ANALYSIS OF GROUND MOTIONS FROM THE 2010-2011 NEW ZEALAND EARTHQUAKES

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SUMMARY:
The 22 February 2011 Lyttelton earthquake is one of the devastating natural catastrophes worldwide, causing a large number of casualties and severe damage to the city of Christchurch, New Zealand. Though the magnitude of 6.3 was relatively low, the ground motions of the Lyttelton earthquake were unexpectedly strong. To understand the uniqueness of the Lyttelton event, this paper focuses on the investigation and characterization of the ground motions from the recent 2010-2011 earthquakes, including the February 2011 Lyttelton and September 2010 Darfield events. By analyzing the ground motion records at selected GeoNet stations in the vicinity of the city of Christchurch, the characteristics of spectral demands at ground motion recording stations from both events were discussed. Then we examine the empirical New Zealand ground motion models to investigate if the ground motion prediction models can explain the unusual destructiveness of the strong ground motions. This study can be helpful to gain a better knowledge of the characteristics and variability of ground motions in the recent strong earthquakes in New Zealand and provide insights to understand the implications to other New Zealand locations and to the rest of world in future earthquakes with similar rupturing mechanism and local condition.

Keywords: Ground motion characteristics; New Zealand earthquakes

1. INTRODUCTION

The 2010-2011 earthquakes that caused wide-spread damage and extensive losses in New Zealand are the most devastating natural disaster in the country's history. The 4 September 2010 Darfield earthquake occurred on a previously unknown east-west fault about 30 km to the west of city of Christchurch (GNS Science 2010), causing considerable damage and NZD 4 billion economic losses (New Zealand Treasury 2010). The Darfield earthquake was then believed to be the most damaging earthquake in New Zealand since the 1931 magnitude 7.8 Hawke's Bay (Napier) earthquake (GNS Science 2010). Six months later, on 22 February 2011, the city of Christchurch was struck again by the Lyttelton earthquake, resulting in 181 fatalities and insured loss between USD 7-10 billion (Munich Re 2011), making this magnitude 6.3 event one of the most costliest disasters in New Zealand history. The Lyttelton event also occurred on a previously unrecognized dipping blind fault that trends northeast to southwest (Bradley and Cubrinovski 2011). The city of Christchurch, in particular the central business district and the eastern suburbs sustained wide-spread and severe damage due to the close proximity of the Lyttelton event. The 2010-2011 events produced the strongest ground motions in New Zealand history (Fry and Gerstenberger 2011): at some locations unexpectedly high ground motions (e.g., horizontal peak ground accretions up to 1.5 g and vertical peak ground accelerations as much as 2.2 g from a M_w6.3 event) were observed. Such strong ground motions are usually not explained well by existing empirical ground motion prediction equations.

To characterize and understand the ground motions from the 2010-2011 Darfield and Lyttelton earthquake events, this paper examines the strong motion records from New Zealand's GNS Science and investigates the performance of empirical ground motion predication equations. In addition to exploring possible connections between the abnormality of ground motions and uncertainty from the perdition models, we discuss the New Zealand seismic code provisions and include the consideration of soil amplification and large stress drop. This paper can be helpful to improve the empirical ground motion models currently used for seismic assessment in New Zealand and to provide insights to understand the implications to other countries and regions in future earthquakes.

2. Source Models and Strong Motion Records

2.1. Source models

In both the Darfield and Lyttelton events, the rupture occurred on the faults that were previously unmapped in a historically low seismicity region (Beavan et al. 2011). The Darfield earthquake ruptured the previously unrecognized Greendale fault with a 30 km surface trace and caused surface rupture up to 5 m (Van Dissent et al. 2011). Figure 1 (red line on the left) illustrates the source model for the Darfield event, which is modelled with a single-segment slip model on the strike-slip Greendale fault with about 30 km in length and 11 km in depth (Holden et al. 2011; Quigley et al. 2010; Zhan et al. 2011).

The fault ruptured as oblique-thrust for the Lyttelton earthquake, which is a mix of reverse faulting (up-dip) and right-lateral strike slip (Beavan et al. 2011). While there was no evidence of surface rupture, fault slip was as much as 2.5m on the subsurface fault rupture near the Avon-Heathcote estuary (Beavan et al. 2011). The single-fault model by Beavan et al. (2011) is employed as the source model, in which the oblique-thrust fault is modelled as a plane with a strike of 59° and a dip of 66.5° to the southeast (Figure 1, blue plane on the right). The plane is 16 km in length and 7 km in width and the depth of upper edge is 1 km.

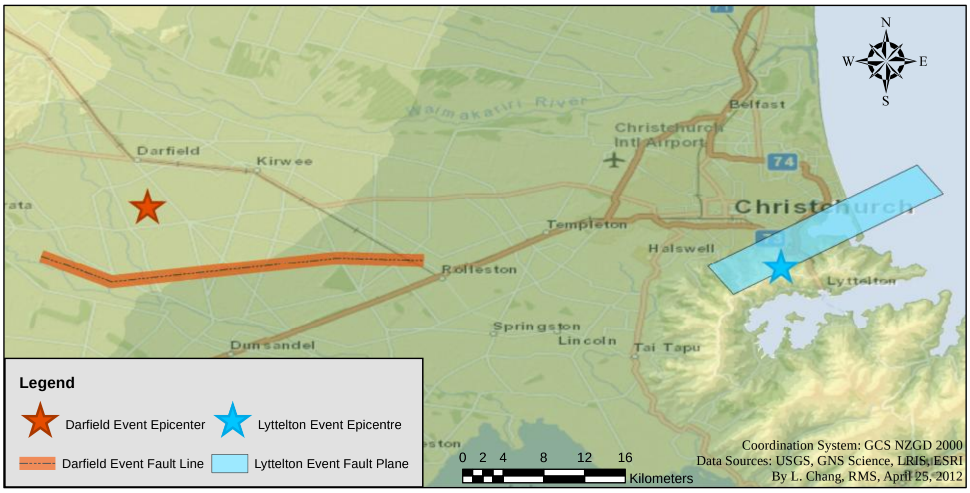

Figure 1. Source models for the September 2010 Darfield earthquake (left) and the February 2011 Lyttelton event (right). Epicenters are marked by stars and coordinates obtained from the US Geological Survey (USGS).

2.2 Strong motion records

Observed near-source ground motion records are obtained from the GeoNet strong motion database (ftp://ftp.geonet.org.nz/), a real-time seismic monitoring and data collection system in New Zealand. The volume 1 data is processed in frequency domain with an extended band-pass filter to keep long-period ground motions for near-source records. Baseline corrections are not performed because the ground motion records are all recorded by digital instruments. Processed records from 65 GeoNet stations are used for the Darfield earthquake, and 46 stations for the Lyttelton event. Characteristics of

5% damped spectral acceleration (Sa) at 0.3, 0.5, 1, and 3 s from the two events are used to investigate the abnormality of ground motions. In this paper, we focus only on horizontal ground motions and vertical component is not covered. Observations used in the rest part of this paper correspond to the geometric mean of horizontal components.

3. NEW ZEALAND DESIGN SPECTRA AND OBSERVED RESPONSE SPECTRA

Christchurch used to be considered a region of low seismicity in New Zealand prior the 2010-2011 earthquakes. However, the Lyttelton event caused unusual and wide-spread destructiveness, especially in the central business district (CBD) of Christchurch city. As a result, it has been recommended that the 500-yr elastic design spectrum be increased by 36% to address the increase risk of M6-6.5 events close to the CBD (Hare 2011). In this section, we examine the seismic demands in a similar manner to Bradley and Cubrinovski (2011) and compares different rates of expectancy (or the hazard factor Z specified in NZS1170) to investigate the connection between the unusual destructiveness and design code provision in New Zealand, in which the McVerry et al. (2006) ground motion model is used in deriving the hazard spectra in NZS 1170 (Standards New Zealand 2004).

The acceleration response spectra of the observed ground motions at three selected GeoNet stations CCCC (Christchurch Cathedral College), HVSC (Heathcote Valley School), and LPCC (Lyttelton Port) are illustrated in Figure 2 for the Darfield earthquake (dotted lines) and Lyttelton event (solid lines). Also illustrated in Figure 2 are the 500-yr elastic design spectra (soil class D) from NZS 1170, which is used to design buildings with the ultimate limit states design principles. Note that the response spectra are geometric mean of horizontal components and the design spectra in NZS 1170 are based on the larger horizontal component.

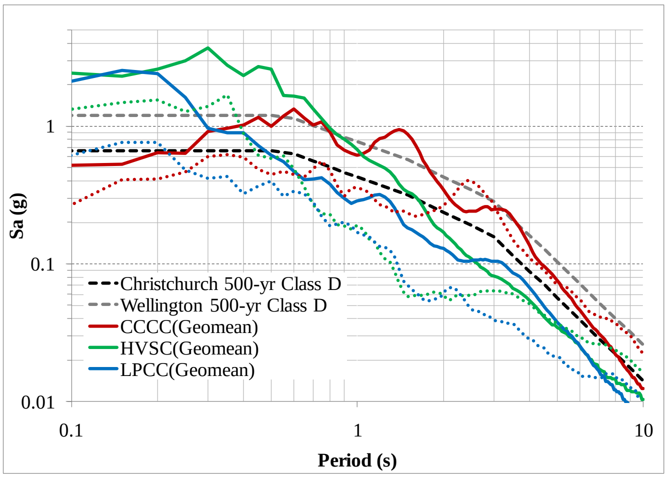

Figure 2. Comparison of New Zealand elastic design spectra (NZS 1170.5) and 5% damped horizontal spectral acceleration. Dotted lines are for the Darfield earthquake and solid lines for the Lyttelton event.

The CCCC station is located in the CBD where medium-rise and tall buildings sustained significant damage. It is evident that the acceleration response spectrum of CCCC (solid red curve) from the Lyttelton event has two apparent peaks at around 1.3 s and 3.1 s, respectively. Such increased mid- and long-period amplitudes are likely caused by the underlying deep sedimentary basin (Bradley and Cubrinovski 2011). Figure 2 shows that the spectral accelerations from the Lyttelton earthquake (solid lines) are stronger than those from the Darfield event (dotted lines) at short periods; while the demands for these two events are similar at longer periods. The recorded spectral amplitude at CCCC for the Darfield earthquake (dotted red curve) is below the design spectra at shorter periods (<2 s). However, the demand of CCCC at longer periods (i.e., 2-3 s) from the Darfield earthquake exceeds that of the Lyttelton event. Short-period (<0.3 s) ground motions at HVSC and LPCC are significantly higher than the design spectra possibly because of the low attenuation through the underlying volcanic rock (Bradley and Cubrinovski 2011). It can be seen from Figure 2 that the ground motions recorded in the

CBD during the Lyttelton event (solid red curve) exceed the NZS1170 500-yr design spectrum on a wide range of period (i.e., 0.3-5 s); while for the Darfield event, seismic demands exceed the design spectrum at long periods from 2-5 s. Even if the earthquakes were happened in Wellington area, a region with higher seismicity than that of Christchurch, the NZS 1170 design spectrum is deficient over a wide range of periods for the observed records in the February 2011 Lyttelton event.

4. GROUND MOTION PREDICTION WITH CONSIDERATIONS OF SOIL AMPLIFICATION AND STRESS DROP

To further investigate the abnormality of ground motions, the empirical New Zealand ground motion model by McVerry et al. (2006) was employed to predict the ground motions. This empirical model has been widely used in seismic hazard studies and is also the basis for the development of elastic site spectra in New Zealand standards for earthquake loads (NZS 1170.5). Using the McVerry et al. (2006) attenuation model (hereinafter referred to as the McV06 model) and the fault information described in Section 2, the ground motions (i.e., Sa at 0.3, 0.5, 1, and 3 s) were predicted for the Darfield and Lyttelton events in Christchurch area. Figure 3 and Figure 5 compare the predicted ground motions for soil class D with the observed records at the selected GeoNet stations for the Darfield and Lyttelton earthquake, respectively.

The large apparent stress drop from the 2010-2011 events is a contributing factor to the near-filed strong ground motions (Fry and Gerstenberger 2011). Instead of applying a stress drop scaling term, this study increased the magnitude from 6.3 to 6.7, the energy magnitude of the Lyttelton event, as a proxy to represent the large apparent stress drop. In addition, this would take into account the possible magnitude uncertainty and deficiency of the GMPEs in magnitude scaling. Predicted ground motions for both magnitudes are plotted in Figure 5 (soil class D) and Figure 6 (soil class E).

To illustrate the amplification effects of different soil classes on the predicted ground motions, Figure 6 gives the predicted ground motions on soil class E for the empirical McV06 and NGA models as a comparison. The solid lines are the predicted median ground motions using the empirical ground predictions equations while the dashed lines are the 90% confidence bands (i.e., the 16^{th} and 84^{th} percentile ground motions) for the McV06 model. It should be noted that distance metric used in this paper is the closest distance to co-seismic rupture plane (R_{rup}).

It can be seen from Figure 3 that the predicted spectral accelerations by the McV06 model show a good fit in general to the observations from the Darfield earthquake—most of the observations are within the 90% confidence interval (CI) bands. For the Lyttelton event, however, the performance of empirical ground motion prediction equations at long periods (i.e., >1s) is not as good as that in the Darfield earthquake: the empirical prediction equations tends to underestimate ground motions within 10 km while accelerations are over-predicted at distance greater than 10 km (Figure 5 and Figure 6).

In order to investigate if the ground motion prediction models can explain the unusual strong ground motions, four next-generation attenuation (NGA) models are selected as reference models, namely AS08 (Abrahamson and Silva 2008), BA08 (Boore and Atkinson 2008), CB08 (Campbell and Bozorgnia 2008), and CY08 (Chiu and Youngs 2008). Here we do not attempt to rigorously evaluate the adequacy or performance of the ground motion models against the observed records, but rather to simply illustrate the deviation of nominally expected ground motions from the observed ones in general.

Figure 4 compares the observed and predicted ground motions for the Darfield earthquake using these NGA models. For the Darfield earthquake, it can be seen from Figure 3 and Figure 4 that the McV06 model performs well and showed no significant difference to the NGA models; while for the Lyttelton event, it is evident from Figure 5 and Figure 6 that the overall goodness-of-fit of the NGA models tends to be better at distance >10 km. However, it is noted that these NGA models share similar pattern of over- and under-estimation of the observed ground motions with the McV06 model.

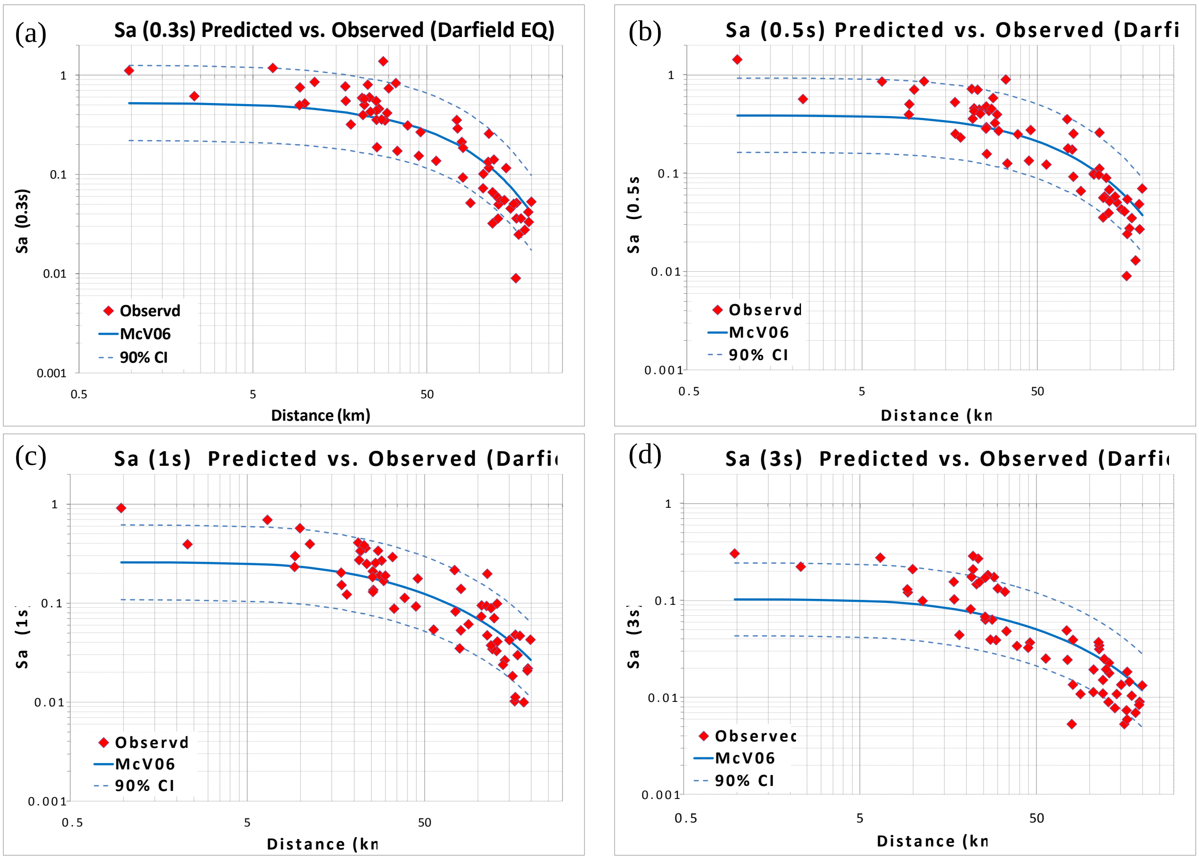

Figure 3. Comparison of observed and predicted Sa (McV06 on soil class D) for the Darfield earthquake

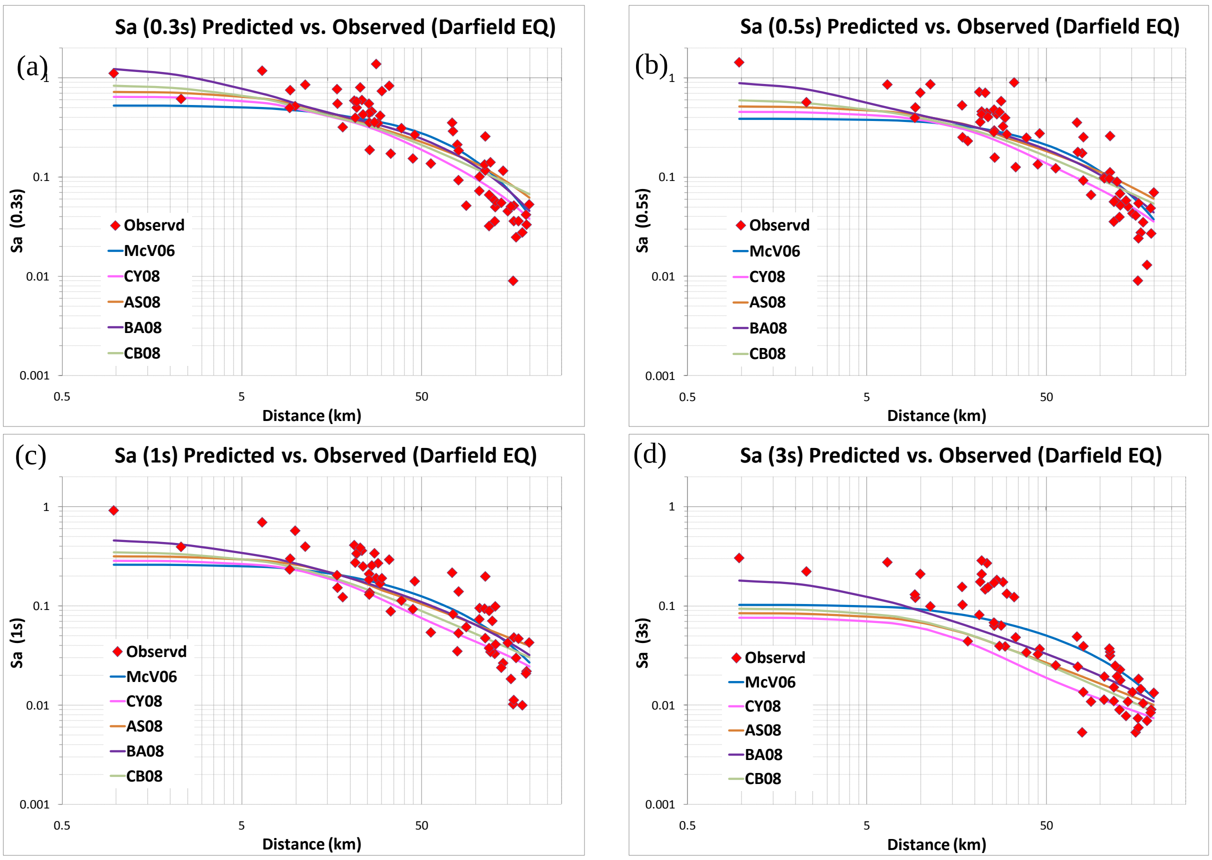

Figure 4. Comparison of observed and predicted Sa (McV06 and NGA on soil class D)
for the Darfield earthquake

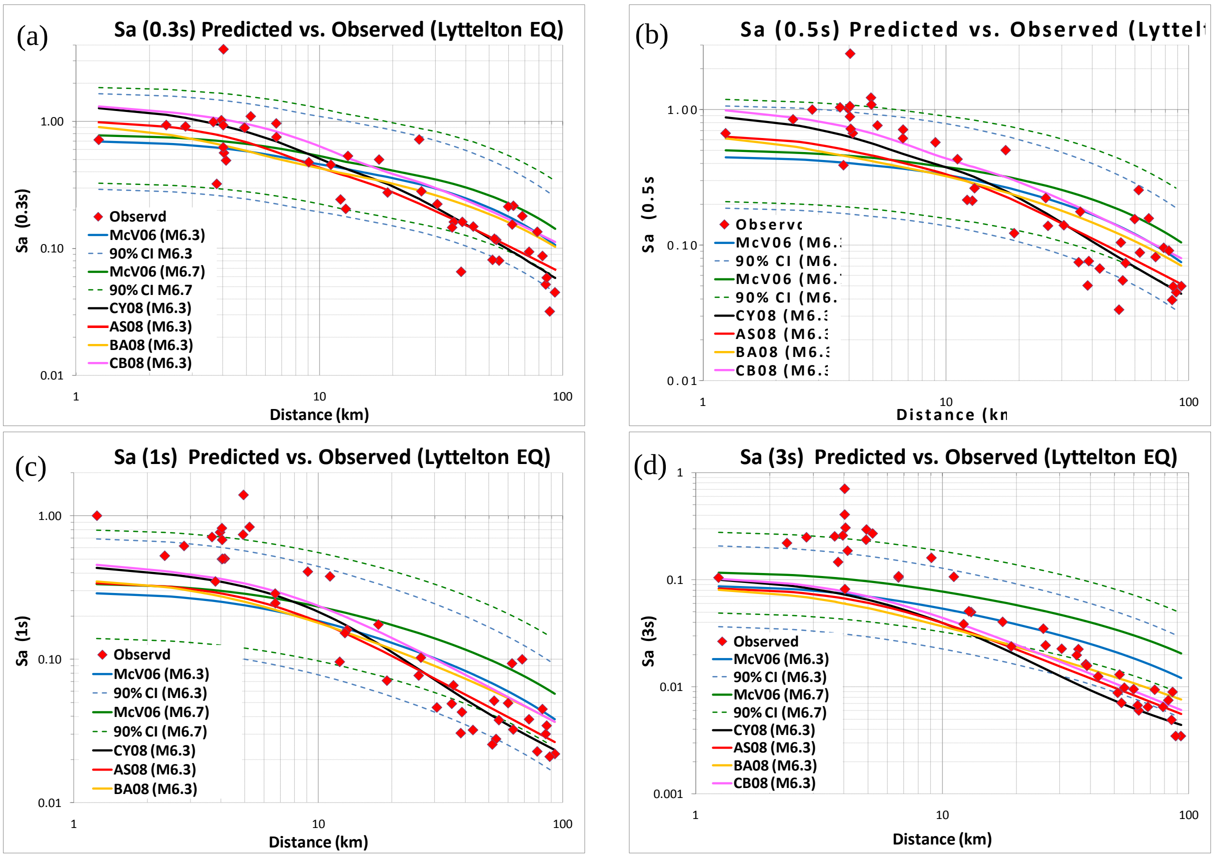

Figure 5. Comparison of observed and predicted Sa (McV06 and NGA on soil class D) for the Lyttelton earthquake

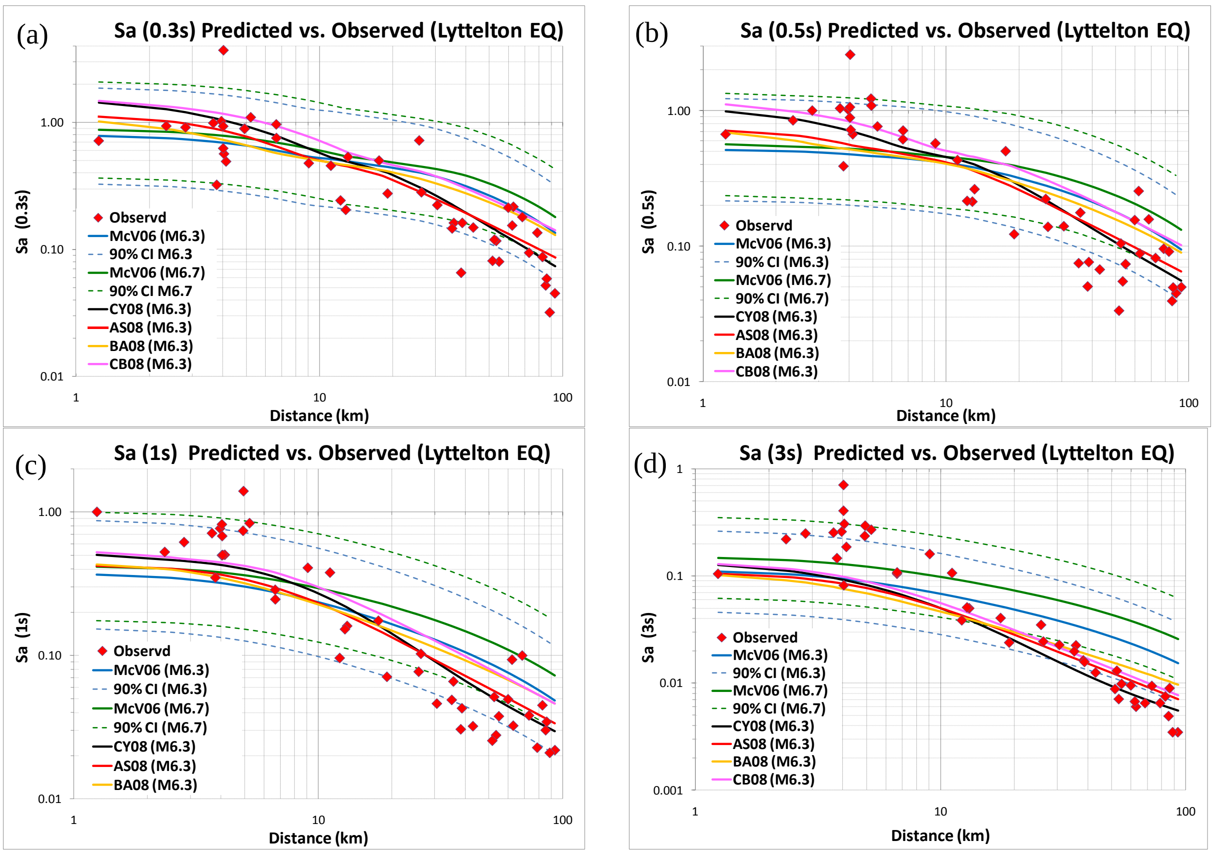

Figure 6. Comparison of observed and predicted Sa (McV06 and NGA on soil class E) for the Lyttelton earthquake

Residual analysis is a commonly-used approach to characterize prediction uncertainty of ground motion models. In order to evaluate the relative performance of ground motions prediction models, statistical tests are performed on the residuals of spectral accelerations between the observed ground motions and the predicted median values from the McV06 model. The residuals are calculated as the difference between the natural logarithms of the observed and predicted ground motions, i.e., $\ln(Sa_{Predicted})-\ln(Sa_{Observed})$, in which positive residuals indicate over-estimation and negative under-estimation. The uncertainty inherent in the empirical McV06 model for the Darfield and Lyttelton events was investigated by analyzing the residuals.

Figure 7 and Figure 8 illustrate normalized residuals from the Darfield earthquake and Lyttelton event (M6.3 and M6.7), respectively. The residuals are normalized by σ, the uncertainty of geometric mean horizontal components in the empirical McV06 prediction equation (McVerry et al. 2006). It is evident that, for both the events, residuals at short periods (e.g., 0.3 s) distribute more evenly and tightly around zero than at long periods and at distance more than 20km, suggesting a better performance of the empirical prediction equation at shorter periods. For the Lyttelton event, residuals at long periods such as 2 s and 3 s tends to be positive (i.e., over-estimation) beyond 10 km and under-estimate within that distance. In contrast with the Lyttelton event, the McV06 empirical predication equation shows better performance in the Darfield event: residuals at all periods are within ±3σ range and evenly distributed around the predicted medians.

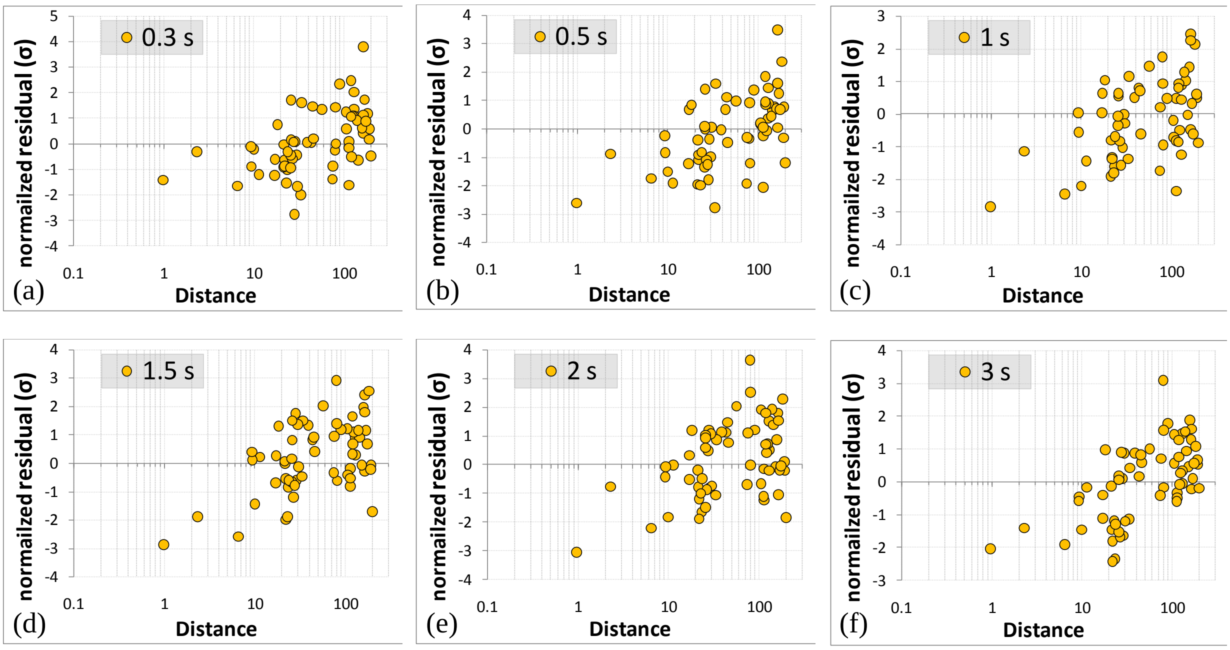

Figure 7. Normalized residual (in σ) of 0.3, 0.5, 1, 1.5, 2, and 3s Sa (McV06) for the Darfield event

Results of statistical analysis are given in terms of σ (Table 1) to illustrate the range of uncertainty inherent in the empirical prediction equation. In general, the predictions are within 3σ at distance >10km for both the events with only a few exceptions. Statistical results for the Darfield earthquake show less uncertainty than that of the Lyttelton event, suggesting a better agreement with observations. For the Lyttelton event, Table 1 shows that near-source ground motions within 10 km tend to deviate from the observations (under- or over- estimated); while ground motions are generally within 2σ range when distance>10 km. It can be seen from Table 1 that at short periods, the McVerry et al. (2006) model shows better performance in general. For example, most test results (especially for the two Lyttelton cases) for the 0.3 s period are within 3σ range; while more than 50% of the 3 s results are beyond 2σ range. This suggests that the unusual characteristics of ground motions at mid- to long periods in the Lyttelton event may not be well predicted by ground motion models alone and could be related to other factors such as source and site effects.

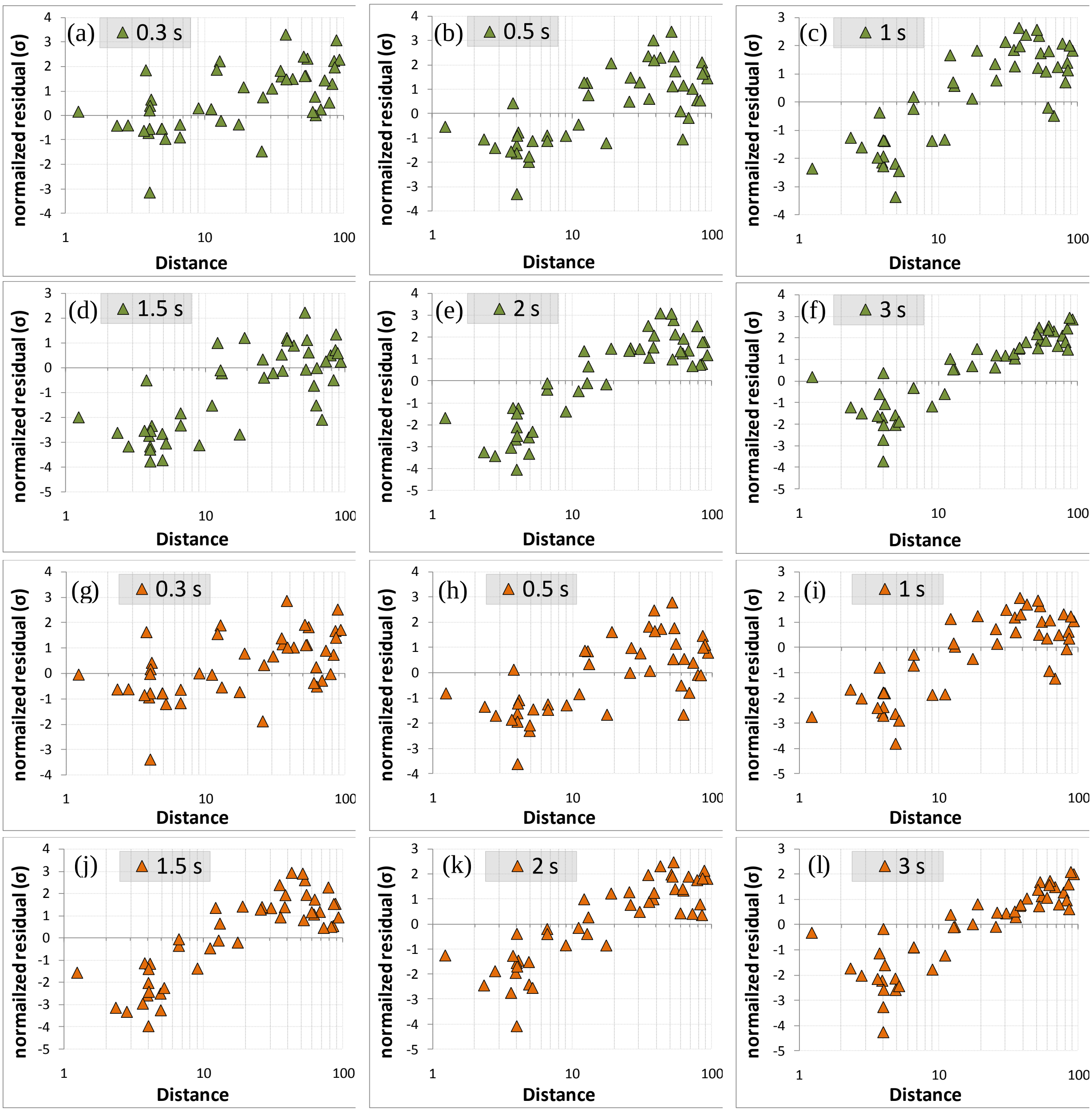

Figure 8. Comparison of the normalized residual (in σ) of 0.3, 0.5, 1, 1.5, 2, and 3s Sa (McV06) for the M6.3 Lyttelton event (top two rows) and M6.7 Lyttelton event (bottom two rows)

Table 1. Statistical analyses results of the residuals from the McVerry et al. (2006) model

Events	Distance Bins (km)	Periods					
		0.3 s	**0.5 s**	**1 s**	**1.5 s**	**2 s**	**3 s**
Darfiled	(0-10)	1.89 σ	3.23 σ	3.74 σ	3.38 σ	3.43 σ	3.18 σ
	(10-50)	2.58 σ	3.40 σ	2.76 σ	0.19 σ	0.68 σ	3.04 σ
	(>50)	1.10 σ	0.27 σ	1.30 σ	1.24 σ	0.93 σ	1.87 σ
Lyttelton M6.3	(0-10)	2.56 σ	6.72 σ	8.69 σ	8.95 σ	7.28 σ	8.15 σ
	(>10)	0.91 σ	2.23 σ	3.37 σ	0.83 σ	0.38 σ	2.11 σ
Lyttelton M6.7	(0-10)	1.55 σ	5.40 σ	6.95 σ	11.21 σ	9.20 σ	5.91 σ
	(>10)	3.57 σ	0.96 σ	0.53 σ	7.14 σ	0.21 σ	2.48 σ

5. DISCUSSIONS, IMPLICATIONS, AND CONCLUSIONS

This paper examined the GeoNet ground motion observations from the GNS Science to investigate and characterize the ground motions from the recent September 2010 Darfield and February 2011 Lyttelton earthquakes in New Zealand. We discussed the characteristics of seismic demands in Christchurch and the New Zealand design codes provisions in other New Zealand regions such as Wellington. Ground motions using empirical ground motion models are predicted by using the McVerry et al. (2006) empirical model for New Zealand and several NGA models and the results were compared with the observed. Soil amplification effects are included for the predicted ground motions to be consistent with the observations. The magnitude for the Lyttelton event was increased to 6.7 as a proxy to represent the large stress drop. The results indicate that the difference in the results between the GMPEs and the observed is not due to the deficiency in the magnitude scaling of the GMPEs or due to magnitude uncertainty. Statistical tests were conducted to compare the observations to the range of uncertainty inherent in ground motion prediction equations. This study characterized the ground motions in the recent strong 2010-2011 earthquakes in New Zealand and can be helpful for improving the seismic risk assessment in Christchurch region and provide insights to understand the implications to other regions with similar local condition and rupturing mechanism to the 2010-2011 New Zealand earthquake series.

The New Zealand empirical prediction equation by McVerry et al. (2006) agreed well with ground motion records from the Darfield earthquake and no significant difference was found between the empirical McVerry et al. (2006) model with the selected NGA models. In addition, the empirical New Zealand model performed generally better in the Darfield earthquake as compared with the Lyttelton event. Though the selected NGA models tend to perform better at farther distance in the Lyttelton event, they shared the similar under- and over-estimation pattern against the observed records.

Statistical tests for the Lyttelton event showed that near-source observations within 10 km are generally higher than the predicted ground motions; while the empirical prediction equation tends to over-estimate ground motions at longer distance (>10 km). It was also found that for the Lyttelton event, the number of outliers of ground motion residuals at long periods is larger than the short periods, suggesting better fit of the empirical McVerry et al. (2006) prediction equation at shorter periods. Comparisons from the NGA models suggested similar conclusions.

The results suggest that the unusual characteristics of the ground motions in the Lyttelton earthquake may not be well modeled by ground motion prediction models that represent the average earthquake and local ground conditions. The strong spectral response at mid- to long-periods could be related to a specific combination of source and site effects. Because of the strong shaking at the near source and the observed spectral shape, the usual suspects would include rupture directivity, basin edge effects, the source spectrum, the underlying deep sedimentary basin, or a combination of these. In addition, extreme ground motions may be common with shallow intraplate earthquakes such as the New Madrid Seismic zone in the central United States (Fry and Gerstenberger 2011; Elnashai et al. 2009) and the paucity of high-amplitude observations from these low-probability, high-consequence events may not be sufficient to validate empirical prediction models.

In this paper we only focused on the horizontal ground motions, although very large vertical ground motions were observed in the 2010-2011 New Zealand earthquakes. Normally, the vertical ground motions are not considered to be a significant contributor to the risk of building damage, but the extreme vertical ground motions are likely a factor in the significant liquefaction and other ground failures observed in the Lyttelton event. More work is needed to understand the effects of directivity and other source and site effects to near-source motions. Discussion on the calibration of ground motions and structural damage using field data collected by the RMS reconnaissance team is presented in a separate paper.

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