefaction as the major cascading hazard causing widespread damage. Lateral spreading affects a smaller share of buildings (30.3%) but shows the highest relative severity, with 70.1% of exposed buildings experiencing ‘Extensive’ or ‘Complete’ damage. 14.0% of total buildings were exposed to landslide hazard potential, with 48.4% of exposed structures in higher damage states. Tsunami exposure is limited to 16.6% of buildings and contributes minimally to severe damage overall (0.3%). Overall, liquefaction dominates widespread damage, while the other hazards produce more localised but potentially severe impacts.

Table 1: Relative contributions to higher damage states (DS4 & DS5) (e.g. non-occupiable buildings) by hazard type focusing on cascading hazards.

Hazard	No. of buildings exposed	Exposure percentage	No. of buildings in extensive and collapse damage states	Relative contribution as per exposure
Liquefaction	33905	88.4%	18520	54.6%
Lateral Spreading	11617	30.3%	8145	70.1%
Landslide	5380	14.0%	2604	48.4%

Tsunami	6369	16.6%	20	0.3%
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Our future research scope includes understanding effects of a climate-change scenario 100 years from now on the cascading hazards induced by the same earthquake scenario. This will explore, for example, liquefaction due to an altered groundwater-table level, tsunami hazard inundation extent due to sea-level rise and so on. The results presented in this study will form the basis for comparing the impacts for the climate-change scenario.

5 SUMMARY

We presented a simulation-based probabilistic approach to estimate the impact from an earthquake scenario and its cascading hazards and demonstrated its features through a case study. A potential earthquake source of M_w 8.4 was chosen from the HSZ and included liquefaction, lateral spreading, landslides and tsunami as its cascading hazards and estimated their impact on residential buildings by propagating uncertainties from various sources in a systematic and logical manner. The results presented helps to understand collective impact from all hazards considered and their relative contributions, thus enabling to plan for suitable risk mitigation measures. The methodology is modular and can account for additional hazards including long-term climate-change effects.

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