Modeling earthquake hazard and risk in Australia and New Zealand

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ABSTRACT: The earthquake risk profiles of Australia and New Zealand are very different despite the geographical and cultural proximity between the two countries. Australia's earthquake hazard is not well known because of its low level of seismic activity and its short historical earthquake record. Although New Zealand has a much higher rate of seismic activity, some aspects of its risk are poorly understood, as demonstrated by the occurrence of very strong shaking and liquefaction during the 2010 – 2011 Christchurch earthquake sequence. To understand earthquake risk in both countries, we use earthquake catastrophe loss models. In both countries there has been limited historical damage data with which to validate these loss models, with the result that both have large uncertainties. Recent improvements in the accuracy of earthquake loss modeling in both countries include the use of a broadband capacity spectrum method to estimate damage ratios, allowing for the evaluation of the site-specific vulnerability of each building type to each event in the earthquake event set that is used to represent the hazard. Another development is the use of simplified methods for estimating the liquefaction hazard at each site and the calculation of losses due to liquefaction. We illustrate these issues in detail, describing how similarities or differences in modelling approaches reflect particular conditions in each country, such as those of earthquake source models, data availability, and building inventory models, using historical past events in Australia and New Zealand as test cases.

1 EARTHQUAKE SOURCE MODELS

1.1 Australia

We derived a spatially distributed earthquake source model (Hall et al., 2007) from the spatial smoothing of historical seismicity using the earthquake catalogue described by Leonard (2008). This approach was used to describe the seismic potential of the eastern United States in the U.S. National Probabilistic Seismic Hazard Maps (Frankel, 1995). The spatial smoothing approach has the advantages of simplicity and of avoiding uncertainty in the geological definitions of zones, but has the disadvantage of not making use of potentially informative geological data. The spatially distributed earthquake source model is in the form of a-values and b-values on a 10 km x 10 km grid throughout Australia.

1.2 New Zealand

We used the GNS (Stirling et al, 2012; Litchfield et al., 2014) earthquake source model for New Zealand. This source model includes two categories of earthquakes that are modelled using discrete active faults: shallow crustal faults located both onshore and offshore, and subduction interface faults. The other earthquakes, which are modeled using volume sources, include shallow crustal and subduction slab earthquakes.

2 GROUND MOTION PREDICTION MODELS

2.1 Australia

There are few ground motion recordings of earthquakes in Australia, and these are all from small magnitude earthquakes, so these data alone do not provide a direct means for developing ground motion models for Australia. Consequently, physics-based methods have been used to develop ground motion prediction models for Australia. Somerville et al. (2009) demonstrated their ability to simulate the recorded ground motions of small earthquakes that occurred in Eastern and Western Australia, and developed earthquake source scaling models for Australian earthquakes based on earthquake source modelling of the Mw 6.8 1968 Meckering the Mw 6.25, 6.4 and 6.6 1968 Tennant Creek earthquakes. They then used a broadband strong ground motion simulation procedure based on the elastodynamic representation theorem and Green's functions calculated from crustal structure models for various regions of Australia to calculate ground motions for earthquakes in the magnitude range of 5.0 to 7.5. These ground motions were then used to develop ground motion prediction equations, which were checked for consistency with available data from Australian earthquakes at each step. These ground motion models predict response spectra for two crustal domain categories: Cratonic Australia and Non-Cratonic Australia. The cratonic regions of Australia include much of Western Australia (but not the coastal strip west of the Darling Fault, including Perth); south-central South Australia (including the site); the northern part of the Northern Territory; and northwestern Queensland (Clark et al, 2011). Non-Cratonic Australia consists of the remainder of Australia, including Eastern Australia and part of the coastal margin of Western Australia, and includes all of the state capital cities.

The ground shaking level is also strongly affected by the local soil conditions at the site. Site response is represented using the National Earthquake Hazard Reduction Program (NEHRP) site classification system, following the procedure described by McPherson and Hall (2006). NEHRP classes were assigned to each mapped rock unit, based on the relationship between site class, the shear wave velocity of the top 30m, and the geological site description. The Risk Frontiers and Geoscience Australia 500 year ARP hazard maps for Australia are shown in Figures 1 and 2.

2.2 New Zealand

Bradley (2010; 2013) found that the Chiou and Youngs (2008) NGA GMPE provided the best fit of all the NGA models to the New Zealand strong motion data set (prior to the inclusion of the Canterbury Plain events). Based on the New Zealand strong motion data set, he used the functional form of the Chiou and Youngs (2008) model to develop a ground motion model for application in New Zealand, modifying some of the coefficients and adopting the remaining ones from that model. Bradley (2012) demonstrated that his model provides a better fit to the Canterbury Plain data than the McVerry et al. (2006) model. The Bradley model has the advantages of being based on a large global data set, of having been calibrated to optimally fit New Zealand data (pre Canterbury), and of being compatible with the Canterbury data. The Risk Frontiers and GNS Science 500 year ARP hazard maps for New Zealand are shown in Figures 3 and 4.

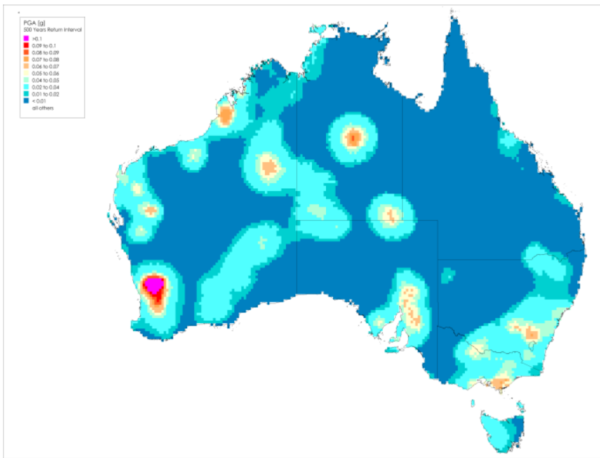

Figure 1: Risk Frontiers 500 Year Hazard Map for Australia for Local Soil Conditions

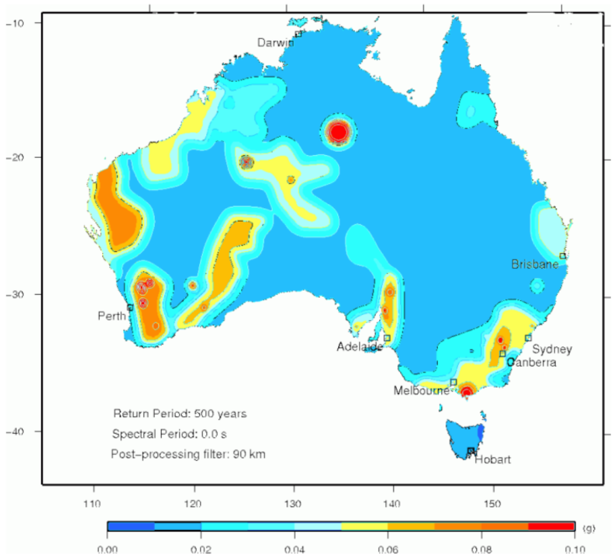

Figure 2: Geoscience Australia Preferred 500 Year Hazard Map for Rock Site Conditions, from Burbidge (2012).

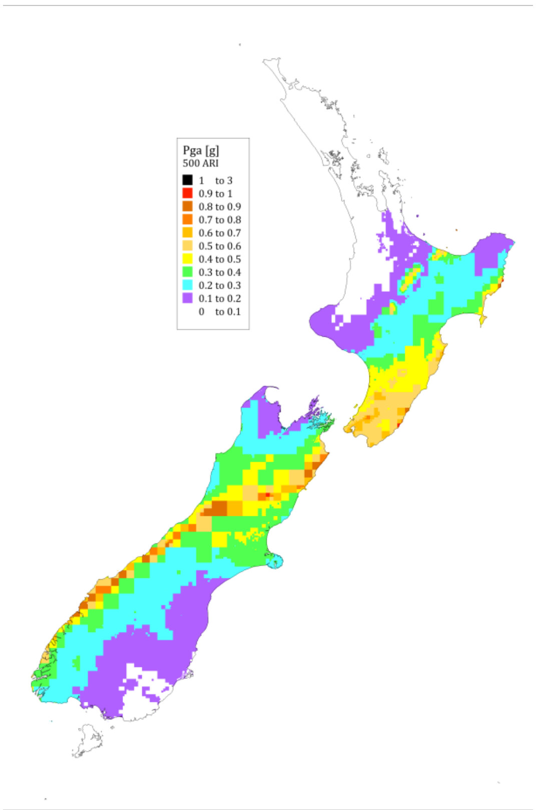

Figure 3: Risk Frontiers 500 Years Hazard Map for New Zealand for Local Soil Conditions.

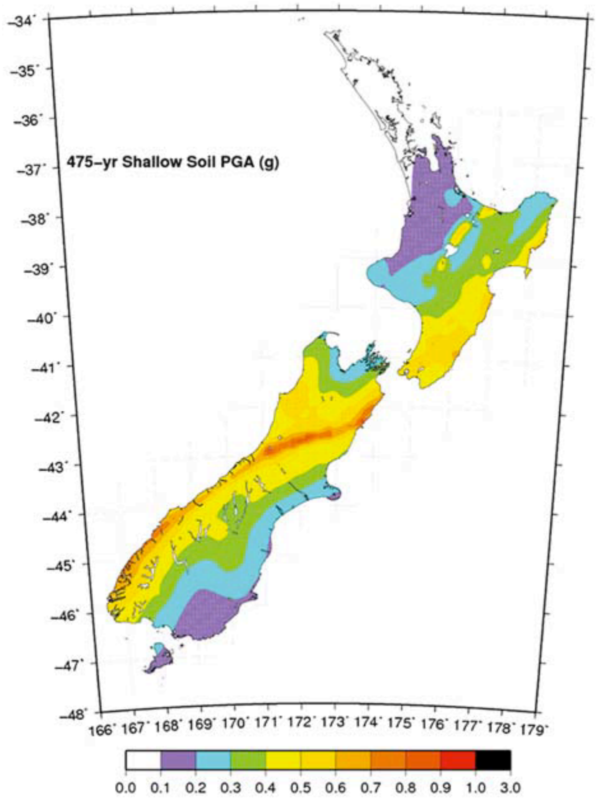

Figure 4: GA 475 Years Hazard Map for New Zealand for Shallow Soil, Stirling et al. (2012)

3 EXPOSURE

3.1 Australia

G-NAF (Geocoded National Address File) is a geocoded address index listing all valid physical addresses in Australia. It contains approximately 12.6 million physical addresses, each linked to its unique geocoded (specific latitude and longitude of the address). NEXIS (National Exposure Information System) is a database developed by Geoscience Australia containing building details for residential commercial and industrial buildings in Australia at a Statistical Area 2 (SA2) level. There are 2214 SA2 in Australia. G-NAF and NEXIS data are aggregated at the variable resolution calculation grid level. Whenever data from NEXIS are not available, a conservative approach is assumed, considering every building to be low-rise unreinforced masonry. Wood, Mid-rise Steel, Concrete, and Reinforced Masonry and low-rise Unreinforced Masonry buildings damage ratios are always computed to allow for personalised portfolios.

3.2 New Zealand

We select the building types and vintages to include in QuakeNZ based on review of the literature on the building stock in New Zealand (Kam et al. (2011), Uma et al. (2008), King and Bell. (2006)): light wood frame, reinforced and un-reinforced masonry buildings of a variety of vintages have been considered to be representative of the residential exposure. We also designed a market portfolio as an ensemble of the modeled buildings. Unlike in Australia, where the NEXIS database has been developed by GA, we do not have information about a local building stock composition and therefore the market portfolio is assumed to be the same nationally.

4 BUILDING DAMAGE ESTIMATION

4.1 Methodology

Building damage is estimated using a broadband capacity spectrum method based on the HAZUS99 methodology (Kircher et al., 1997) that takes account of the balance between capacity and demand.

The capacity curve describes the capacity of the building to withstand earthquake ground shaking, described by its static pushover curve, which describes its expected drift (horizontal displacement of the roof relative to the ground) as a function of the base shear (horizontal acceleration of the ground). The capacity curve is based on simplified characteristic engineering parameters that reflect the construction material, lateral stability system and stiffness degradation of the building as shaking progresses. The demand curve describes the level of ground shaking that the building is subjected to, represented by the response spectrum of the ground motion

Damage for a given level of ground shaking intensity is estimated by determining the structure's performance point, which is conceptually represented by the intersection of the capacity and demand curves when both are expressed in terms of spectral acceleration and spectral displacement. This level of building deformation must be determined iteratively due to the nonlinear interaction of stiffness degradation and hysteretic damping with spectral demands. Demand curves are iteratively modified to account for the energy dissipated by plastic deformation. This extra damping acts to further reduce the performance point.

The performance point is then used to generate a set of four fragility curves that estimate the probability of a building being in one of four particular damage states – none, slight, moderate, extensive or complete as a function of peak ground acceleration. Damage is summed from structural damage due to displacement and non-structural components sensitive to both displacement and acceleration. Similar fragility curves are also used for contents damage, which is considered to be sensitive to acceleration.

Conventional earthquake loss estimation uses fragility functions that have been precomputed using standard capacity curves for each building category of interest, using a simplified representation of the demand curve. Instead of representing the entire broadband response spectral shape of the ground motion, the demand curve is conventionally specified by prescribing a single ground motion parameter, usually the peak acceleration or the response spectral acceleration at a period of 1 second, and scaling a standard response spectral shape to that value.

However, the shape of the demand curve (the broadband response spectrum of the ground motion) varies with many factors, including the earthquake magnitude, earthquake category, distance, and soil category at the site. Accordingly, our loss model dynamically calculates fragility curves for each building category at each site for each earthquake in the event set. This produces building- and event-specific fragility curves for each building category for each event, enhancing the accuracy of the loss calculation.

The demand curves are calculated at the centroid of an orthogonal variable resolution grid which is refined with increasing exposure. Figure 5 shows the implementation for New Zealand. This allows for the optimal use of resources and the highest resolution where most needed.

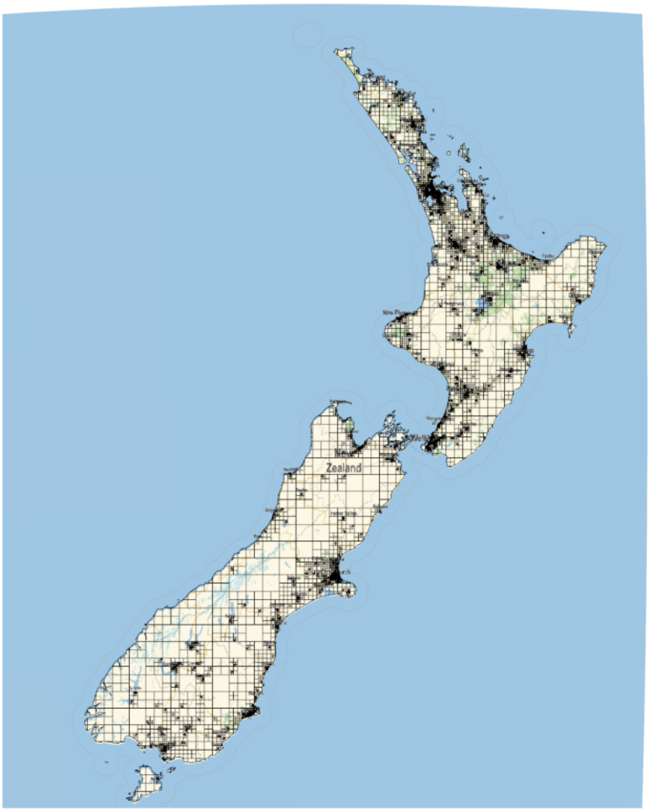

Figure 5: Variable Resolution Grid in New Zealand

4.2 **Implementation in Australia**

The variable resolution grid for Australia is created using the G-NAF database. The cells' sizes range between 200 km and 1.6 km and host a maximum of 800 addresses each. QuakeAus analyses building and content residential property losses, and building, content and business interruption losses for commercial and industrial properties.

Although HAZUS99 is a general and powerful tool, damage curves generated using HAZUS99 only capture the average performance of a limited set of regular, conventional structural systems. Although certain specific elements of building information such as height and local soil conditions can explicitly be incorporated, the detrimental impact of plan and vertical irregularities on the average building performance will not be captured.

Accordingly, we used the FEMA Rapid Visual Screening (RVS; ATC, 2002) in the field to assess about 50 buildings in Perth and Sydney in order to test the reliability of the HAZUS99 methodology in Australia. The RVS provides a procedure for identifying buildings that might pose serious risk of loss of life and injury, or severe curtailment of community services when a damaging earthquake occurs. Surveyed buildings are divided into two categories: those acceptable as to risk to life safety, and those that may be seismically hazardous and should be analysed in more detail by a professional engineer experienced in seismic design.

This performance is encapsulated by the RVS score, which corresponds to the likelihood of total building collapse at a single hazard level, the maximum considered event (MCE) earthquake. With both the FEMA and HAZUS99 frameworks, the MCE earthquake is assumed to correspond to an event with a recurrence interval of ≈ 2,475 years, or alternatively an event having a 2% chance of being exceeded in the nominal assumed design life of standard building structures, 50 years. Our conclusion from this analysis is that the HAZUS fragility curves we have used provide a conservative representation of the collapse probabilities of the buildings that we examined in the field.

We have tested QuakeAUS by comparing actual and modelled losses from a set of seven Australian earthquakes. There is a large degree of variability in the degree of agreement between actual and modelled losses in individual events. For example, the 1968 Mw 6.8 Meckering earthquake was unusual in that it ruptured downdip, from shallow depths to deeper depths. This caused most of the energy to be focused downwards and away from the ground surface. The downward and eastward rupture directivity of the Meckering earthquake away from Perth is clearly manifested in the intensity pattern of the earthquake. The intensities were low generally and especially in Perth. We do not take rupture directivity into account in our loss modeling, causing the predicted damage to exceed the actual value in this case. It is appropriate that our model behaves this way, because most earthquakes will not behave like Meckering.

The damage caused by the 1989 Newcastle earthquake was concentrated in a region immediately southwest of Newcastle. Using the preferred epicentral location of the Newcastle earthquake causes a concentration of damage southwest of the actual zone of damage concentration and a gross underestimate of the actual losses. However, if we allow for the uncertainty in the location of the Newcastle earthquake and move its hypocenter to the northeast, then we are able to reproduce both the observed pattern of damage and the losses caused by the earthquake, as shown in Figure 7.

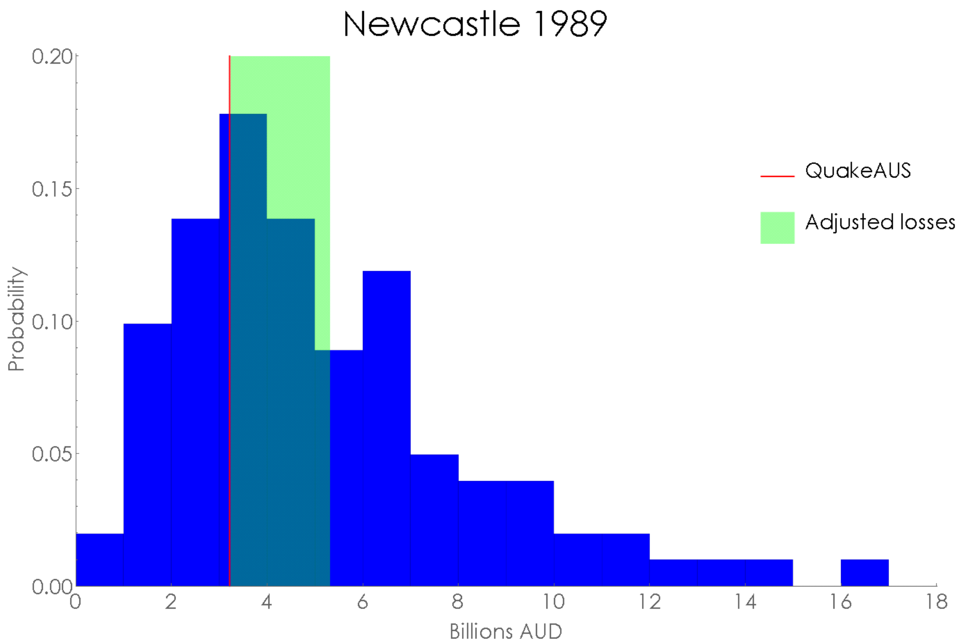

Figure 6: 1989 Newcastle Earthquake, Total Loss. Blue: QuakeAus simulation, Red line: Median result from QuakeAus, Green: Adjusted losses in today's values.

4.3 **Implementation in New Zealand**

The variable resolution grid for New Zealand is created using the Linz NZ street addresses database. The cells' sizes range between 32 km and 500 m and host a maximum of 200 addresses each. The current release of QuakeNZ analyses only building and content residential property losses.

QuakeNZ includes a liquefaction model on top of the ground shaking loss model which is similar to the one developed for QuakeAus. We analysed liquefaction exposure and developed ratings by overlaying data on elevation, Vs30, distance from water bodies (rivers, lakes and coastline) and lithology following the approach of Knudsen et al. (2009), to produce a liquefaction potential hazard map, Figure 7, which assigns to each location a risk category ranging from None to Very High in six steps. While the methodology was developed following the Knudsen approach, we also considered the liquefaction occurrence during the Canterbury sequence of events in 2010-2011 in devising the threshold limits for the risk categories. We follow the HAZUS methodology to determine the expected lateral spreading displacement given a certain liquefaction potential risk and PGA. We then model the probability of a building sustaining extensive or complete damage due to liquefaction-induced lateral spreading as a cumulative lognormal distribution function as suggested by HAZUS.

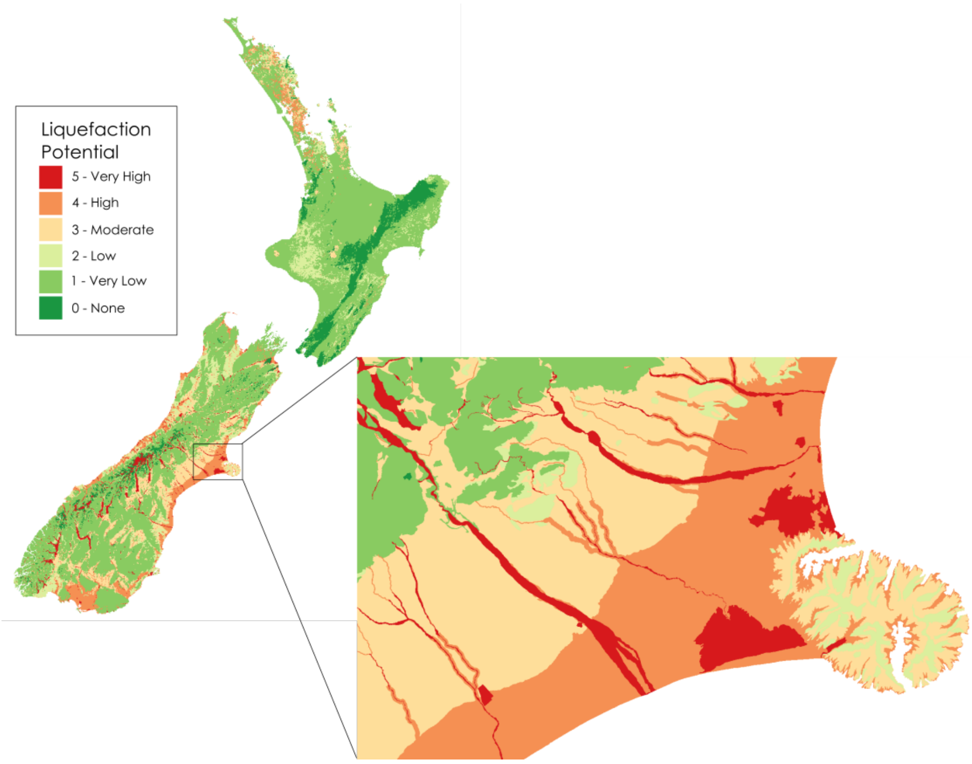

Figure 7: Liquefaction Potential Hazard Map for New Zealand

We tested QuakeNZ by comparing actual and modelled losses from the 2010 Darfield earthquake, with the results shown in Figure 8. Losses include building and content damage for residential properties and are modeled using both the ground shaking and the liquefaction models. Losses are compared with the actual claims for that event (Source: EQC). The actual losses fall well within the range of possible scenarios simulated by QuakeNZ for the Darfield event.

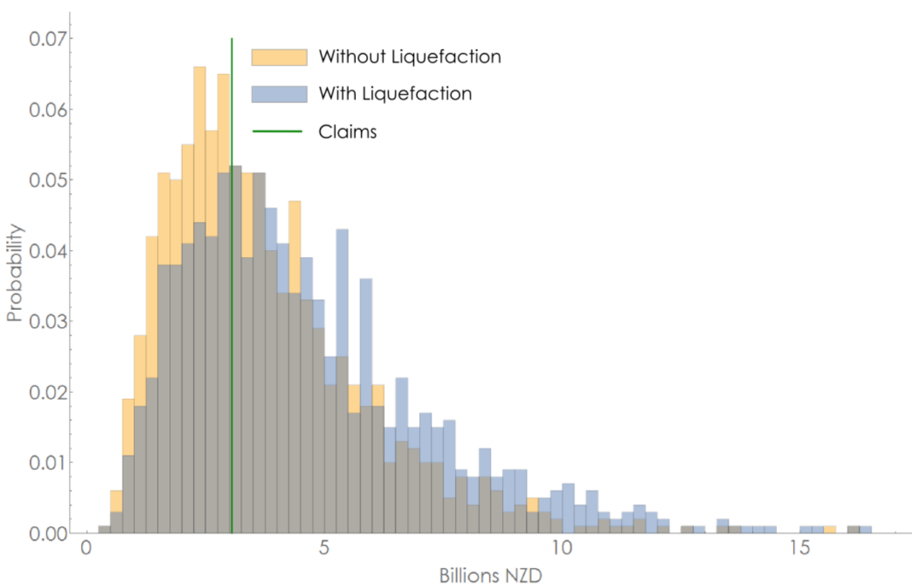

Figure 8: Darfield Earthquake, Building and Content Residential Losses. Histograms: QuakeNZ simulation, Green line: estimated actual claims.

CONCLUSIONS

Although the earthquake hazard and risk profiles of Australia and New Zealand are quite different, we have been able to develop earthquake loss models for both countries using similar methodologies. In

Australia, we use an earthquake forecast model based on the spatial smoothing of historical seismicity, whereas in New Zealand we use seismic source zones and active faults to generate the earthquake forecast. Ground motion prediction models for Australia are based mainly on physics-based strong ground motion simulations because of the sparsity of strong motion recordings, whereas the model for New Zealand is based on modifying models derived from other regions using New Zealand data. In both countries, we use a broadband capacity spectrum method to estimate damage ratios, allowing for the evaluation of the site-specific vulnerability of each building type to each event in the earthquake event set that is used to represent the hazard. We also use a simplified method to estimate liquefaction hazard and calculate losses due to liquefaction. We illustrate the implementation of these methods in both countries using historical earthquakes as test cases.

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