Appendix D: Probabilistic Seismic Hazard Analysis for Christchurch Soil Sites

- **Report prepared by Bradley Seismic Ltd.**

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Seismic hazard analysis for urban Christchurch accounting for the 2010-2011 Canterbury earthquake sequence

Technical Report Prepared for the New Zealand Earthquake Commission (EQC) and Tonkin and Taylor Ltd.

Brendon A. Bradley[1,2]

[1]Director, Bradley Seismic Limited

[2]Senior Lecturer, Department of Civil and Natural Resources Engineering, University of Canterbury

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Executive Summary

This report presents seismic hazard estimates for urban Christchurch based on state of the art methods. The on-going Canterbury earthquake sequence is directly incorporated in the adopted earthquake rupture forecast (ERF) based on a first-principles analysis of the observed earthquake activity rates and empirical models based on the Gutenberg-Richter and modified-Omori aftershock laws.

The seismic hazard analyses performed suggest that the PGA seismic hazard averaged over the next 50 years is 40-50% higher than that prior to the Canterbury earthquake sequence. However, the magnitudes which dominate this seismic hazard are 0.3-0.5 M_w units lower than the pre-2010 hazard.

Using a commonly adopted magnitude scaling factor, MSF, magnitude-correct PGA values, $PGA_{7.5}$, are determined from the seismic hazard analysis results in this study. Comparison with the provisional design values in the MBIE guidelines suggests that those values are a factor of 2-3 greater than the values obtained here based on rigorous first-principles analysis, and therefore an urgent reassessment of the MBIE values is warranted.

1. Introduction

The 2010-2011 Canterbury earthquake sequence produced significant ground motion shaking in urban areas of Christchurch, and associated damage. Although the activity rates associated with this sequence have reduced significantly there is still an on-going seismic hazard associated with this sequence that is not adequately accounted for in prior forecasts. The intention of this document is to illustrate the magnitude of the increased seismic hazard resulting from this on-going sequence.

Section 2 of this document examines the size, spatial, and temporal distribution of earthquake activity in the Canterbury earthquake sequence in order to develop a model to forecast the hazard posed by the on-going decay of this sequence over the typical 50 year design life of future structures and infrastructure. Section 3 presents the seismic hazard analyses that are performed using this aftershock sequence model in additional to the pre-2010 knowledge of the seismic hazard posed to the Canterbury region. Section 4 provides an explicit comparison between the seismic hazard values obtained in this study in comparison to the MBIE provisional design guidelines for liquefaction assessment.

2. Canterbury earthquake sequence activity

In this section the size, spatial, and temporal distributions of the Canterbury earthquake sequence are examined in order to develop the necessary models to represent the future predicted seismicity from this sequence into future NZ earthquake rupture forecasts.

In order to examine the earthquake activity from the on-going Canterbury earthquake sequence, the moment tensor catalogue compiled by John Ristau was obtained from GeoNet (www.geonet.org.nz; last accessed 1 July 2014). The analyses performed herein were also undertaken based on the alternative GNS catalogue of event locations and Richter magnitudes, with results found to be comparable. Based on examining the spatial distribution of events within the Canterbury region, geographical bounds of Lat=[-43.75,-43.25] and Lon=[172,173] were selected for further analysis. These bounds consider essentially all of the seismicity occurring during the Canterbury earthquake sequence in the vicinity of the urban Christchurch region, and in particular, all events of engineering significance ($M_w \geq 4$).

2.1. Observed magnitude-frequency distribution

Figure 1 illustrates the magnitude-frequency (i.e. size) distribution of all events within the region from the moment tensor catalogue. For comparison, the Gutenberg-Richter distribution for $b = 1$ is also illustrated, as given by:

$$\log_{10} N = a - bM_w \tag{1}$$

where a and b are empirical constants. Typically $b \approx 1$, and a is the activity rate (which varies in both space and time, as elaborated upon subsequently). It can be seen in Figure 1 that the Gutenberg-Richter scaling holds well for M_w>3.5, largely because the moment tensor catalogue becomes incomplete for M_w<3.5. Therefore M_w=3.5 is used as the cutoff magnitude for the subsequent analyses.

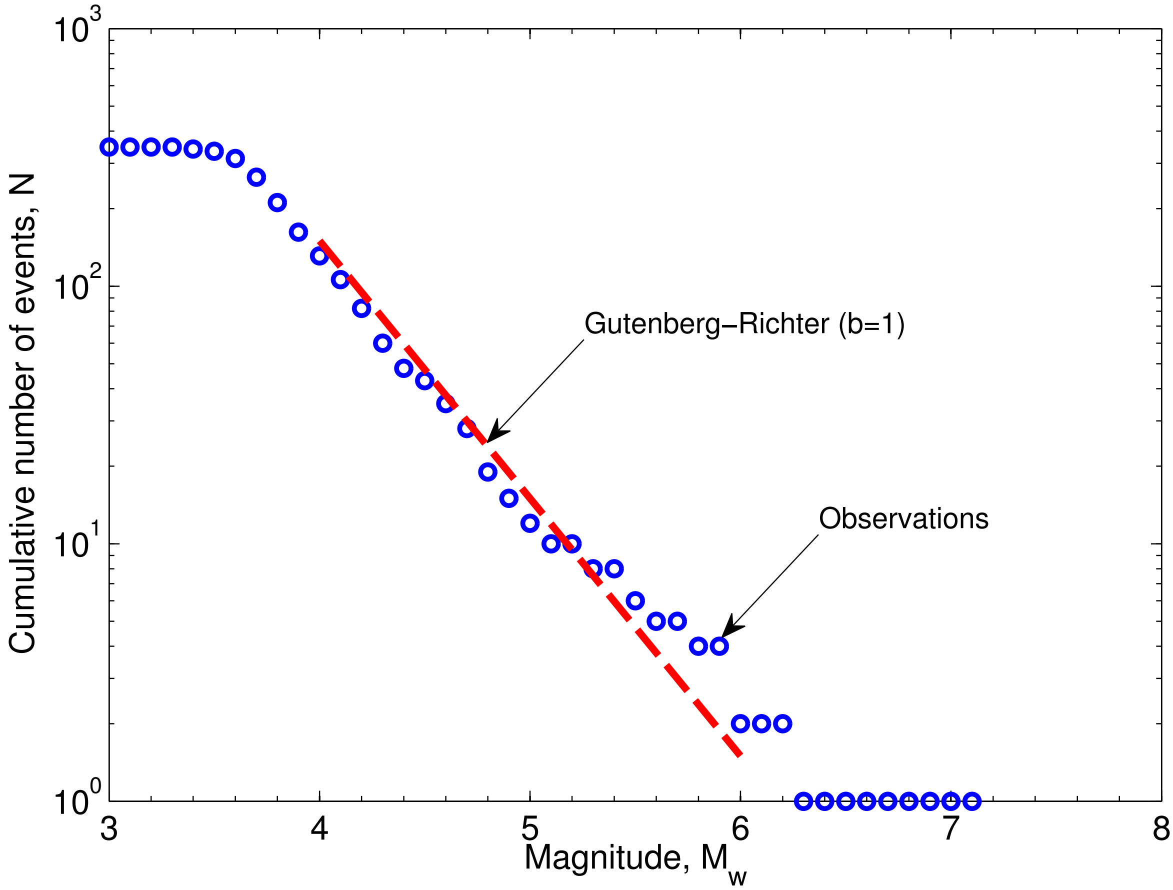

Figure 1: Magnitude-frequency distribution of earthquake events in the Canterbury earthquake sequence within the considered region of Lat=[-43.75,-43.25] and Lon=[172,173].

2.2. Observed spatial distribution

Figure 2 illustrates the spatial distribution of $M_w \geq 3.5$ events within the considered region from 1 September 2010-present. It can be seen that there is a significant clustering of events. To the South-west of the Christchurch urban area is a significant clustering of events associated with structural complexity between the rupturing faults on the 4 September 2010 and 22 February 2011 (Beavan et al. 2012). Significant clustering also exists to the South and South-east of the urban Christchurch area, in the vicinity of the locations of the 22 February, 13 June, and 23 December 2011 earthquakes (Beavan et al. 2012). The spatial distribution of future seismicity associated with this sequence is accounted for by using a spatially variable a-value in Equation (1) based on the assumption that the future seismicity will be well represented based on this recent seismicity.

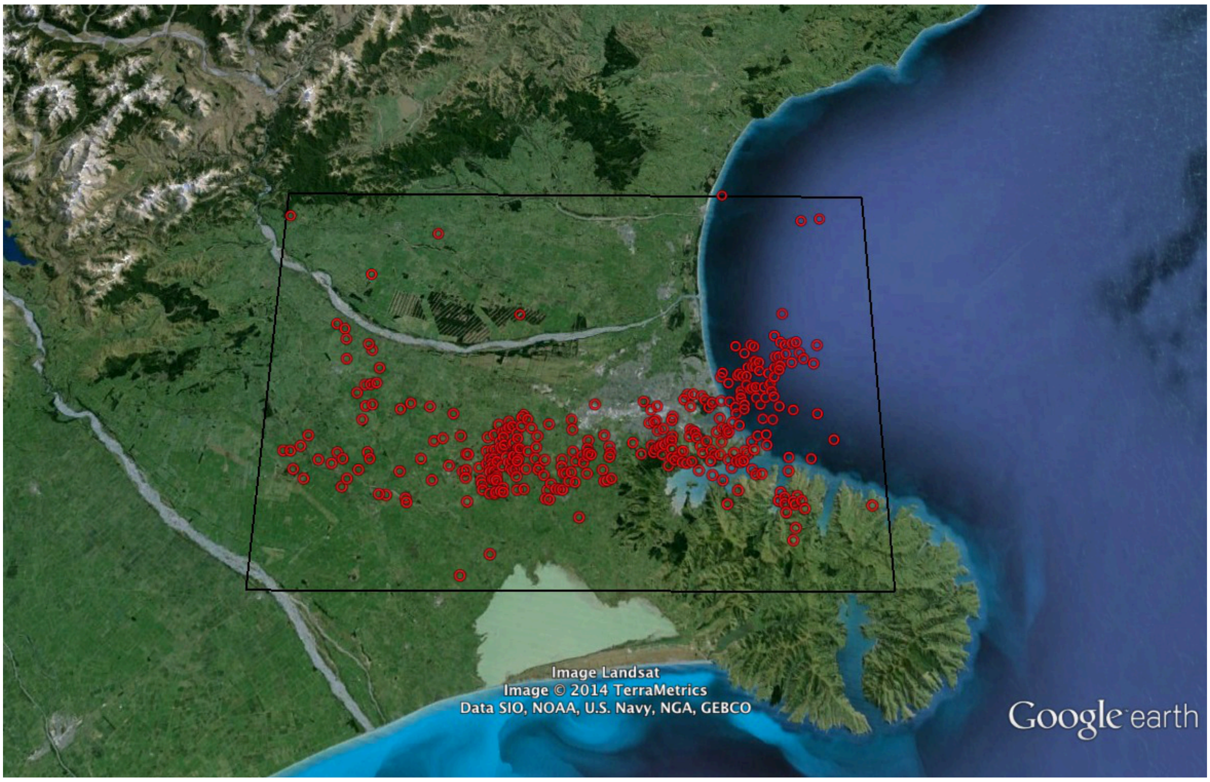

Figure 2: Spatial distribution of $M_w \geq 3.5$ earthquake events in the Canterbury earthquake sequence. The considered region of Lat=[-43.75,-43.25] and Lon=[172,173] is shown in the black polygon.

2.3. Observed temporal distribution

Figure 3 illustrates the cumulative number of events in the moment tensor catalogue with time. It can be seen that there is relatively little seismicity prior to the Canterbury earthquake sequence. The sequence, and its aftershock decay is dominated by 4 key events (4 Sept 2010, 22 Feb 2011, 13 June 2011, 23 Dec 2011), which is the reason for the complex aftershock activity rate with time.

The observed temporal earthquake activity rate is modelled with a modified-Omori law comprised of the 4 different sub-sequences as in Shcherbakov et al. (2012). The modified-Omori law for each sub-sequence is given by:

$$r = \frac{dN}{dt} = \frac{1}{\tau\left(1 + \frac{t}{c}\right)^{p}} \tag{2}$$

where r is the activity rate (the derivate of the number of events, N, with time, t); and τ, c, p are empirical constants. Note that Equation (2) can be integrated analytically to obtain:

$$N = \frac{c}{\tau(1-p)}\left[\frac{1}{\left(1 + \frac{t}{c}\right)^{p-1}} - 1\right] \tag{3}$$

For the four different sub-sequences which comprise the overall Canterbury earthquake sequence, the total activity rate can be expressed as $r = \Sigma r_i$, thus:

$$r(t) = \sum_{i=1}^{4} \frac{H\{t - t_i\}}{\tau_i \left(1 + \frac{t - t_i}{c_i}\right)^{p_i}} \tag{4}$$

where the subscript i is used to represent each sub-sequence, t_i is the time (in days) for the start of each sub-sequence, and $H\{t - t_i\}$ is the Heaviside 'step' function, such that $H = 1$ for $t - t_i \geq 0$ and $H = 0$ otherwise.

Table 1 provides the numerical values of the parameters of the modified Omori law describing the temporal decay of earthquake activity in the study region, while Figure 3 illustrates the adequacy of these parameters for modelling the observed activity. It can be seen that a satisfactory fit was obtained with constant values of the parameters c and p for all 4 sub-events. This simplicity is desired to prevent 'over-fitting' of this empirical model to the specific dataset (because of the potential for poor extrapolation).

Table 1: modified Omori-law parameters in Equations (2)-(4).

	Sub-sequence event			
Parameter	4 Sept 2010	22 Feb 2011	13 June 2011	23 Dec 2011
t_i	0	171	282	475
τ	0.06	0.13	0.23	0.145
c	2.8	2.8	2.8	2.8
p	1.2	1.2	1.2	1.2

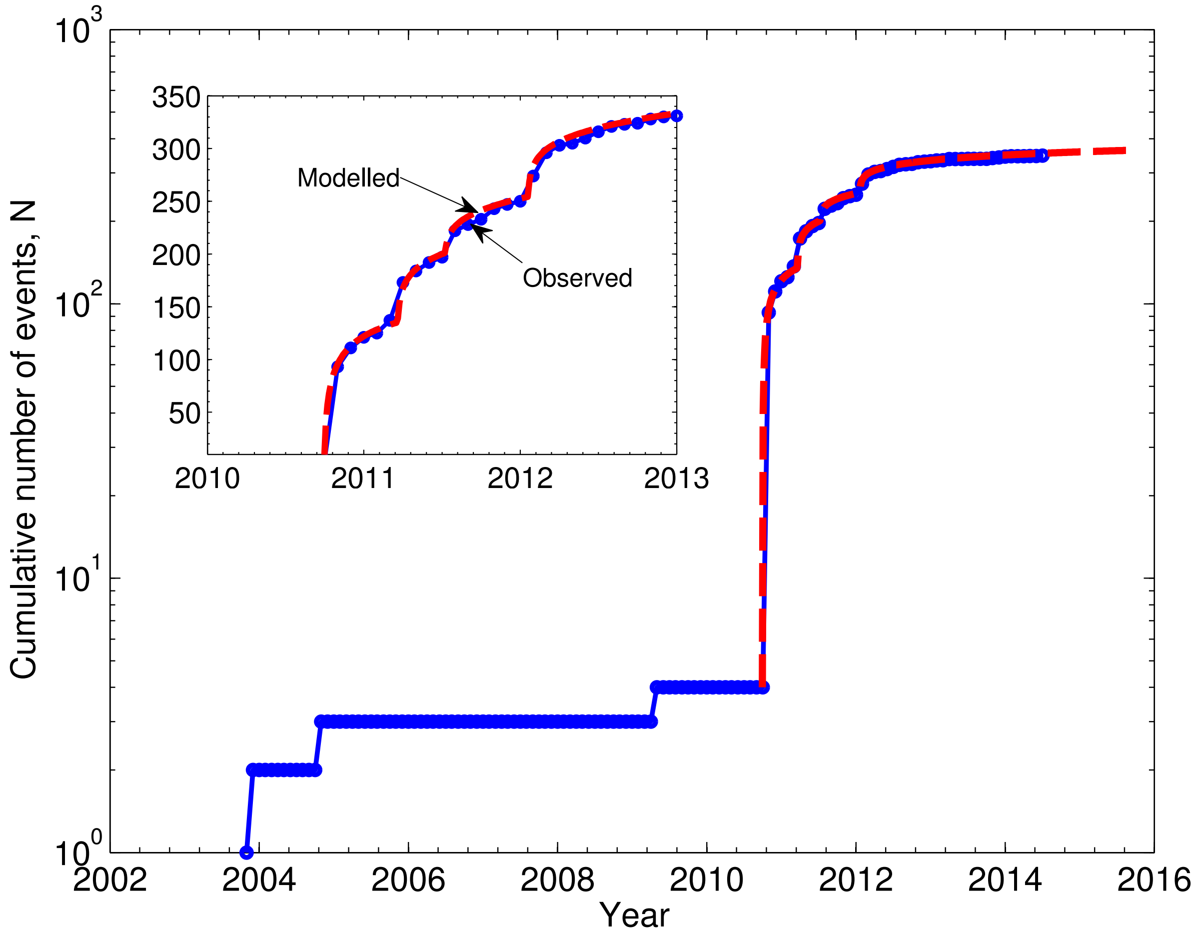

Figure 3: Temporal distribution of the number of events with M_w>3.5 illustrated via a cumulative distribution. The observed and modelled distributions are shown in blue and red, respectively. The inset figure is used to illustrate the comparison more directly.

2.4. Predicted future seismicity associated with the Canterbury earthquake sequence

Based on the modified Omori law utilized in the previous section, Figure 4 illustrated the extrapolated prediction for the earthquake activity associated with the Canterbury earthquake sequence over the 50 years from 1 July 2014. As one might expect, it can be seen that the activity rate decays over this period. The model predicts approximately 63 M_w>3.5 events in the region considered over the coming 50 years due to this aftershock sequence alone. That is, this modelling includes only earthquake events resulting from the temporal decay of this specific earthquake sequence, and not any future sequences, which are discussed subsequently. Taking into account the Gutenberg Richter distribution (with $b \approx 1$ as shown in Figure 1), this implies approximately 1.99 $M_w \geq 5$ events over the next 50 years in the region considered. Figure 4 also illustrates that over approximately the last 1 year the observed activity rate is slightly less than the modelled rate, however, this discrepancy is minor and not statistically significant.

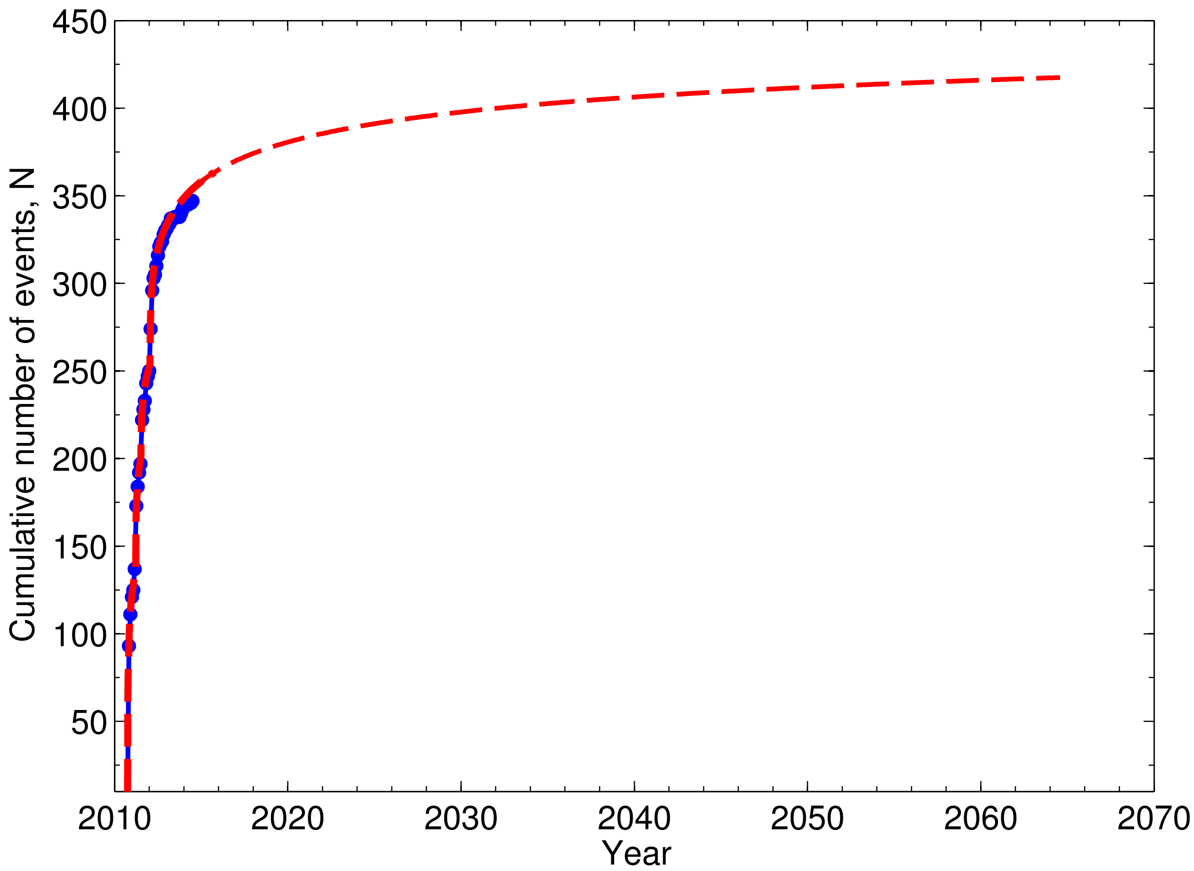

Figure 4: Illustration of the predicted rate of aftershocks in the region over the 50 year period from 1 July 2014-1 July 2064

2.5. Modelling Canterbury earthquake sequence seismicity in the NZ ERF

In the NZ national seismic hazard model (or earthquake rupture forecast, ERF) of Stirling et al. (2012), there are a total of 55 point sources (for 5 Latitudes and 11 Longitudes values on a grid of 0.1 degrees) to represent the background seismicity in the region considered. Two options were considered for representing the spatial distribution of seismicity: (i) spatially uniform; and (ii) spatially clustered. In the spatially uniform model the expected 1.99 Mw>5 events in the next 50 years can be divided by 50 years and the 55 sources to obtain a rate of λ =7.24e-3 Mw>5 events per point source per year. In the spatially clustered model, the activity rates were assigned to each of the 55 point sources based on the spatial clustering of the earthquake sequence to date as shown in Figure 2 (specifically based on an inverse distance weighting scheme, with distance weighting exponent of 2.0). The spatially clustered model is based on the assumption that past seismicity is the best indicator of future seismicity, while the uniform model could be based on the assumption that stress transfer could lead to the more ‘quiet’ regions in the sequence to date becoming more active. Both of these two approaches were considered in the subsequent seismic hazard analyses. It was found that the spatially clustered model, which is arguably more realistic, provides approximately 10% larger ground motion intensities and therefore only the resulting using this model are explicitly documented here.

The obtained spatially variable activity rates for $M_w \geq 5$ events in the Canterbury earthquake sequence are added on top of the existing background seismicity rates for these point sources in the Stirling et al. (2012) model. The reason for the addition (rather than replacement, for example) of these activity rates is that the activity rates in the Stirling et al. (2012) model account for the 'background' rate of earthquake in this region, and therefore does not account for aftershock sequences.

3. Probabilistic seismic hazard analysis (PSHA)

3.1. Adopted earthquake rupture forecast (ERF) models

The seismic hazard analyses performed herein utilize two models for the earthquake rupture forecasts. The first is the model of Stirling et al. (2012), which was completed in mid-2010, and represents a national consensus model as at this time. The second model is obtained from this first model with two specific modifications: (i) the earthquake activity rates in the Canterbury region are modified to account for the aftershock activity in the Canterbury earthquake sequence based on the documented methodology in the previous section; and (ii) the earthquake source depths are modified from a minimum of 10km, to 5km to account for the un-conservative nature of the former assumption, as discussed at length in Bradley (2012b).

The earthquake activity from the Canterbury earthquake sequence is considered using a time-independent Poissonian model, as is conventional in NZ PSHA. Therefore, the time dependent activity rates determined in the previous section are averaged over the 50 year time window considered.

3.2. Adopted ground motion prediction equations (GMPE)

A total of four different GMPEs are utilized in ground motion prediction for the analyses performed herein in a logic tree. The NZ-specific Bradley (2010, 2013) GMPE is given 70% weighting as the only NZ-specific GMPE which has been extensively validated against observations from the Canterbury earthquake sequence (Bradley 2012a, Bradley 2012c, Bradley and Cubrinovski 2011). The remaining three models from the NGA-West project considered are: Abrahamson and Silva (2008), Campbell and Bozorgnia (2008), Boore and Atkinson (2008), each of which is prescribed a logic tree weight of 10% each. It is noted that in addition to the Bradley model bring NZ-specific, it has also be modified to accurately model small magnitude earthquakes, which as shown, dominate the seismic hazard in Christchurch. The other three models, have been documented to over-predict ground motions from small magnitude events (i.e. $M_w \leq 6$) and thus are given an appropriate weight.

3.3. Generic site considered

A generic site at location: Lat=-43.53; Lon=172.6203 is used for the seismic hazard analyses presented herein. This location represents the centre of the urban Christchurch region. Several locations in the urban Christchurch region were considered, but the differences observed were very small, and therefore only results for this single location are presented.

The generic site is considered to have a 30-m averaged shear wave velocity of $V_{s30} = 200m/s$ and a basin-depths of $Z_{1.0} = 500m$ and $Z_{2.5} = 1.0km$, based on recent research by the author in the development of a seismic velocity model for the entire Canterbury region (Lee et al. 2014, McGann et al. 2014). Sensitivity analyses illustrates that the PSHA results were not overly sensitive to these parameters within their reasonable ranges.

3.4. Seismic hazard analysis results

Based on the modified seismic activity in the immediate vicinity of Canterbury resulting from the Canterbury earthquake sequence, seismic hazard analyses were performed to obtain the peak ground acceleration (PGA) seismic hazard.

Figure 5 illustrates the obtained seismic hazard curves for the two different earthquake rupture forecasts considered (i.e. pre- and post-Canterbury earthquake sequence models). The seismic hazard curve values for return periods (i.e. the inverse of the annual exceedance rate) of 25, 100, 500, and 2500 years are annotated with markers.

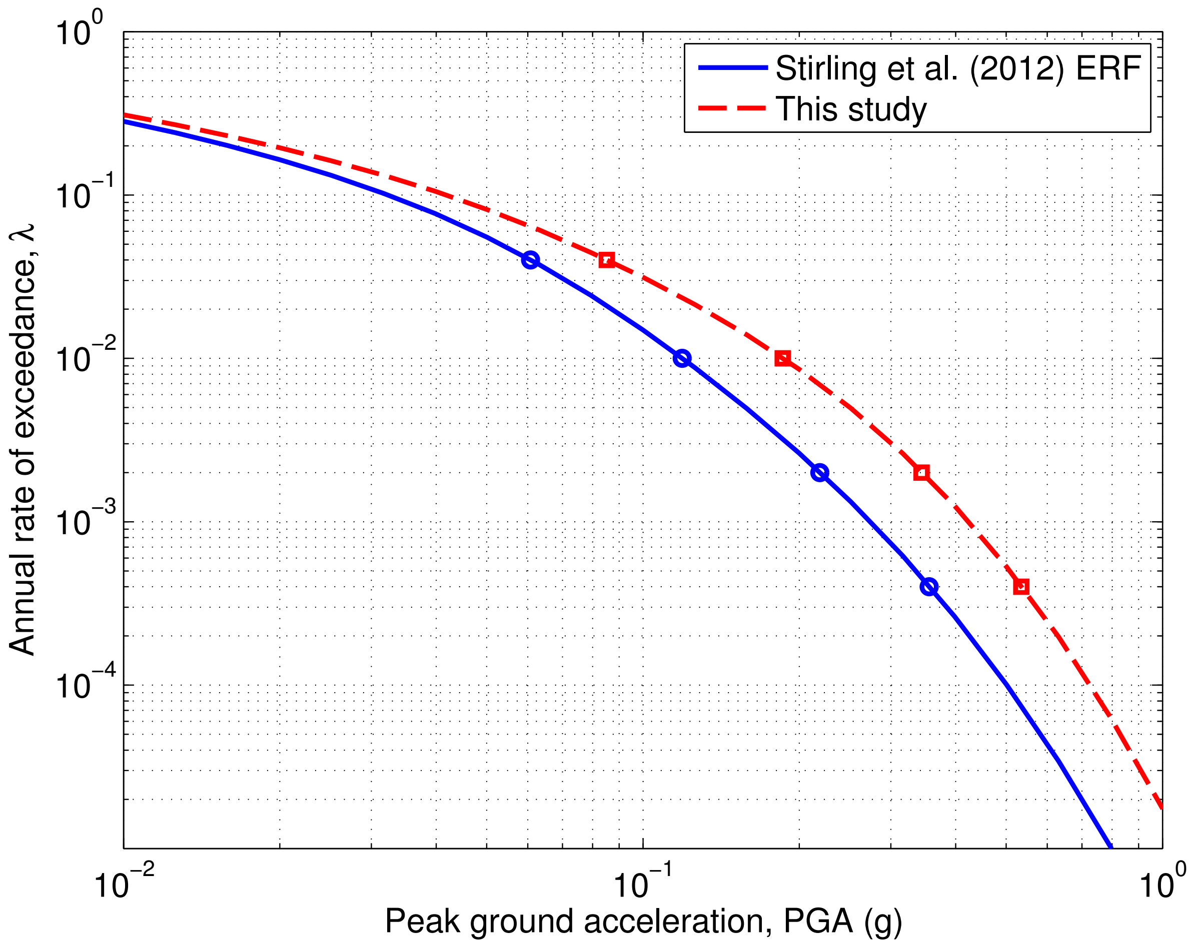

Figure 5: Seismic hazard curve comparison for peak ground acceleration (PGA) based on both the pre-Canterbury earthquake sequence model of Stirling et al. (2012) and the model developed here. Both analyses use the same set of GMPEs. The values for return periods of 25, 100, 500, and 2500 years are annotated with markers.

Because the seismic hazard curves shown in Figure 5 represent the aggregate seismic hazard resulting from all potential earthquake sources then it is insightful to understand the relative contributions of each of the seismic sources. Figure 6 and Figure 7 illustrate the seismic hazard deaggregation plots for the four return periods of interest with the pre- and post-Canterbury earthquake sequence ERF's, respectively. It can be seen that for all cases, the PGA hazard is dominated by small magnitude, near source seismicity. This is particularly the case for the post-Canterbury earthquake sequence model, because of the increased rate of near-source seismicity due to the on-going aftershock sequence.

Table 2 summarizes the PGA hazard values and mean magnitudes from deaggregation for these four return periods of interest. It can be seen that the PGA hazard values are approximately 40-50% larger for the results in this study (accounting for the Canterbury earthquake sequence) as compared to the values based on the pre-Canterbury earthquake sequence seismicity. However, it can also be seen that the mean magnitudes are 0.3-0.5 M_w units smaller. As already noted, this is because the only reason for the increased seismicity is the elevated rate of near-source seismicity, which is Gutenberg-Richter distributed.

Table 2: Summary of PGA values and mean magnitude values from probabilistic seismic hazard analysis.

		Return period (years)			
Model		25	100	500	2500
Stirling et al. (2012) ERF	PGA (g)	0.061	0.12	0.22	0.36
	mean M_w	6.35	6.29	6.19	6.11
This study	PGA	0.085	0.19	0.34	0.54
	mean M_w (g)	5.92	5.80	5.81	5.82

It is important to emphasise that the results shown for the "Stirling et al. (2012) ERF" case are not expected to be directly compatible with the NZS1170.5:2004 values for several reasons:

1. The seismic hazard values underlying NZS1170.5:2004 are based on the use of the Stirling et al. (2002) ERF, where as the results presented here represent the Stirling et al. (2012) ERF
2. The NZS1170.5:2004 values make use of the McVerry et al. (2006) GMPE only, where as the results presented here make use of a logic tree with significantly more robust GMPEs.
3. The NZS1170.5:2004 values use a 'magnitude-weighting' to modify the directly predicted PGA values, however the magnitude weighting function is very different to that used in contemporary geotechnical design. Through the Canterbury Earthquakes Royal Commission it was apparent that the use of the this 'magnitude-weighting' was adopted to account for the fact that the McVerry et al. (2006) GMPE significantly over-predicts ground motions from small magnitude earthquakes (i.e. $M_w < 6$), which are very important for Christchurch (particularly so following this earthquake sequence) .
4. The values presented here are 'direct' results obtained from probabilistic seismic hazard analyses, and not 'codified' values within a functional methodology adopted for design codes. The "Z" value in NZS1170.5:2004 is not intended to represent the design PGA, but rather the response spectra for a vibration period of $T = 0.5s$, and therefore the fact that the Z value is numerically equal to the design PGA for rock sites is based on the assumed spectra shape (McVerry 2003).

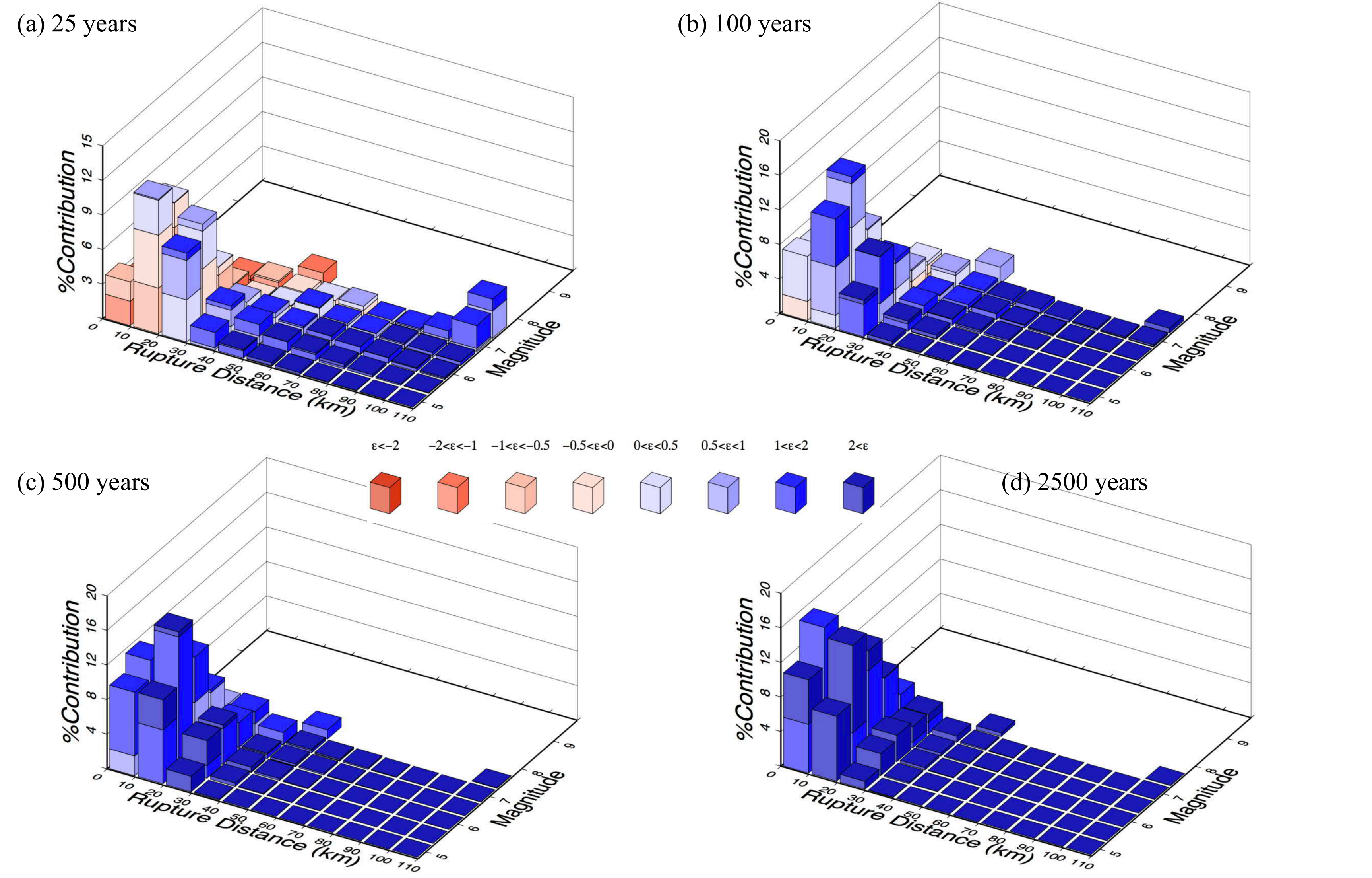

Figure 6: Deaggregation plots for seismic hazard analysis with increased seismicity from the Canterbury earthquake sequence

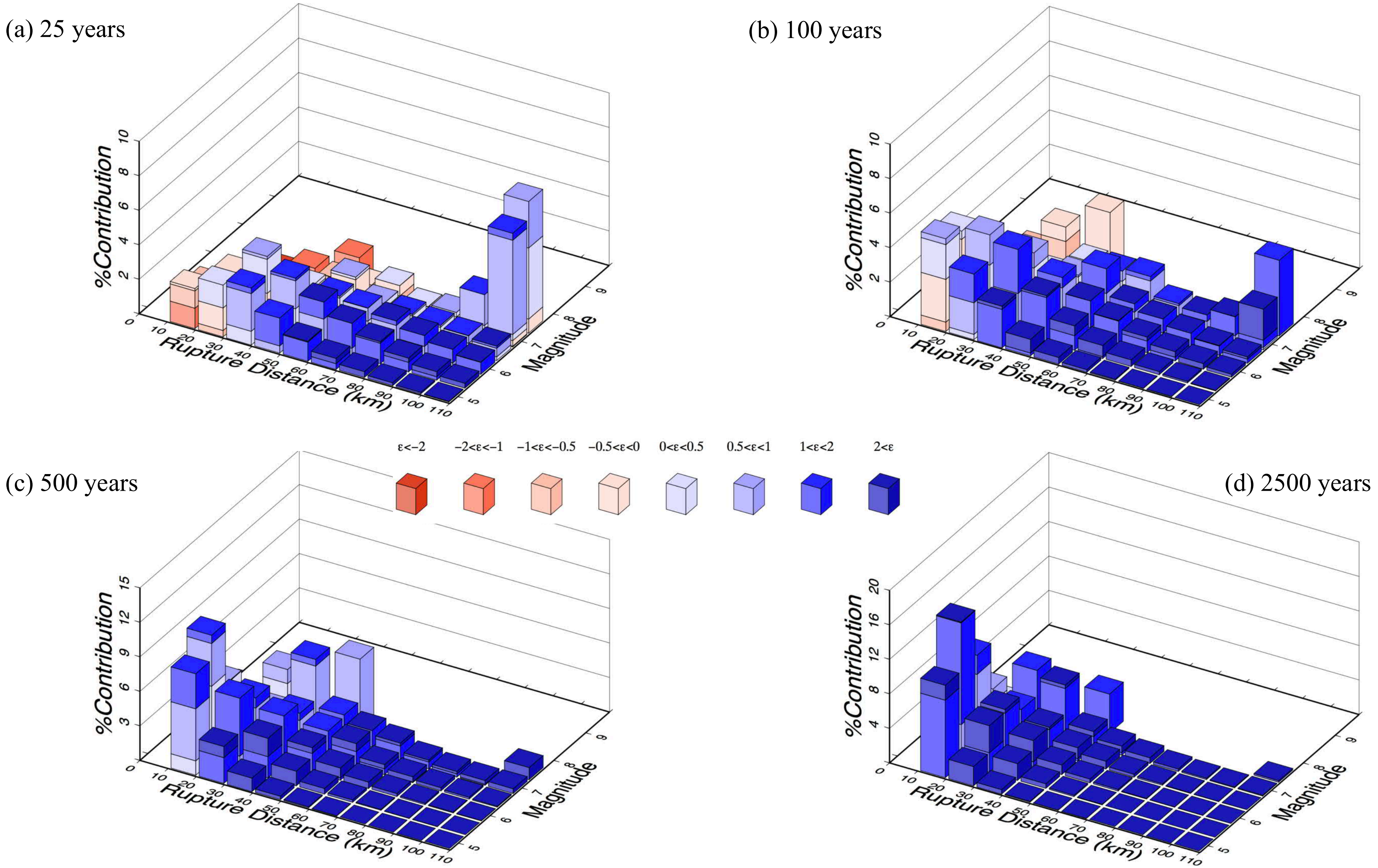

Figure 7: Deaggregation plots for seismic hazard analysis prior to the Canterbury earthquake sequence (i.e. Stirling et al. (2012))

4. Comparison with other seismic hazard analysis values for the Christchurch region

This specific study has been commissioned to provide input into geotechnical analysis and design and therefore in this section a brief comparison is made with existing guidelines in this field.

Table 3 illustrates the three performance limit states that have been provisionally recommended by the Ministry of Business, Innovation and Employment (MBIE) for earthquake geotechnical design in the Christchurch urban region. It is noted that the MBIE-recommended design levels all correspond to a $M_w = 7.5$ event as compared to the more realistic representation of the dominant magnitudes for the PGA seismic hazard shown in Table 2.

Table 3: Provisional performance limit states adopted by MBIE

Performance limit state	Return period (years)	Design PGA (g)	Design magnitude
SLS	25	0.13	7.5
ILS	100	0.20	7.5
ULS	500	0.35	7.5

While magnitude scaling factors, MSF, are potentially a function of soil properties in addition to earthquake magnitude, for the purposes of comparison herein, the model of Idriss and Boulanger (2008) is utilized, which is given by:

$$MSF = 6.9 * \exp\left(-\frac{M_w}{4}\right) - 0.058 \leq 1.8 \quad (5)$$

from which the magnitude-corrected PGA, $PGA_{7.5}$, can be obtained from:

$$PGA_{7.5} = PGA * \frac{1}{MSF} \quad (6)$$

Figure 8 compares the $PGA_{7.5}$ values for the three different performance criteria: MBIE, Stirling et al. (2012); and this study. It is re-iterated that the Stirling et al. (2012) values are based on pre-Canterbury earthquake sequence activity and are shown here only for reference. It can be seen that the MBIE suggested values are 2-3 times greater than the values presented in 'this study'.

As far as the author is aware, no documentation of the scientific basis behind the numerical values adopted by MBIE in Table 3 has been provided. However, it is noted that this study has adopted a rigorous first-principles approach to determine the seismic hazard in the Christchurch region, and on this basis it is argued that the MBIE-adopted values are significantly conservative and warrant urgent review.

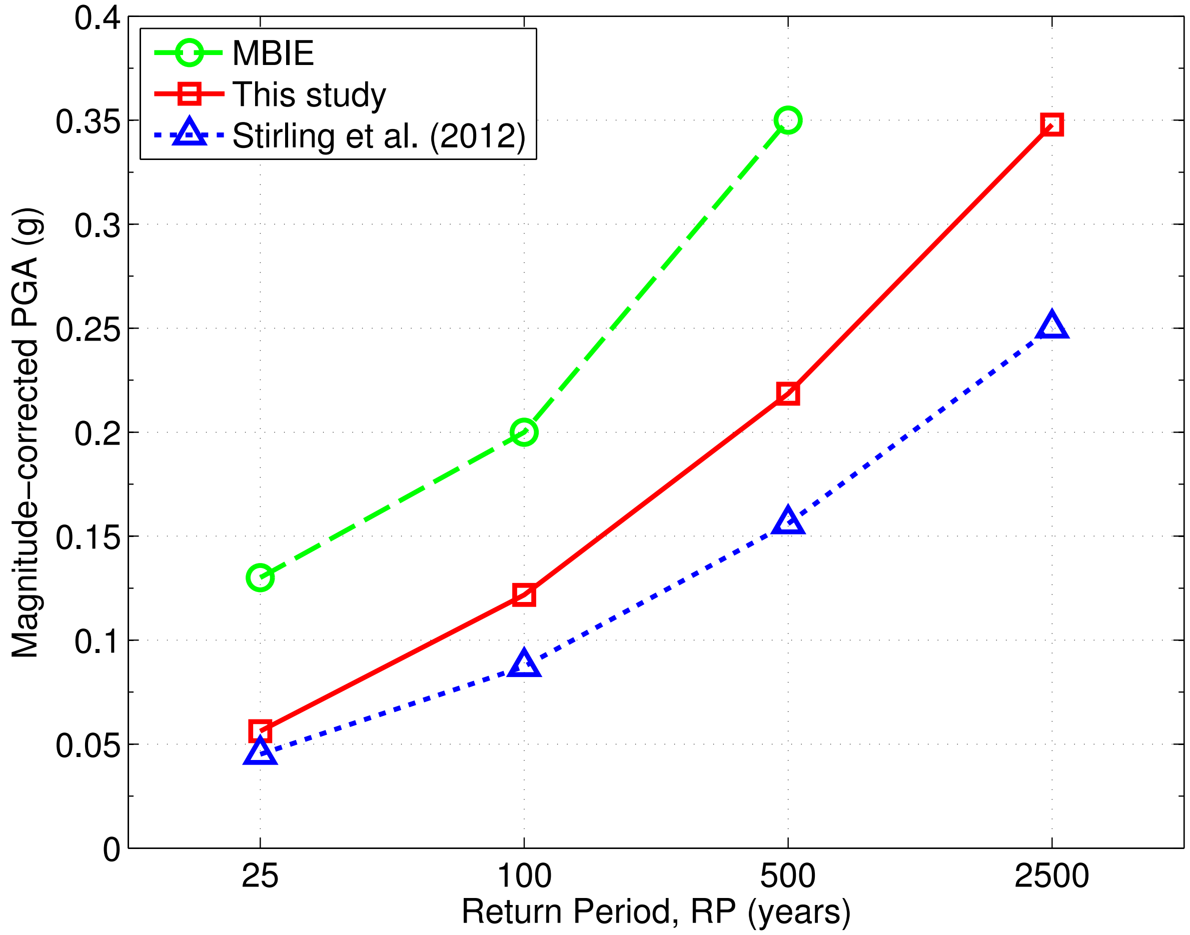

Figure 8: Comparison of the magnitude-corrected $PGA_{7.5}$ design values from MBIE, compared to those in this study.

5. Conclusions

This report has developed seismic hazard estimates for urban Christchurch based on state of the art methods. The on-going Canterbury earthquake sequence has been directly incorporated in the adopted earthquake rupture forecast (ERF) based on a first-principles analysis of the observed earthquake activity rates and empirical models based on the Gutenberg-Richter and modified-Omori aftershock laws.

The seismic hazard analyses performed suggest that the PGA seismic hazard averaged over the next 50 years is 40-50% higher than that prior to the Canterbury earthquake sequence. However, the magnitudes which dominate this seismic hazard are 0.3-0.5 M_w units lower than the pre-2010 hazard.

Using a commonly adopted magnitude scaling factor, MSF, magnitude-correct PGA values, $PGA_{7.5}$, were determined from the seismic hazard analysis results in this study. Comparison with the provisional design values in the MBIE guidelines suggests that those values are a factor of 2-3 greater than the values obtained here based on rigorous first-principles analysis, and therefore an urgent reassessment of the MBIE values is warranted.

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