

Consistency of Seismicity and Ground Motion Modelling with the Canterbury Earthquakes

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ABSTRACT: This paper examines the consistency of seismicity and ground motion models, used for seismic hazard analysis in New Zealand, with the observations in the Canterbury earthquakes. An overview is first given of seismicity and ground motion modelling as inputs of probabilistic seismic hazard analysis, whose results form the basis for elastic response spectra in NZS1170.5:2004. The magnitude of earthquakes in the Canterbury earthquake sequence are adequately allowed for in the current NZ seismicity model, however the consideration of ‘background’ earthquakes as point sources at a minimum depth of 10km results in up to a 60% underestimation of the ground motions that such events produce. The ground motion model used in conventional NZ seismic hazard analysis is shown to provide biased predictions of response spectra (over-prediction near $T = 0.2s$, and under-predictions at moderate-to-large vibration periods). Improved ground motion prediction can be achieved using more recent NZ-specific models.

1 INTRODUCTION

The recent sequence of earthquakes in the Canterbury region has caused widespread damage to commercial, industrial, and residential structures and infrastructure (NZSEE 2010, NZSEE 2012). Naturally, these earthquakes and earthquake-induced ground motions that have been observed can be used to scrutinize current seismicity and ground motion models which are used in seismic hazard analysis for New Zealand, and whose results underpin the prescribed elastic response spectra in NZS1170.5:2004. The aim of this paper is to provide a brief overview of the salient features of such an examination. Further details can be found in Bradley (2012) and references therein.

2 SEISMIC HAZARD ANALYSIS AND DESIGN GROUND MOTIONS

2.1 *Seismicity modelling*

Seismicity modelling involves assessment of the location, size, and frequency/likelihood of earthquakes. Because earthquakes cannot be predicted, then seismicity models are typically probabilistic (giving probabilities of earthquake occurrence within a given time interval). Since instrumental records of earthquake occurrence are short, relative to the recurrence intervals of earthquakes on specific faults, it is not possible to develop a useful seismicity model on the basis of observational data alone (in the manner in which flood hazard is often assessed, for example). As a result, in order to maximise available data and theories, seismicity modelling conventionally incorporates geologic, geodetic, and instrumental seismology data.

Conventional seismicity models comprise two components. The first component, referred to as fault-based seismicity, represents fault sources which are explicitly considered in the model, and whose characteristics are determined often on the basis of geologic and paleoseismic investigations. The second component, referred to as background seismicity, represents all potential earthquakes that may occur on faults that are not explicitly considered in the fault-based seismicity component of the model. Since geological evidence at the earth’s surface is often not discernable for active faulting which produces small-to-moderate magnitude earthquakes, and/or faulting with a relatively long recurrence

interval between significant earthquake events, then such cases are typically predominantly represented within background seismicity. Based on the occurrence statistics of observed historical seismicity, the spatial distribution of frequencies of ‘background seismicity’ can be determined.

2.2 Ground motion modelling

For the purpose of determining ground motion intensity measures, (e.g. SA), for seismic design, empirical ground motion prediction equations (GMPEs) are conventionally employed. Such GMPEs are mathematical functions derived based on historically recorded ground motions. Such functions are empirical in nature, and therefore should be considered as only representative for use in modelling ground motion for scenarios which are well represented by the database of historically recorded ground motions. Unfortunately, as a simple result of the fact that moderate-to-large earthquakes occur infrequently, and that strong motion instrumentation must be in-place to record the ground motions from such events, there is a paucity of recorded strong motions from such events, particularly at close source-to-site distances (which are the situations which are most relevant for seismic design of structures).

Because of the complexity of the process of earthquake rupture, wave propagation, and local effects of the surficial soils directly beneath the site, the characteristics of ground motions as predicted by empirical GMPEs are highly uncertain. As a result it is conventional that a GMPE is a probabilistic function of the predictor variables (e.g. earthquake magnitude, source-to-site distance, local soil conditions etc), and therefore provides a distribution of ground motion intensity, rather than a unique (deterministic) value. Example comparisons between GMPE predictions and observations which illustrate the magnitude of uncertainty are shown subsequently.

2.3 Probabilistic seismic hazard analysis (PSHA)

Seismic hazard analysis involves the combination of seismicity and ground motion models in order to develop insight into the potential for strong ground motions to be observed at a specific location in a specific time period. Probabilistic seismic hazard analysis (PSHA) is one form of seismic hazard analysis in which both seismicity and ground motion modelling, and their combination, are treated in an explicit probabilistic formulation. The key steps of PSHA are:

- For each potential earthquake rupture in the seismicity model, compute the distribution of the ground motion intensity measure of interest, $f(IM|Rup_i)$. Determine the probability that $IM > im$, $P(IM > im|Rup_i)$, and multiply by the mean annual rate of occurrence of the earthquake rupture scenario, $\lambda(Rup_i)$, to obtain the mean annual rate at which Rup_i occurs and produces a ground motion with $IM > im$.
- By assuming each earthquake rupture is independent, compute the mean annual rate of $IM > im$, from all potential earthquake ruptures ($N_{ruptures}$), by summing the contribution from individual ruptures.

The formal equation for PSHA can thus be written as:

$$\lambda(IM > im) = \sum_{i=1}^{N_{ruptures}} P(IM > im|Rup_i)\lambda(Rup_i) \quad (1)$$

Since Equation (1) is a function of the value of IM selected, then different values are obtained for different ground motion intensities. A plot of $\lambda(IM > im)$ for a range of IM values is referred to as a ground motion hazard curve.

2.4 Scrutinizing PSHA results with earthquake and ground motion observations

Comments are often made that observed ground motions that exceed the design seismic intensities provide evidence that the design seismic intensities are flawed, as a result of flawed inputs, or a flawed methodology. However, when attempting to reconcile observations with design values it is necessary to understand how the design values are obtained. For example, previous sections have demonstrated

that a PSHA is obtained by summing over all of the potential earthquake sources which contribute a ground motion hazard for the site considered, including the likelihood of the earthquake source rupturing, and including uncertainty in the ground motion prediction. Hence comparison of the results of a PSHA with an observed ground motion, which is produced from a single earthquake source, that has occurred, is strictly incorrect.

In order to scrutinize probabilistic seismic hazard analyses, based on a single earthquake and its observed ground motions, it is necessary to compare the observations with the predictive models which are inputs to PSHA, namely: (i) the seismicity model; and (ii) the ground motion prediction equation (GMPE). It must also be borne in mind that the causal earthquake(s) and its/their recorded ground motion(s) represent merely a sample (often small) from the seismicity and ground motion models, and therefore caution must be exercised to ensure that over-interpretation of the results is avoided. In the following sections, the characteristics of the seismicity model and GMPE's are scrutinized relative to observations from the Canterbury earthquakes.

3 THE NEW ZEALAND SEISMICITY MODEL AND THE CANTERBURY EARTHQUAKES

A seismicity model, in a general sense, provides the location, size, and frequency of earthquakes in a particular region. Therefore scrutinizing a seismicity model based on an observed earthquake should consider the following fundamental question: "Does the seismicity model allow for the possibility of an earthquake to occur at the observed location and of the observed magnitude?". It should be noted, in particular, that the 'frequency' aspect of a seismicity model represents a probabilistic quantity, and hence this cannot be explicitly scrutinized based on the deterministic occurrence of an earthquake.

None of the fault structures which have ruptured in the Canterbury earthquake sequence have occurred on known active faults which form the fault-based component of seismicity in the New Zealand seismicity models. However, this does not imply that the model is deficient, as it should be recalled that 'off-fault' seismicity is also accounted for via background seismicity sources.

Design ground motion intensities in NZS1170.5:2004 are based on seismic hazard analyses using the seismicity model of Stirling et al. (2002). For the Canterbury region in which the Canterbury earthquake sequence has occurred, the background seismicity model of Stirling et al. (Stirling, et al. 2002) allows for the possibility of background earthquakes of reverse-faulting mechanism to occur with magnitudes up to M_w 7.0. These same background details were also used in a Canterbury-specific seismic hazard update in 2007 (Stirling, et al. 2007). Hence, it may be argued that the 4 September 2010 Darfield earthquake (M_w 7.1, predominantly strike-slip deformation) is not strictly accounted for in the seismic hazard analyses that underpin NZS1170.5:2004, and the most up-to-date hazard analysis at the time of the event. It is worthy of note however that the 2010 update of the Stirling et al. (2002) model allows for background earthquakes in the Canterbury region of up to M_w 7.2 (Stirling, et al. 2011). Therefore, in terms of magnitude, these events are adequately allowed for in the most up-to-date New Zealand seismicity model.

The background seismicity models of Stirling et al. (2007, 2011, 2002) consider background earthquakes as point sources located at depths of 10, 30, 50, 70, and 90 km. Events in the Canterbury earthquake sequence have had centroid depths which are notably shallower than that minimum background depth of 10km. All other things equal, shallow earthquakes result in stronger ground motions at the earth's surface as a result of smaller geometric spreading attenuation, which is principally a function of the distance from the earthquake source to the site of interest.

Even for small-to-moderate earthquake events, the finite size of the fault plane is important in ground motion prediction at locations in the near-source region. It was noted previously that background earthquakes are treated as point sources in New Zealand seismicity models. However, ground motion prediction equations (GMPEs) use finite-fault source-to-site distance metrics. For example, while the centroid depth of the 22 February 2011 Christchurch earthquake had a centroid depth of 3km, it is inferred to have a fault plane with significant slip at depths as low as 1km (Beavan, et al. 2011). Similarly, while the 4 September 2010 Darfield earthquake had a centroid depth of 8km, it resulted in surface rupture and therefore has a finite fault depth of 0km. The same ideas also apply for

consideration of the fault plane in the horizontal direction, for example, the centroid of the 4 September 2010 Darfield earthquake is approximately 37km from central Christchurch, as compared to the nearest distance on the fault plane being only 15km. As finite-fault source-to-site distances are always less than their respectively point-source-to-site distances then the point source representation of background seismicity in the current New Zealand seismicity models provides un-conservative seismic hazard estimates.

In order to illustrate the significance of the un-conservatism resulting from a minimum depth of 10km, and the assumption of point sources for background seismicity, it is insightful to consider how these affect the predicted ground motions in the earthquake events that have occurred. Figure 1 illustrates the predicted median response spectrum amplitudes at Christchurch Hospital (CHHC) from the 22 February 2011 and 4 September 2010 earthquakes. The predictions are based on the New Zealand-specific Bradley (2010) GMPE. Figure 1 illustrates the predicted response spectra assuming: (i) that the earthquake depth is 10km and that the earthquake is a point source (what current New Zealand seismicity models consider); (ii) that the earthquake depth is equal to the calculated event-specific centroid depth, but still a point source; and (iii) the correct consideration of the earthquake geometry by using its finite fault. It can be seen that, as previously noted, approaches (i) and (ii) provide an un-conservative estimate of the ground motion as compared to the consistent approach of representing earthquakes as finite faults in seismicity modelling. The reason for the difference in the response spectra is a result of the different source-to-site distance, R_{rup} , which is input into the ground motion model as annotated. It can be seen that generally the under-prediction increases with vibration period, with the point source approximations leading response spectral amplitudes which are up to 60% less than that obtained using the consistent (i.e. finite fault) approach. Hence, clearly the current considerations of a minimum depth of 10km and point source approximation for background seismicity results in a significant under-prediction of the expected ground motions. For regions in which background seismicity provides a significant contribution to the seismic hazard, such as Christchurch, the aforementioned approximations are likely to also result in a significant under-prediction of PSHA results, such as those that underpin NZS1170.5:2004.

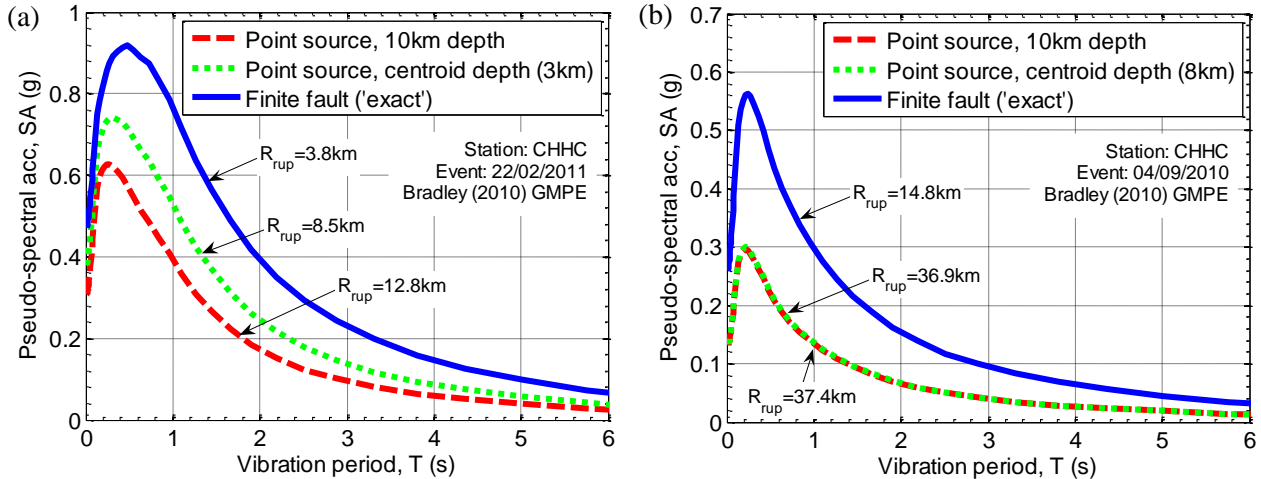


Figure 1: Effect of minimum earthquake depth of 10km and point source approximation in seismicity modelling on median response spectral amplitudes predicted at Christchurch hospital (CHHC) during: (a) 22 February 2011; and (b) 4 September 2010 earthquakes. The 'Finite fault' prediction is the correct prediction in terms of consistency between seismicity and ground motion modelling.

4 STRONG GROUND MOTIONS OBSERVED IN THE CANTERBURY EARTHQUAKES

For brevity, in this section attention is restricted to comparison of ground motions observed in the 22 February 2011 Christchurch earthquake with empirical ground motion prediction equations (GMPEs). Comparisons for the 4 September 2010 Darfield earthquake, and elaborated discussion, can be found in Bradley (2012).

It cannot be over-emphasised that the processes which lead to earthquake-induced ground motions

exciting engineered structures are extremely complex. GMPEs do not seek to represent the complex physics which produce ground motions as described above. Instead, GMPEs utilize ground motions that have been recorded in historical earthquakes, and develop a mathematical/statistical equation which can be used to predict (albeit with uncertainty) the severity of a ground motion intensity measure (e.g. SA at a given vibration period) given a particular site and earthquake scenario of interest.

Recent nationwide seismic hazard analyses for New Zealand, in particular those underpinning NZS1170.5:2004, use the McVerry et al. (2006) GMPE. While the McVerry et al. model was published in the public domain in 2006, it was developed much earlier, being completed in 1997 and first published (but without equations and coefficients) as a conference paper in 2000 (McVerry, et al. 2000). The McVerry et al. model used an empirical database comprising a total of 49 earthquakes and 435 records from New Zealand in the period 1966-1995. As a result of the GeoNet project, there are presently more than 3000 strong ground motion records recorded from earthquakes in New Zealand. Due to the significant increase in strong motion data, Bradley (2010) developed a NZ-specific active shallow crustal GMPE (using 2852 ground motions) based on the Chiou et al. (2010) GMPE for California, with modifications for NZ-specific features. Hence both the McVerry et al. and Bradley GMPEs will be considered with respect to the observed ground motions from the Canterbury earthquakes. For brevity, these two different models will be referred to as B10 and McV06, respectively.

Figure 2 and Figure 3 illustrate the amplitudes of response spectral ordinates observed in the 22 February 2011 Christchurch earthquake compared to the predictions of the B10 and McV06 GMPEs, respectively. The prediction of the empirical models is shown for the median (i.e. 50th percentile), as well as the 16th and 84th percentiles. Each plot shows the response spectral amplitudes as a function of the nearest distance from the earthquake source (i.e. finite-fault) to the site at which the ground motion was recorded, R_{rup} ; and data are also coloured according to the NZS1170.5:2004 site class of each instrument location. Ground motion data beyond $R_{rup} = 50\text{km}$ are not shown as their amplitudes are small enough to not be of concern for engineered structures. In addition to the visual comparison between observations and prediction, the normalized inter-event residual (η) is also shown in the inset of each figure, and can be considered as a measure of the overall bias of the model for all recorded ground motions (within 50km in this case), and for the particular spectral ordinate considered. A value of $\eta = 0$ indicates no bias, while a value of $\eta = 1.0$, for example, indicates that the observations are, on average, one standard deviation above the median prediction.

The results of Figure 2 illustrate that the B10 GMPE is able to capture the source-to-site distance dependence of the observations with good accuracy (i.e. low bias) and precision (i.e. correct variability). The inter-event term, η , indicates that the model has very small bias for vibration periods of $T=0.0, 0.2$ and 1.0s (i.e. $\eta=-0.217, -0.28$, and 0.106 , respectively), but that there is a notable under-prediction of SA(3s) amplitudes for distances less than 10km (i.e. $\eta=0.907$). The potential reasons for the under-prediction of long-period ground motions at these short source-to-site distances are primarily attributed to near-source directivity, basin-generated surface waves, and nonlinear response of surficial soils (Bradley 2012).

The results of Figure 3a illustrate that the McV06 model generally provides a good prediction of the observed PGA's within 50km, although there is a slight under-prediction ($\eta = 0.499$), particularly for distances beyond 25km. Figure 3b illustrates that the prediction of SA(0.2s) of the McV06 model is significantly above the average of the observations for all source-to-site distances ($\eta = -1.513$). Figure 3c illustrates that the McV06 model incorrectly models the variation in SA(1s) amplitudes as a function of source-to-site distance, with the observed amplitudes attenuating with distance notably faster than that predicted by the McV06 model. Because of the under-prediction of the model for short distances, and over-prediction for larger distances, the small value of $\eta = -0.106$ is obtained for SA(1s). Figure 3d illustrates that the McV06 significantly under-predicts the SA(3s) amplitudes that were observed ($\eta = 2.102$).

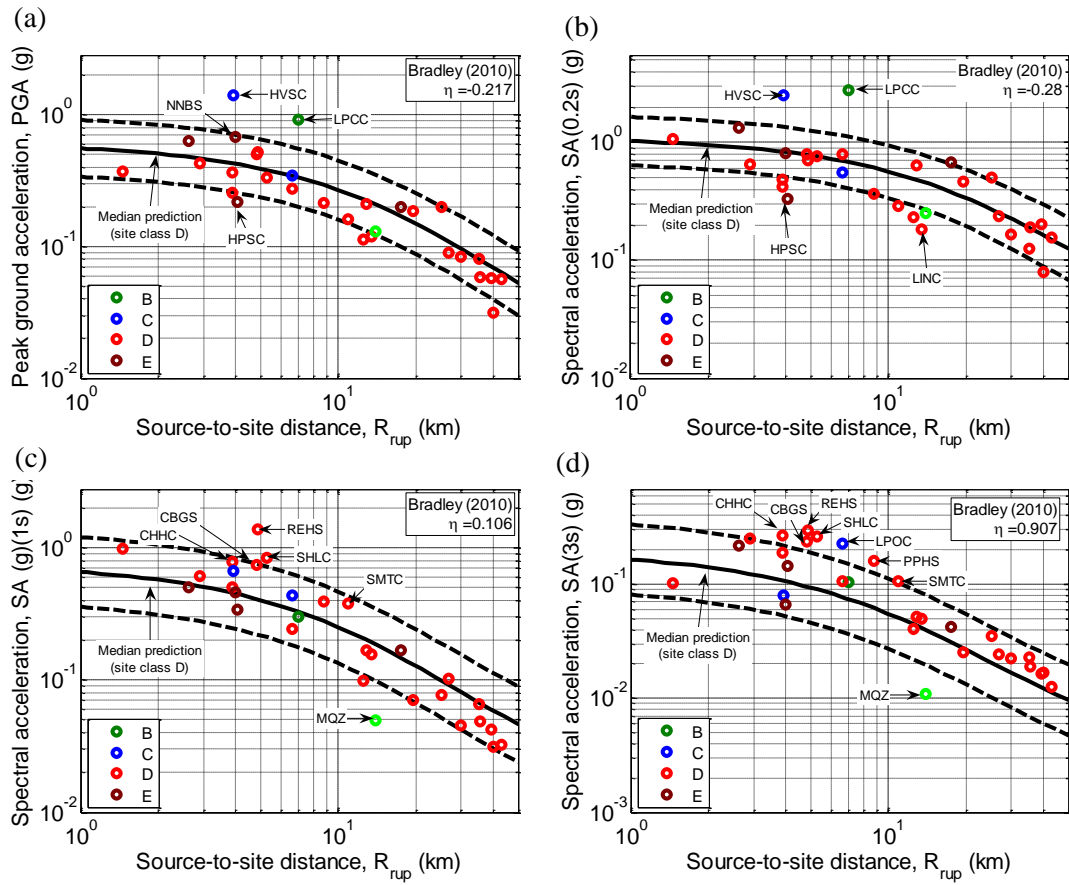


Figure 2: Observed spectral accelerations from the 22 February 2011 Christchurch earthquake with the Bradley (2010) GMPE for site class D soil conditions.

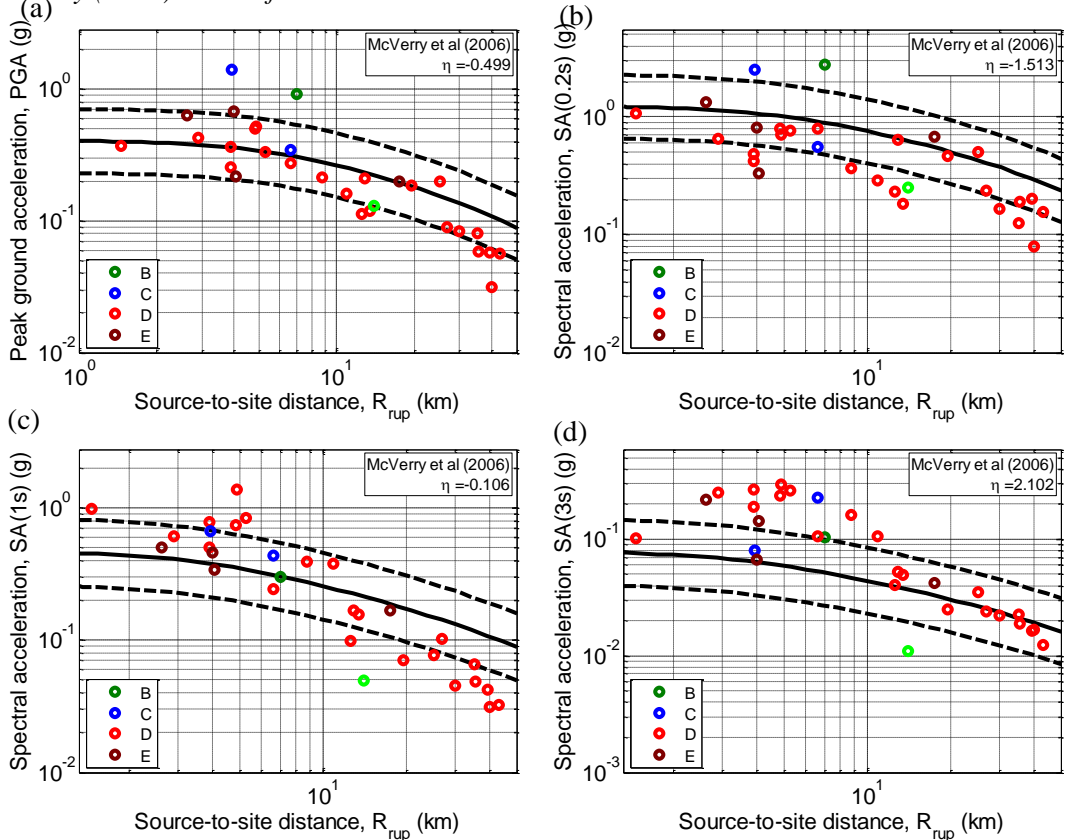


Figure 3: Observed spectral accelerations from the 22 February 2011 Christchurch earthquake with the McVerry et al. (2006) GMPE for site class D soil conditions.

In order to clearly illustrate the results of Figure 2 and Figure 3, Figure 4 provides a comparison of the response spectra of the ground motion observed at Christchurch Hospital (CHHC) resulting from the 22 February 2011 earthquake. The observed response spectra are presented for the north and east components of the ground motion, as well as the geometric mean response spectrum, and model predictions (also for the geometric mean). Figure 4a illustrates that, over all vibration periods the B10 model provides a good prediction of the observed ground motion response spectra with the observed geometric mean being close to that of the median prediction. In contrast, Figure 4b illustrates that the McV06 model significantly over-predicts the short period response spectra at around $T=0.2s$ (i.e. as illustrated in Figure 3b), and that the McV06 model significantly under-predicts the ground motion for longer vibration periods (i.e. as illustrated in Figure 3c at close distances and Figure 3d).

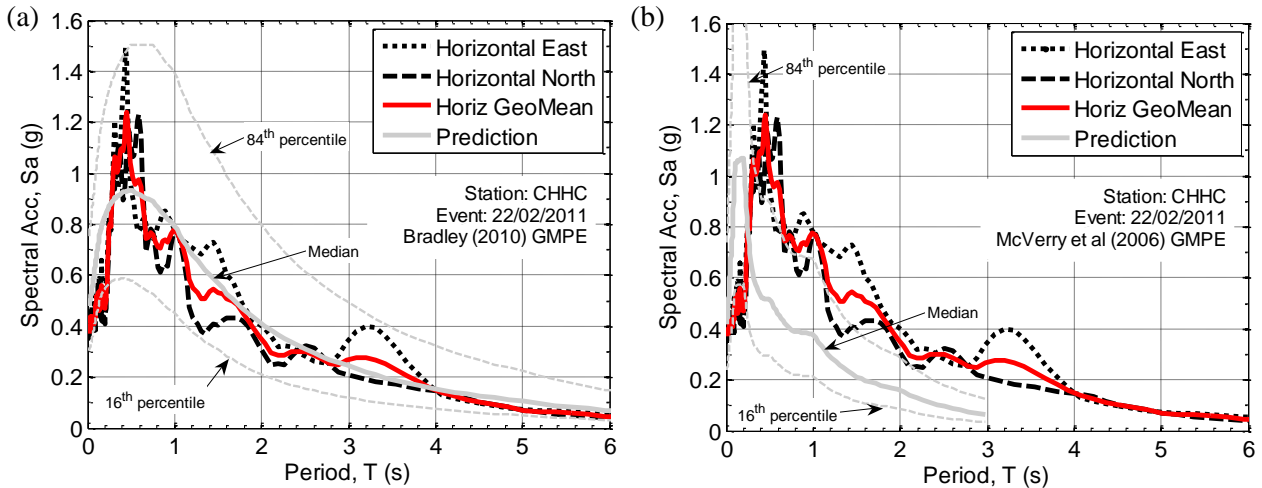


Figure 4: Comparison of the pseudo-acceleration response spectra (SA) observed at Christchurch Hospital (CHHC) during the 22 February 2011 Christchurch earthquake (both North and East components, and the geometric mean) with the empirical prediction based on the NZ-specific: (a) Bradley (2010) model; and (b) McVerry et al. (2006) model. Note that the McVerry et al. model provides predictions for $T \leq 3s$ only.

The brief comparisons above illustrate that, in general, the ground motions from the 22 February 2011 earthquake are consistent with the Bradley (2010) GMPE, which is a New Zealand – specific version of the Chiou et al. (2010) model for California, and consistent with the state of the art in GMPE modelling at present. In contrast, the McVerry et al. (2006) model, which is used in the majority of New Zealand seismic hazard analyses, in particular those underpinning NZS1170.5:2004, provides a biased prediction of spectral amplitudes, other than PGA, particularly at small source-to-site distances, for which ground motions are sufficient to cause significant damage to well engineered structures.

5 CONCLUSIONS

On the basis of the comparisons between seismicity and ground motion modelling in New Zealand and the Canterbury earthquake sequence, the following points can be made:

- At present, background seismicity in NZ seismicity models are considered as point sources which have a minimum depth of 10km. Shallow centroid depths and the effect of the finite fault source geometry are important for ground motion modelling. For the 4 September 2010 and 22 February 2011 earthquakes these two assumptions result in up to a 60% reduction in response spectral amplitudes, and subsequently should be corrected in future seismic hazard analyses in NZ.
- Observed response spectral amplitudes in both the 22 February 2011 discussed here (and 4 September 2010 earthquake (Bradley 2012)) illustrates that the McVerry et al. (2006) GMPE provides a biased prediction as compared to more recent GMPEs (such as the Bradley (2010) model). As such, future seismic hazard analyses for New Zealand should avoid the use of the McVerry et al. (2006) model.

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