Time-varying and long-term mean aftershock hazard in Wellington

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2014 NZSEE Conference

ABSTRACT: The New Zealand National Seismic Hazard model (NSHM) follows the well-established practice of most probabilistic seismic hazard analysis (PSHA) to exclude aftershocks from the hazard estimations. A Task of the 'It's Our Fault' Project investigates whether there are any potential deficiencies in the currently used uniform hazard spectra for Wellington due to the exclusion of aftershocks. In this study, we distinguish between time-varying and long-term mean aftershock hazard. Time-varying aftershock hazard represents the average annual decay of aftershocks over a period of 50 years following a main shock. For long-term aftershock hazard we spread the temporal occurrence of aftershocks over the recurrence interval of the fault rupture. We model aftershocks using the Short-Term Earthquake Probability (STEP) model. We calculate the time-varying annual frequency of exceedance of peak ground acceleration (PGA) for up to 50 years after a main shock and compare the hazard curves from the aftershocks alone to the NSHM. The shapes of the curves are quite different; and only after about 30 years is the aftershock hazard less for all PGAs than from the NSHM. For the long-term hazard, we include four major Wellington fault sources and replace the NSHM background seismicity model with the time-averaged aftershock rates from these sources. The difference in absolute acceleration in comparison to the NSHM peaks at about 0.1 second. The accelerations increase by a maximum of around 10%, 20%, 38% and 70% for return periods of 2500, 1000, 475, and 150 years respectively. Both our approaches are simplified methods to illustrate the potential effects of including aftershocks in PSHA.

1 INTRODUCTION

The New Zealand National Seismic Hazard model (NSHM; (Stirling et al., 2002; Stirling, et al. 2012) is the basis for seismic hazard assessment in New Zealand. The NSHM applies the well-established practice of probabilistic seismic hazard analysis (PSHA). There are three key components to PSHA: the fault source model, the distributed source model, and ground motion prediction equations (GMPEs). The distributed source model is derived from earthquake catalogues. As is standard practice in PSHA, aftershocks are removed from the earthquake catalogue. The most notable major New Zealand aftershock sequence, the Canterbury earthquake sequence, increased the seismicity rate in Canterbury drastically. This warranted the development of a new time-varying seismic hazard model for the previously low hazard Canterbury region because the NSHM was expected to underestimate the seismic hazard due to on-going aftershocks and the possibility of further triggered earthquakes (Gerstenberger et al., 2014). One task of the 'It's Our Fault' Project set out to investigate whether there are any potential deficiencies in the currently used probabilistic Wellington earthquake design spectra due to the exclusion of aftershocks (Rhoades et al., 2012). In this paper, we distinguish between time-varying and long-term mean aftershock hazard. For the time-varying aftershock hazard we calculate annual aftershock rates for the first 50 years following a scenario M7.5 Wellington Fault earthquake as further explained in Section 2.1. For the long-term mean aftershock hazard we normalise the number of aftershocks expected in 50 years by the mean recurrence interval of the main shock for four major faults in the Wellington region as further explained in Section 2.2. Section 3 briefly discusses the parameters that had to be changed in the hazard runs compared to the standard NSHM application. Section 4.1 discusses how the annual frequency of exceedance of peak ground accelerations (PGA) decays with time from the main shock. We also show the 10% probability of exceedance of PGA in g for selected years as a function of period. Section 4.2 compares the hazard spectra for shallow soil (subsoil class C, Standards New Zealand 2004) in central Wellington, for return periods of 150, 475, 1000 and 2500 years for the NSHM where the standard distributed source model rates are replaced by the long-term mean aftershock rates. This paper closes with discussions and conclusions.

2 AFTERSHOCK MODELLING

To calculate aftershock occurrence rates we use the Short-Term Earthquake Probability (STEP) aftershock model (Gerstenberger, 2003; Gerstenberger et al., 2005). The model normally comprises two components: 1) a background seismicity model; and 2) a time-dependent clustering model. In our simplified application of the model, it does not include a background model, as it pertains to the aftershock occurrence only. The average aftershock rates are calculated based on the Omori-Utsu law for aftershock decay (Utsu et al., 1995) with average parameters for New Zealand (Pollock, 2007). A previous study in the 'It's Our Fault' Project demonstrated the sensitivity of the number of large aftershocks to different aftershock models and varying model parameters (Christophersen et al., 2013). Here the aftershock model is kept simple and representative of the average New Zealand aftershock behaviour for crustal faults. The locations of the aftershocks depend on the location of the fault. Figure 1 shows two-segment lines based on the NSHM that simplify the location of each of the four faults considered in this study. The aftershock rate tapers off according to the inverse square of the distance from the fault. For this Wellington focussed project, the aftershock rates were estimated on a 0.05-degree-squared grid in a region between latitude 42.8°S and 39.8°S, and longitude 172.8E and 176.8E, and in magnitude bins of width 0.1 magnitude units centred on magnitude 5.0, 5.1, and so on up to magnitude 7.9. Thus, the spatial grid spacing is such that no spatial resolution of hazard at a finer scale than about 5 km is possible. The depth distribution of aftershocks is accounted for in the hazard calculations as further explained in section 3.

2.1 Time-varying aftershock modelling

For the time-varying analysis, the aftershock rates for the Wellington Fault are estimated annually for each of the 50 years following the main shock. Table 1 shows the total expected rate of M≥5.0 earthquakes for the years selected for the hazard calculations in Section 4.1. In comparison, the annual rate of the NSHM is 0.87 as included in the New Zealand earthquake forecast centre (Gerstenberger & Rhoades, 2010) for the specified region. The total rate over 50 years for the STEP model is 103.4 compared to 43.5 from the NSHM for 50 years.

Table 1. The total rate, i.e. number of earthquakes per year of M≥5.0, for the years selected for presentation in Figure 3, compared with the annual rate for the NSHM in the same area.

Year	1	2	3	4	5	10	15	20	25	30	35	40	45	50	NSHM
Rate	81	4.3	2.4	1.7	1.3	0.57	0.37	0.27	0.21	0.17	0.14	0.13	0.11	0.10	0.87

2.2 Long-term mean aftershock modelling

Here we follow the approach undertaken by Rhoades et al. (2012) to annualise the aftershock occurrence by dividing the aftershocks that occur in 50 years by the mean recurrence interval of the main shock. We extend the method by including three further fault sources. Table 2 lists the four fault sources, their magnitude, recurrence interval, the number of M≥5.0 aftershocks in 50 years, and the average number of M≥5.0 aftershocks per year. Figure 1 compares our two-segment simplification of the four fault sources to the fault segments provided in the NSHM fault file, and highlights the location used in the hazard calculations. Figure 2 shows the annual rate density relative to a reference rate (RTR) in which one earthquake per year exceeding magnitude m is expected in an area of 10^m km^2. The aftershock rate file replaces the distributed source model in the hazard calculations.

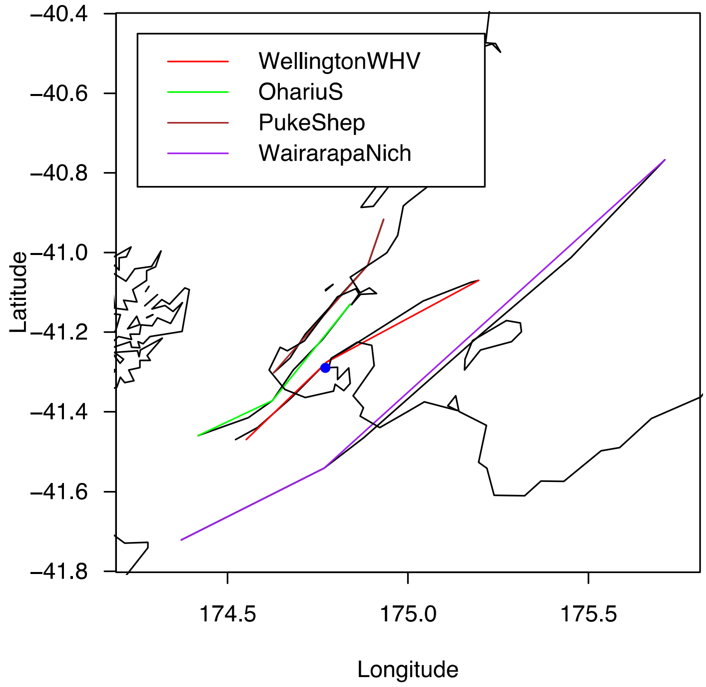

Figure 1. The two-segment simplification of the four fault sources included in the long-term aftershock hazard modelling (in colour) compared to the fault segments provided in the NSHM fault model (black lines) used in Stirling et al (2012). The blue point shows the location of the Wellington site used in the hazard calculations.

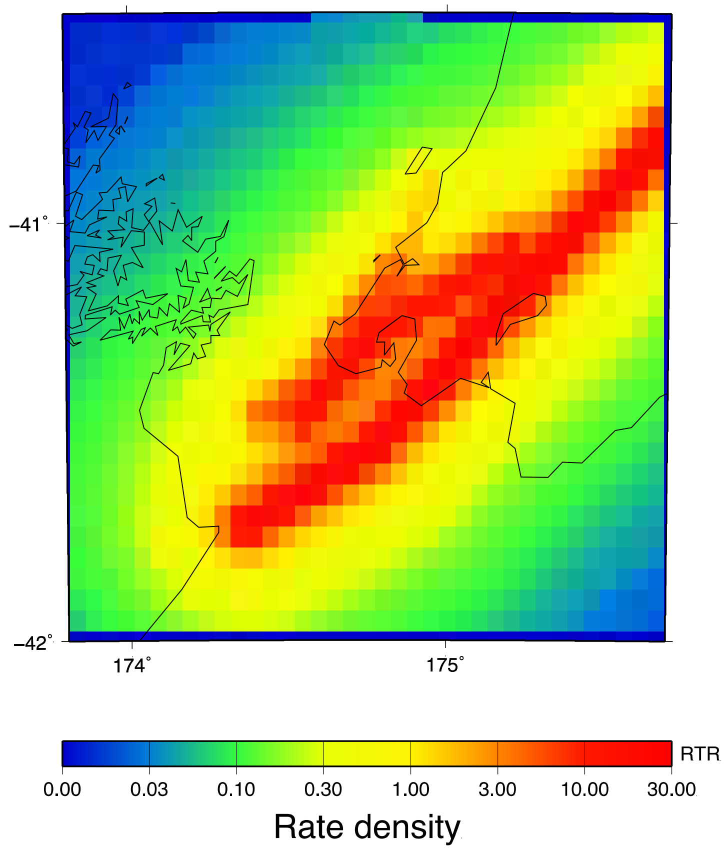

Figure 2. The first 50 years of expected aftershocks from characteristic main shocks on the four selected fault sources in the Wellington region, averaged over the expected return period of the respective faults. The rates are calculated at M5.0 and are relative to a Reference rate (RTR) in which 1 earthquake per year exceeding magnitude *m* is expected in an area of 10^m km^2. The maximum rate plotted is 23.2 RTR.

Table 2. Magnitude, recurrence interval, number of M≥5.0 aftershocks in 50 years, and the average number of M≥5.0 aftershocks per year for the four fault sources included in the long-term aftershock hazard modelling. Magnitude and recurrence interval are from Stirling et al. (2012).

Fault source in NSHM	Magnitude	Recurrence interval (years)	Number of M ≥ 5.0 aftershocks in 50 years	Number of M ≥ 5.0 aftershocks per year
Wellington	7.5	840	103	0.123
Wairarapa	8.2	1200	544	0.453
Ohariu South	7.4	2500	82	0.009
PukeShep	7.3	7000	64	0.033

3 RUNNING THE NATIONAL SEISMIC HAZARD MODEL

The NSHM calculations allow for various parameter options. The new Canterbury hazard model led to a few additional options that we use for the aftershock hazard calculations. The key difference between the standard NSHM and the Canterbury hazard model is the form of the distributed source model. For the NSHM the distributed source model is specified with the *a*- and the *b*-values of the magnitude-frequency relation at different depth layers and for different tectonic zones, including their preferred focal mechanism (Stirling et al., 2012). For the Canterbury model (and the aftershock hazard calculations) the distributed source model is given on a spatial grid and in magnitude bins for all depths. The depth distribution and the preferred focal mechanism are specified separately in the input parameter file. Table 3 compares the mechanism and depth distribution of earthquakes for the Canterbury model with the values selected for the Wellington aftershock modelling.

Table 3. The mechanism and depth distribution of aftershocks for the Canterbury model and the Wellington model used here. 'rs' and 'ss' stand for reverse strike slip and strike slip respectively.

Location	Mech.	Six depths , in km, and associated weights in brackets					
Canterbury	rs	1 (0.03)	2 (0.08)	5 (0.33)	10 (0.37)	20 (0.15)	30 (0.04)
Wellington	ss	3 (0.01)	5 (0.15)	10 (0.33)	15 (0.33)	20 (0.15)	25 (0.03)

Another difference between the hazard models is that the standard NSHM uses the McVerry (2006) GMPEs for which the standard error is magnitude-dependent. They are greatest for magnitude 5.0 and less, and then decline over the M5.0 to 7.0 range to reach the minimum value for magnitude 7.0 and greater. The magnitude-dependent sigma becomes poorly constrained for the smaller magnitudes. Smaller magnitutudes are dominating the hazard calculations in the aftershock model. In this study we use the standard error value of magnitude 6 over all magnitude ranges. This is also the case in the Canterbury model (Gerstenberger, et al, 2011).

When applying the NSHM for engineering purposes the forecasted ground motions are usually magnitude weighted, i.e. amplitudes of smaller magnitude earthquakes are relatively down-weighted to account for the shorter duration of shaking they cause, which is known to be less damaging to structures than longer duration shaking. For the NSHM, the magnitude-weighting factors are those originally proposed by Idriss (1981). For our study, the Idriss magnitude-weighting factor is extended across all periods, rather than just to 0.5s, as was the case for the Canterbury model (Gerstenberger et al., 2014).

Our calculations are for shallow soil (subsoil class C, Standards New Zealand 2004) and earthquakes of magnitude of 5.0 and greater. For the NSHM and the long-term average aftershock hazard we use the standard fault source model. For the time-varying aftershock hazard we exclude the fault source model from the hazard calculations.

4 RESULTS

4.1 Time-varying aftershock hazard

Figure 3 shows the annual frequency of exceedance of PGA for Wellington for selected years following a M7.5 main shock on the Wellington Fault. The hazard is only from the aftershocks and does not include any contribution from other fault sources. The green line shows the long-term hazard from the NSHM as reference. Hazard spectra for the NSHM are calculated for return periods of 150, 475, 1000 and 2500 years, where the 475 years return period corresponds to a 10% probability in 50 years exceedance of PGA. The concept of return period which assumes uniform earthquake occurrence is not relevant for an aftershock rate that decays from year to year. Figure 4 shows the annual 10% probability of exceedance PGA in g for selected years.

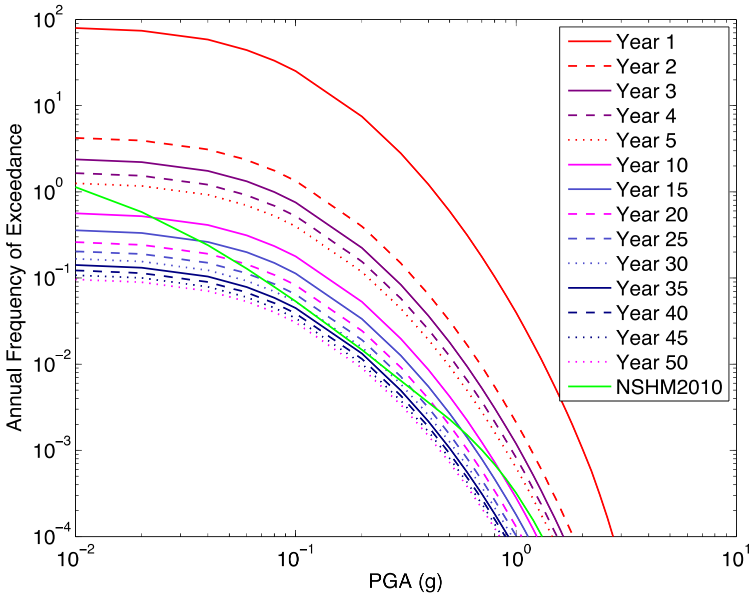

Figure 3. The annual frequency of exceedance of peak ground acceleration (PGA) in Wellington for selected years following a M7.5 main shock on the Wellington Fault. The green line is the long-term hazard from the NSHM.

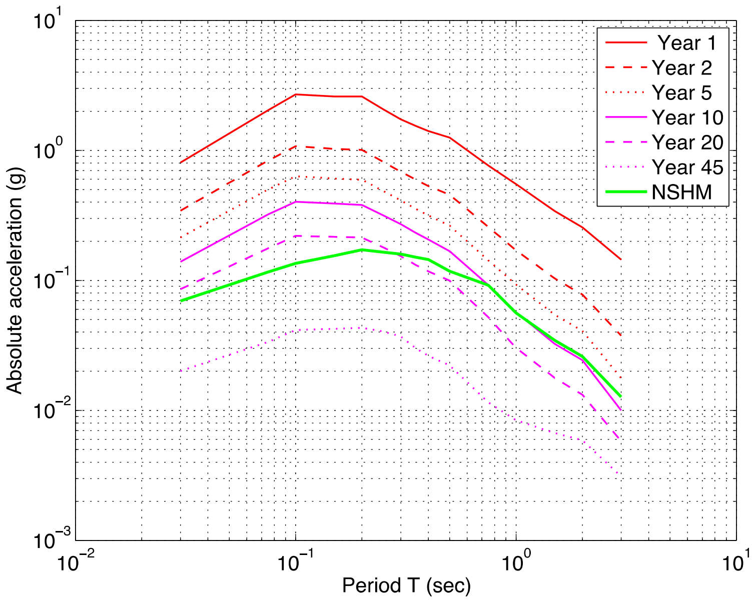

Figure 4. Hazard spectra with an annual 10% probability of absolute acceleration in Wellington for selected years following a M7.5 main shock on the Wellington Fault, compared with the NSHM.

4.2 Long-term mean aftershock hazard

Figure 5 compares the annual frequency of exceedance of peak ground acceleration for shallow soil (subsoil class C) in central Wellington for the NSHM of Stirling et al. (2012) with the annualised mean aftershock rate, for the four major faults we considered in the Wellington region and listed in Table 2. We calculated spectra for both models for return periods of 150, 475, 1000 and 2500 years, which are shown in Figure 6. To make comparison between the two models easier we calculated the ratio of the spectra as shown in Figure 7.

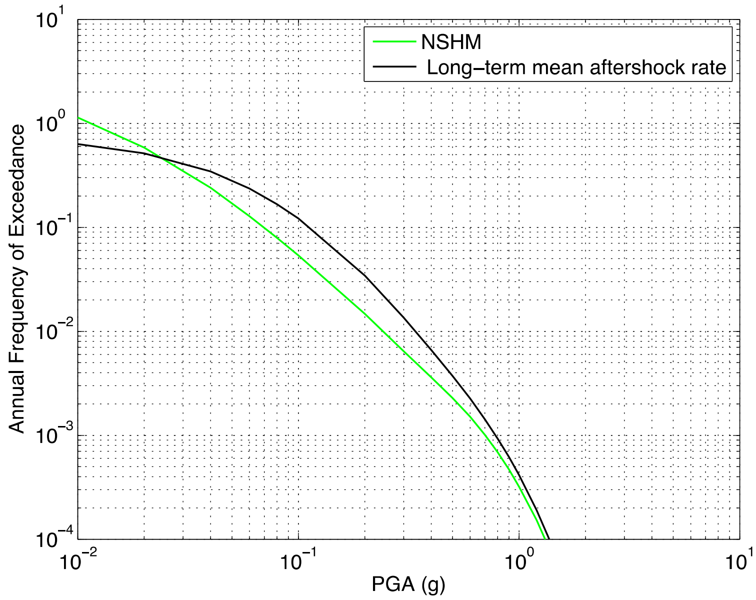

Figure 5. The annual frequency of exceedance of peak ground acceleration (PGA) in g for shallow soil (subsoil class C, Standards New Zealand 2004) in central Wellington for the NSHM of Stirling et al. (2012) and the long-term mean aftershock rate for four faults in the Wellington region.

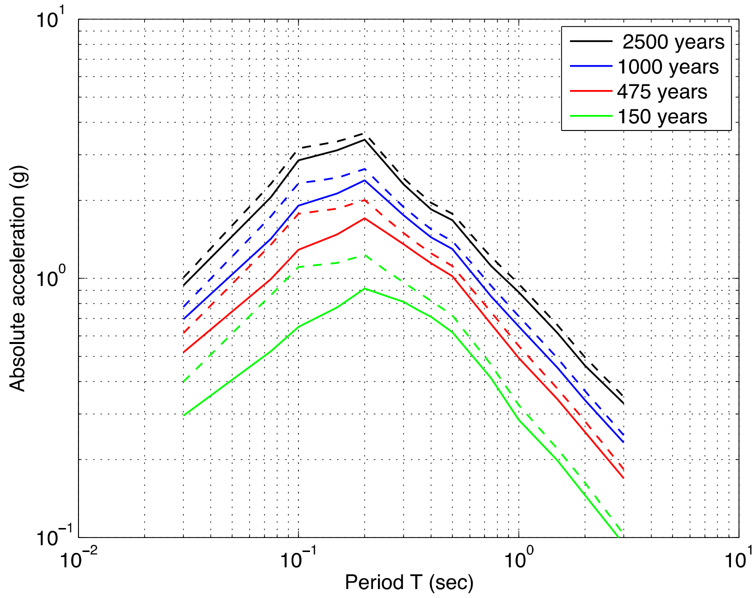

Figure 6. Spectra for shallow soil (subsoil class C, Standards New Zealand 2004) in central Wellington, for return periods of 150, 475, 1000 and 2500 years. Solid curves are for the NSHM of Stirling et al. (2012). Dashed curves are for the fault sources of the NSHM together with the long-term mean aftershock rate for the four specified major faults in the Wellington region. PGA (0.0 sec period) is plotted at 0.03 sec period to enable the spectra to be shown in log-log scale.

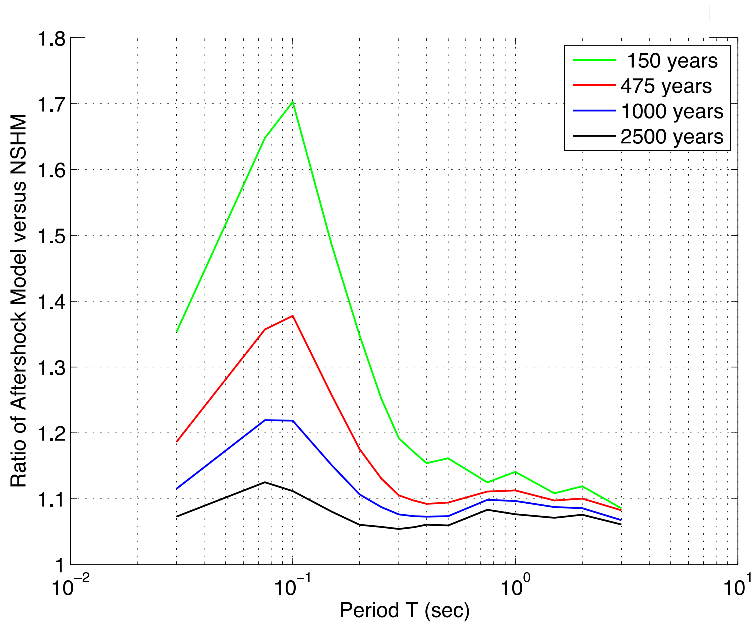

Figure 7. Ratio of the simplified long-term mean aftershock model spectra divided by the NSHM spectra for Wellington for return periods of 150, 475, 1000 and 2500 years.

5 DISCUSSION

Figure 3 shows that the shape of the time-varying aftershock hazard curves, i.e. the annual frequency of exceedance of PGA, differs from the shape of the hazard curve for the standard NSHM. The aftershock hazard curves are flatter for small PGAs up to about 0.1g and then decay faster for larger PGAs than the NSHM. The flat shape for small PGAs could be caused by the limited area considered in the aftershock seismicity model so that no very distant and small ground motions are observed in the hazard calculations. The difference in shape remains when the fault data is added to the hazard model for the long-term average aftershock model in Figure 5.

Figure 3 shows that it takes more than 30 years following a main shock on the Wellington Fault, for the hazard from aftershocks alone to drop below the NSHM for all ground accelarations. The aftershock model does not account for background seismicity that would occur within a 30 year period.

When averaging the aftershocks over the 50-year period, the annual average is 2.1 and thus the average hazard curve would fall between the curves of year 3 and year 4 in Figure 3.

Replacing the distributed source model in the NSHM by long-term mean aftershock rate for four faults in the Wellington region led to an increase in the absolute acceleration (Figure 6). The difference in absolute acceleration in comparison to the NSHM peaked at about 0.1 second. The accelerations increased by a maximum of around 10%, 20%, 38% and 70% for return periods of 2500, 1000, 475, and 150 years respectively (Figure 7). The largest increase is at periods below 1s.

6 CONCLUSIONS

Our study highlights that it is important to consider the effects of aftershocks in hazard modelling. The mean long-term aftershock hazard in Wellington from four faults in the Wellington region is higher than the hazard from the distributed source model in the NSHM. This is without considering the aftershocks of a subduction zone earthquake, which was beyond the scope of the current project to be modelled. The time-varying hazard from aftershock rates alone is higher than the NSHM for all PGAs for five years after the main shock on the Wellington Fault, and it takes more than 30 years following a main shock on the Wellington Fault, for the hazard from aftershocks alone to drop below the NSHM for all ground accelarations. Further work is on-going to address how to best include aftershocks in seismic hazard modelling and subsequent versions of the New Zealand National Seismic Hazard Model.

7 ACKNOWLEDGEMENTS

This study is part of the 'It's Our Fault' project funded by the Earthquake Commission, Accident Compensation Corporation, Wellington City Council, Wellington Region Emergency Management Group, and Greater Wellington Regional Council and Natural Hazards Research Platform. Preparation of this manuscript was supported by public research funding from the Government of New Zealand. We thank Hannah Brackley and Rob Buxton for reviewing this manuscript.

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