Characteristics of Vertical Ground Motions in the Canterbury Earthquakes

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ABSTRACT: This paper presents a critical evaluation of vertical ground motions observed in the Canterbury earthquake sequence. The abundance of strong near-source ground-motion recordings provides an opportunity to comprehensively review the estimation of vertical ground motions via the New Zealand Standard for earthquake loading, NZS1170.5:2004, and empirical ground motion prediction equations (GMPEs). An in-depth review of current GMPEs is carried out to determine the existing trends and characteristics present in the empirical models. Results illustrate that vertical ground motion amplitudes estimated based on NZS1170.5:2004 are significantly unconservative at short periods and near-source distances. While conventional GMPEs provide an improved prediction, in many instances they too underpredict vertical ground motion accelerations at short periods and near-source distances.

1 INTRODUCTION

Significant structural damage was observed in numerous events during the Canterbury earthquake sequence of 2010-2011 due to strong ground motions. In addition to the effect of severe horizontal strong motion amplitudes, vertical ground motion amplitudes exceeding their horizontal counterparts were also a likely contributor to the observed damage, and therefore their characterisation and prediction requires more attention. Vertical ground motion amplitudes are known to be significant in the immediate vicinity of the earthquake source. However, a paucity of near-source records has limited further understanding of the salient features of near-source vertical ground motions (Bradley 2012). The unprecedented number of near-source ground motions obtained in the Canterbury earthquake sequence therefore offers a unique opportunity to comprehensively investigate, and potentially improve, the characterisation of vertical ground motion.

Seismic design provisions for vertical ground motion are often considered for critical structures such as nuclear power plants and dams, but not for regular structures. However, recent studies (e.g. Kunnath et al. 2008) suggest that vertical ground motions can also be significant for the response of structures such as ordinary highway bridges, and buildings with large floor spans located at near-source sites. With the large vertical accelerations that were recorded in the Canterbury earthquake sequence, the need for a simple, yet accurate, procedure for the consideration of vertical ground motions is more prevalent than ever. The current New Zealand standard for earthquake loading, NZS1170.5:2004, assumes that the vertical response spectra is 70% that of the horizontal, clearly a gross assumption that cannot accurately predict the variations which intrinsically occur in vertical ground motions (e.g. Papazoglou and Elnashai 1996). This code prescription considerably underestimates the vertical ground motion at near-source distances and short vibration periods (e.g. Bradley and Cubrinovski 2011).

Vertical ground motion amplitudes can be predicted using empirical ground motion prediction equations (GMPEs), in the same manner that horizontal ground motion amplitudes are estimated. In this paper, numerous vertical GMPEs are evaluated by comparing their predictions, both with one another, and against the strong ground-motion recordings observed during the two major earthquake events from the Canterbury earthquake sequence. Particular attention is given to the difference in predictive capabilities of models which predict either: (i) the vertical-to-horizontal (V/H) spectral ratio, and are subsequently multiplied by the predicted horizontal spectra; or (ii) vertical spectra directly.

2 MOTIVATION FROM THE CANTERBURY EARTHQUAKE SEQUENCE

The 2010-2011 Canterbury earthquake sequence produced multiple instances of large ground motion, both horizontal and vertical. Figure 1 illustrates the spatial distribution of vertical ground motions obtained from various strong motion stations as a result of the 22 February 2011 Christchurch earthquake, as well as the surface projection of the inferred causative fault. It can be seen that the vertical ground motion amplitudes are significantly larger near the source. Papazoglou and Elnashai (1996) provide significant evidence that strong vertical ground motions are a significant contributing factor to structural damage using examples from historical earthquakes; and hence clearly the vertical ground motions in the Canterbury earthquake sequence could also have partially contributed to the extensive damage observed.

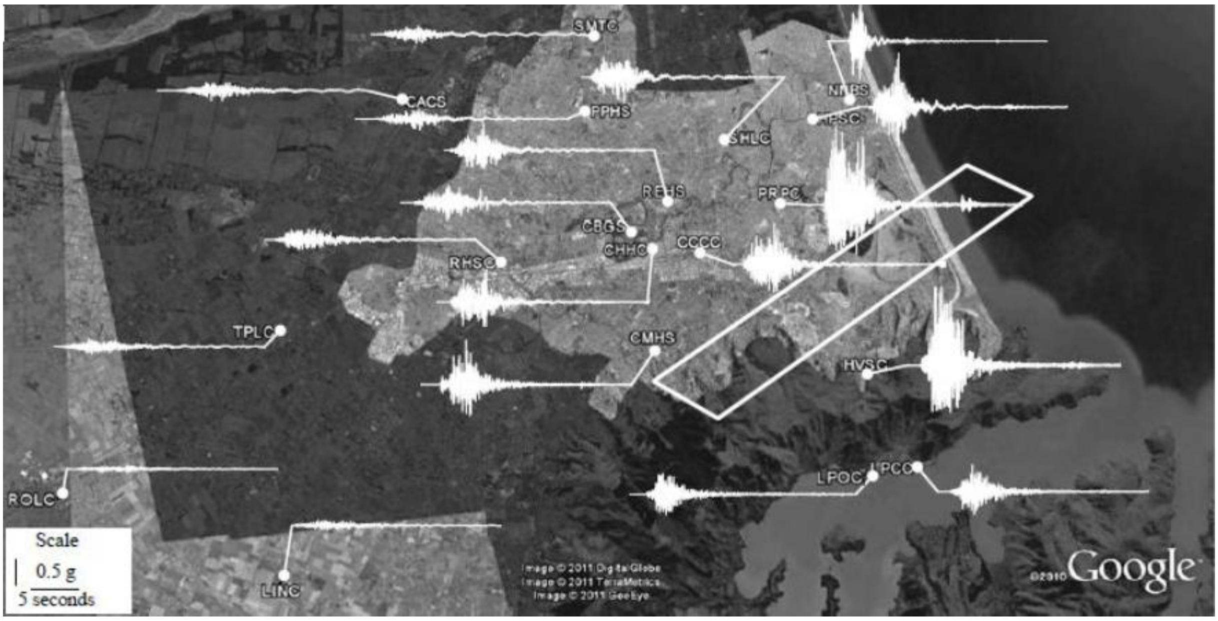

Figure 1. Recorded vertical strong ground motions during the Christchurch earthquake (after Bradley 2012).

2.1 New Zealand Loadings Standard, NZS1170.5:2004

It is firstly insightful to investigate the New Zealand Standard for earthquake loading, NZS1170.5:2004, prescriptions for vertical ground motion in relation to ground motions observed in the Canterbury earthquake sequence. Currently the NZS1170.5:2004 provides a simplistic prescription for vertical spectra which simply consists of scaling the horizontal spectra by 70%. The simplicity of, and error associated with, this prescription is illustrated by comparison with the pseudo-acceleration response spectra for the ground motion recorded at the Christchurch Cathedral College (CCCC) station during the Christchurch earthquake, as shown in Figure 2a. It can be seen that the vertical response spectrum has a peak at approximately T=0.08s, while the horizontal response spectrum peak occurs at approximately T=0.6s. It can also be seen that for high-frequencies it is not uncommon for the vertical response spectral amplitudes to be several times the horizontal spectral amplitudes, but this generally decreases with period, and for long periods the vertical spectral amplitudes are less than the horizontal amplitudes.

Figure 2b illustrates the vertical-to-horizontal (V/H) ratio of peak ground acceleration (PGA) observed from both the 4 September 2010 Darfield and 22 February 2011 Christchurch earthquakes as a function of distance, as well as the NZS1170.5:2004 prescription of V/H=0.7. It can be seen that this prescription significantly underestimates the near-source V/H ratios (source-to-site distance less than R_{rup}=15km).

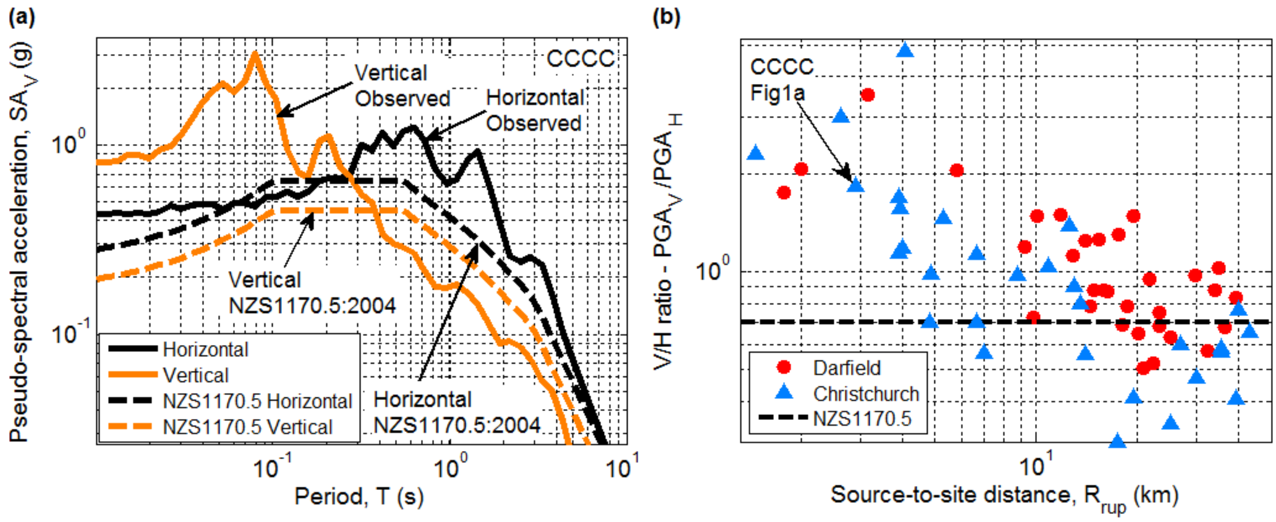

Figure 2. (a) Vertical and horizontal pseudo-acceleration spectra at CCCC recording site for the Christchurch earthquake; and (b) PGA vertical to horizontal (V/H) ratio of sites with source-to-site distance R_{rup}<50km.

The aforementioned differences in ground motion characteristics can be fundamentally attributed to the different dominant wave types of vertical and horizontal ground motion. Due to the refraction of seismic waves towards vertical incidence as they approach the surface, P-waves tend to dominate vertical ground motion (particularly at high frequencies) while S-waves tend to dominate the horizontal ground motion (at high frequencies). Vertical ground motions also tend to have a higher predominant frequency than horizontal ground motions, because the compression (bulk) stiffness of surficial soils is significantly greater than their shear stiffness (for the strains induced), and therefore relatively little modification occurs to vertical ground motion as a result of so-called 'site effects'. Hence, in summary, the different dominant seismic waves and propagation characteristics which cause vertical ground motions means they are intrinsically different than horizontal ground motions, and hence why a constant V/H ratio (as adopted by NZS1170.5:2004) is a poor prescription. The outcome of such physical characteristics is greater V/H ratios at shorter periods and smaller V/H ratios at longer periods. Finally, it is important to note that while vertical accelerations are predominantly high-frequency ground motions, so too is the vertical stiffness of most structures, and hence these similar excitation and natural frequencies mean that significant structural response can occur as a result of vertical ground motions (Papazoglou and Elnashai 1996).

In addition to the current code prescriptions in NZS1170.5:2004, the accompanying commentary provides discussion on the potential for near-source vertical ground motions with high frequency content to exceed their horizontal counterparts for short periods. A V/H ratio of unity is suggested for source-to-site distances of less than R_{rup}=10km, and periods of T=0.3s and less. This suggestion is still an underprediction when compared to the large PGA V/H ratios at less than R_{rup}=10km source-to-site distance shown in Figure 2b. Nonetheless, more appropriate requirements for near-source vertical ground motions should be included in the standard itself, rather than just discussed in the commentary.

The inaccuracies of simply scaling horizontal spectra by a constant to produce vertical spectra have also been observed by others, e.g. Bozorgnia and Campbell (2004). Therefore there is convincing evidence, both in New Zealand and internationally, that conventional code prescriptions are grossly inadequate in properly capturing the nature of vertical ground motions in the near-source region. However, simply changing the nature (e.g. shape or amplitude) of vertical design spectra is unlikely to significantly affect current design processes as vertical ground motions are often ignored. Rather, improvements should be made in both the quantification of, and design against, vertical ground motions, with particular attention given to explicit specification of the circumstances where vertical ground motion design is necessary.

3 COMPARISON OF EMPIRICAL MODELS

Vertical ground motion amplitudes can also be predicted using empirical ground motion prediction equations. These GMPEs can be categorised into two groups: those which predict vertical spectral acceleration directly, SA_v, and those which predict the V/H spectral ratio (and subsequently require multiplication with predicted horizontal spectra). The two categories have several implications regarding the associated error and the ability of such a model to properly capture the underlying physics of strong vertical ground motions which are investigated. The empirical predictions considered are Abrahamson and Silva (1997), Campbell (1997), Ambraseys and Douglas (2003), Bozorgnia and Campbell (2004), Ambraseys et al. (2005), and Gülerce and Abrahamson (2011), which are herein referred to for brevity as AS97, C97, AD03, BC04, A05, and GA11, respectively.

Figure 3 illustrates a comparison of the median predictions of the examined SA_v models as a function of source-to-site distance, R_{rup}, and vibration period, T, at soft/firm soil sites. It can be seen that, in general, there is relatively good agreement between the models. Figure 3a demonstrates the attenuation of SA_v prediction models studied for two event magnitudes, M_w6 and 7. It can be seen that vertical acceleration strongly attenuates with distance and increases with magnitude. The figure shows that the BC04 model is relatively insensitive to changes in magnitude, within the current range shown, for source-to-site distances less than R_{rup}=3km. Therefore, the BC04 model can adequately model magnitude saturation, something the other models are incapable of. Furthermore, this figure shows the relative range of values predicted by the models. The predicted values for R_{rup}>10km show little spread for each respective magnitude, thus confirming consensus in attenuation due to geometric spreading. However, the near-source values have a much larger spread showing a distinct lack of agreement between the models. This is likely due to the relative scarcity of near-source recordings used in the development of some models, and different functional forms. Figure 3b shows the acceleration spectra for a magnitude M_w7 event at two source-to-site distances, R_{rup}=5km and 15km. Comparing the various models, the C97 model generally predicts higher amplitudes within the T=0.1-1s range, while the AS97 model is the highest at very short (T<0.1s) periods. The peak amplitudes for each model occur at approximately T=0.1s which is very similar to the values observed in ground motions throughout the Canterbury earthquake sequence.

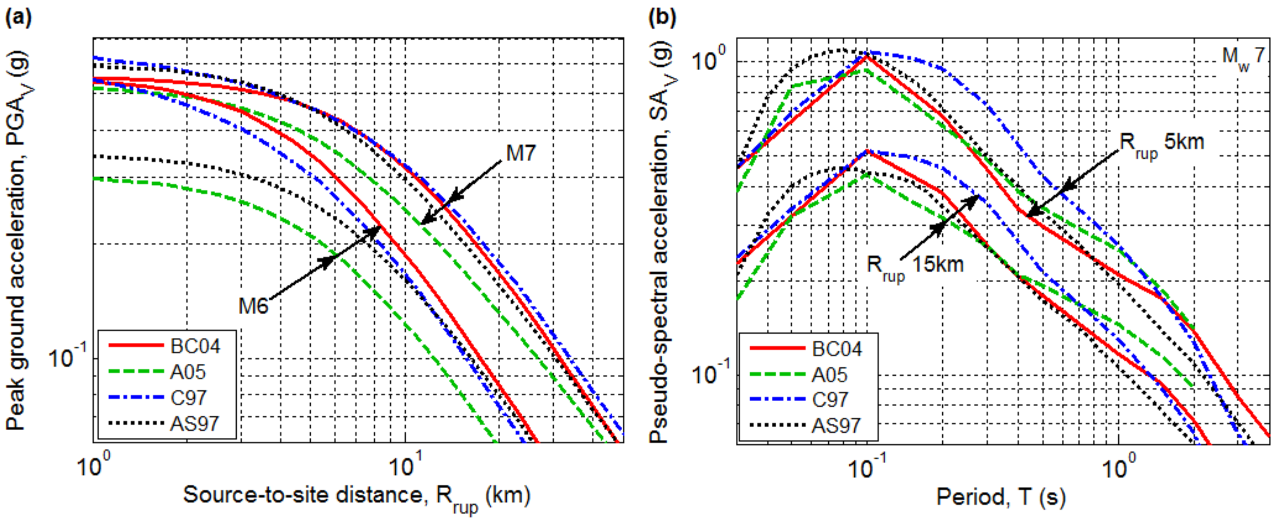

Figure 3. Comparison of various SA_v GMPEs at soft/firm soil sites: (a) PGA attenuation for M_w6 and M_w7; and (b) acceleration spectra for M_w7 at R_{rup}=5km and R_{rup}=15km source-to-site distances.

Figure 4 demonstrates the median predictions of the GMPEs for V/H ratio examined. Figure 4a illustrates the attenuation of PGA V/H ratios for two event magnitudes, M_w6 and 7. It can be seen that the AD03 model is simply a constant, similar to the New Zealand code prescription. For the M_w7 predictions, the BC04 and GA11 models generally show strong agreement in their near-source predictions but diverge at greater source-to-site distances, where BC04 predicts greater V/H ratios. For the M_w6 scenario, the BC04 model consistently predicts greater V/H ratios than the GA11 model. Figure 4b shows the predicted median V/H ratio spectra for source-to-site distances, R_{rup}=5km and

15km. The shape of the V/H spectra is strongly influenced by the different spectral shapes of vertical and horizontal ground motions as previously discussed with reference to Figure 2a. Firstly, the maximum V/H ratios for each model occur at either T=0.05s or 0.1s which corresponds to the peak in vertical spectra (e.g. Figure 2a). Secondly, the depression at roughly T=0.6-1.0s corresponds to the peak horizontal ground motion. As illustrated in Figure 4b, in general, the short period V/H values are larger than the long period values.

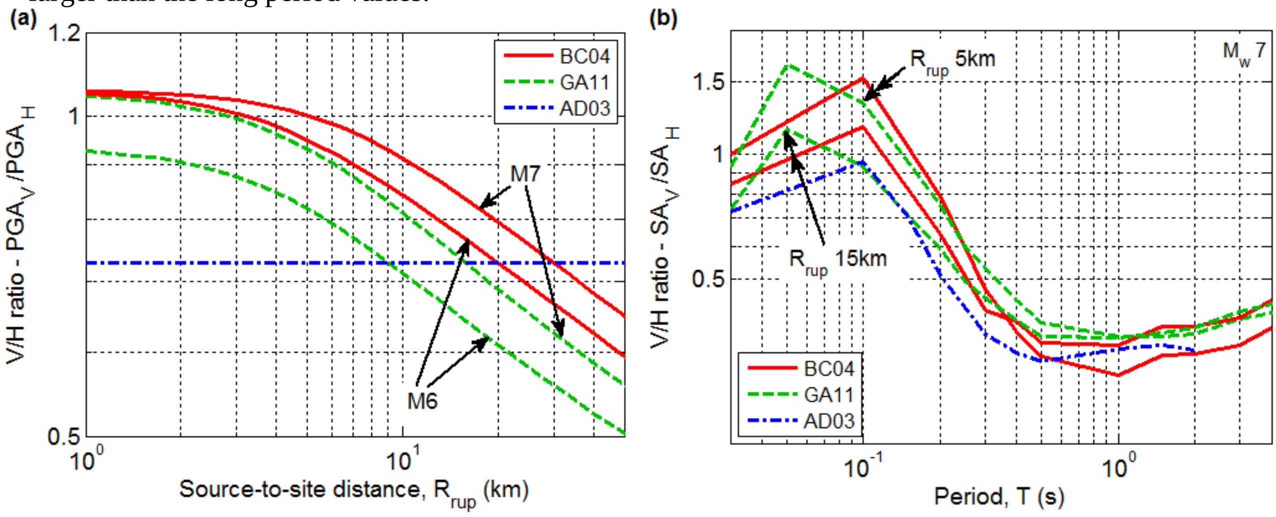

Figure 4. Comparison of various V/H ratio GMPEs at soft/firm soil sites: (a) PGA V/H ratio attenuation for M_w6 and M_w7; and (b) V/H ratio acceleration spectra for M_w7 at R_{rup}=5km and R_{rup}=15km source-to-site distances.

4. EXAMINATION OF EMPIRICAL MODELS VS. CHRISTCHURCH DATA

Following an understanding of the characteristics of the different empirical GMPEs examined in the previous section, these models were then compared with the observed data from the Darfield and Christchurch earthquakes as discussed below. Several trends were observed across multiple models, the most prevalent of which are highlighted.

Figure 5 shows two predicted SA_v models, BC04 and A05, in comparison with data observed from the Christchurch earthquake. Figure 5a illustrates the two models' PGA_v predictions compared to observed values in the Canterbury region with R_{rup}<50km. The results show that the BC04 model predicts the near-source PGA_v values relatively well (R_{rup}<15km), with the exception of a few outliers, but overpredicts the observations at greater distances. However, it is noted that vertical acceleration amplitudes at such distances are generally relatively insignificant. Conversely, the A05 model predicts the observations at large distances well but significantly underpredicts the near-source values (R_{rup}<10km). Figure 5b shows the predicted vertical acceleration spectra of the BC04 and A05 models in comparison with the observed near-source (R_{rup}<7.5km) vertical spectral ordinates for the Christchurch earthquake. Firstly, the BC04 model appears to produce good predictions for all periods shown although slightly underpredicting at very short periods (T=0.05s and 0.1s). Secondly, the A05 model underpredicts at all periods, in particular at short periods.

Figure 6 provides a comparison between the predictions of the BC04 and GA11 V/H ratio models against the V/H ratio observations from the Christchurch earthquake. Figure 6a illustrates the two models' V/H PGA ratio predictions compared to observed values in the Canterbury region with R_{rup}<50km. It can be seen that both models generally provide a prediction which is consistent with the observations at large source-to-site distances. However, both models tend to underpredict the observed V/H ratios at very short distances (R_{rup}<5km). This discrepancy can primarily be attributed to the fact that: (i) these models were based on relatively little data at very short distances, despite short distances being critical in vertical ground motions; and (ii) large nonlinear effects in soft soils during large ground motion shaking (Bradley and Cubrinovski 2011). Figure 6b shows the predicted V/H ratio spectra of the BC04 and GA11 models in comparison with the observed near-source (R_{rup}<7.5km) V/H ratios for the Christchurch earthquake. Both models predict the long period (T>1s) observations relatively well but underpredict the short period (T<0.1s) observations. The GA11 model predicts the intermediate period observations well as opposed to the BC04 model which underpredicts. Also of interest is the inherent uncertainty in each model. The BC04 model has a much larger standard deviation than the GA11 model. This is because the BC04 model is constructed from the combination of two separate spectra, one vertical and one horizontal, without consideration for their correlation, while the GA11 model was developed from a single direct regression against V/H observations.

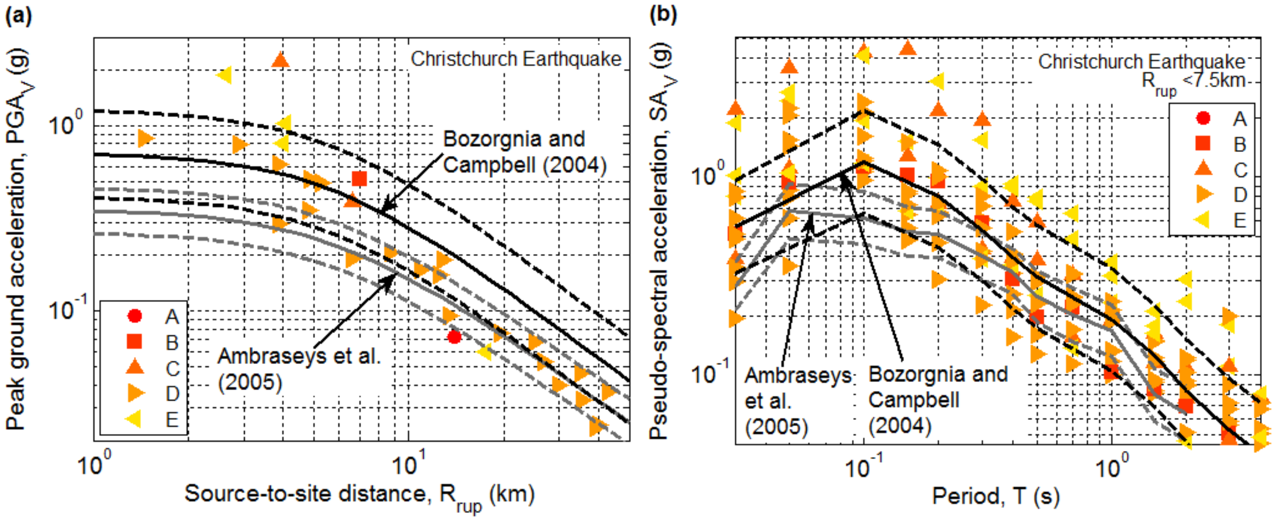

Figure 5. Comparison of Bozorgnia and Campbell (2004) and Ambrasey et al. (2005) SA_v GMPEs against observations from the M_w6.25 Christchurch earthquake: (a) PGA_v with distance, R_{rup}; and (b) predicted SA_v acceleration spectra (using R_{rup}=3.75km). Predictions are for soft/firm soil conditions.

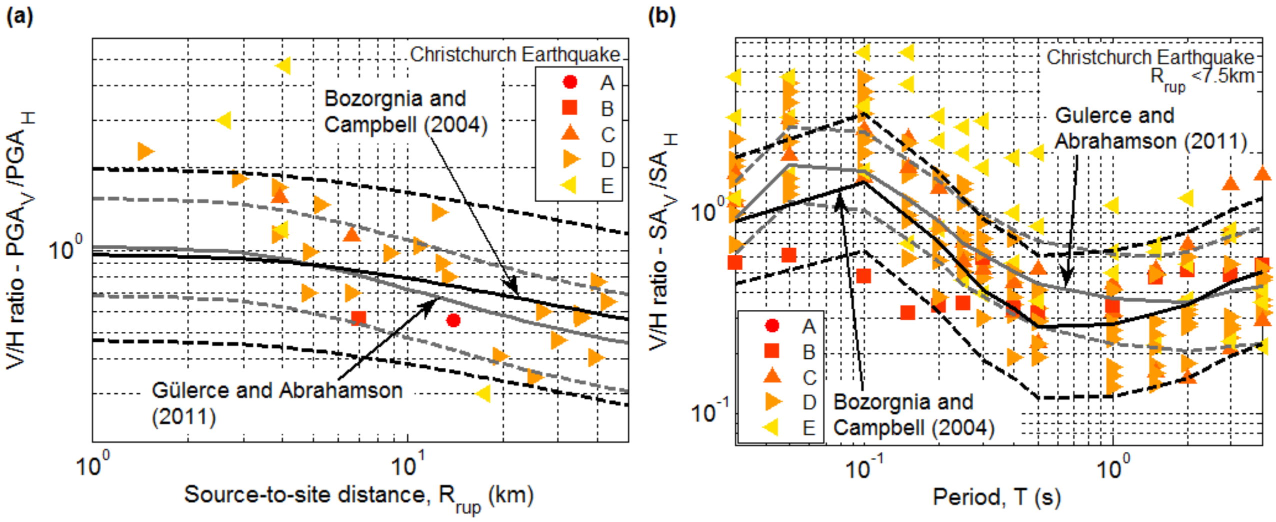

Figure 6. Comparison of Bozorgnia and Campbell (2004) and Gülerce and Abrahamson (2011) V/H ratio GMPEs against observations from the M_w6.25 Christchurch earthquake: (a) PGA_v/PGA_H with distance, R_{rup}; and (b) predicted SA_v/SA_H spectra (using R_{rup}=3.75km). Predictions are for soft/firm soil conditions.

Another significant trend observed by comparing Figure 5 and Figure 6 was that the BC04 SA_v model performed better than the BC04 V/H ratio model. In addition to the results for the Christchurch earthquake in Figure 5 and Figure 6, both of these models are plotted against near-source (R_{rup}<7.5km) observations from the Darfield earthquake in Figure 7. As can be seen in Figure 7a, the SA_v model provides a relatively good prediction to the observations at most periods although the very short period (T<0.1s) values are underpredicted. In contrast, the V/H ratio model in Figure 7b underpredicts the observations at most periods. As noted, Figure 5b and 6b also show the BC04 SA_v and BC04 V/H ratio models, respectively, for the Christchurch earthquake. The SA_v model predicts all periods relatively well with some slight underprediction at short periods (T<0.1s) while the V/H ratio model predicts well for long periods (T>1s) only with significant underpredictions at all other periods. These results are primarily due to the additional uncertainty inherent in the horizontal component of the model contributing to the overall inaccuracy of the prediction. Essentially, a direct prediction of SA_v will derive its uncertainty solely from vertical ground motion uncertainty while a V/H ratio prediction will have sources of uncertainty generated from both the vertical and horizontal components of the V/H ratio. Additionally, the need to multiply the V/H ratio by corresponding horizontal spectra will further increase the uncertainty in the final SA_v prediction.

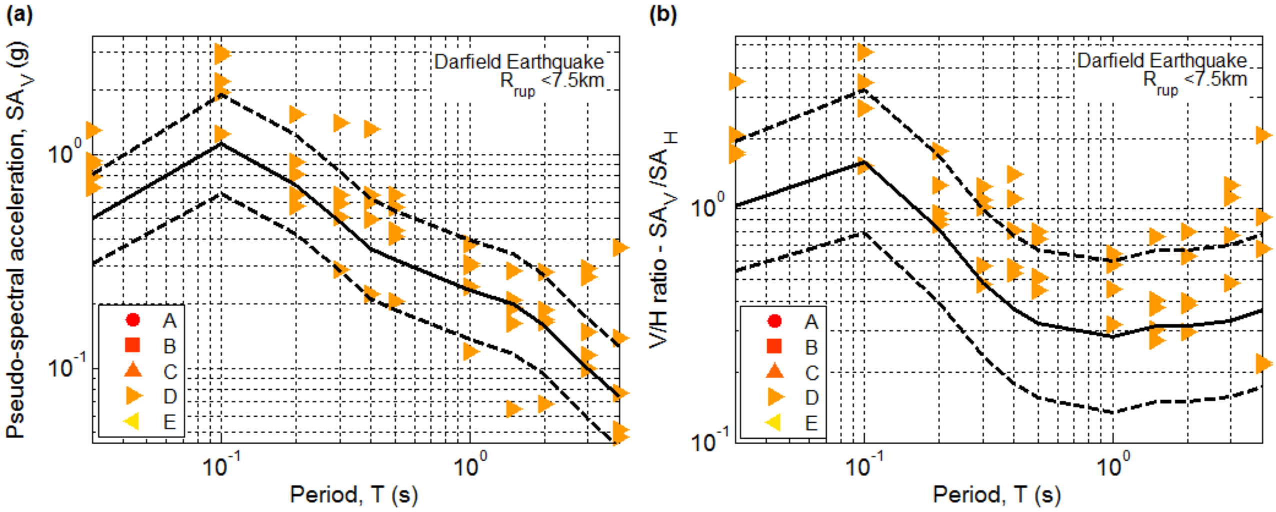

Figure 7. Comparison of Bozorgnia and Campbell (2004) predicted acceleration spectra (using R_{rup}=3.75km) against observations from the M_w7.1 Darfield earthquake: (a) SA_v; and (b) V/H ratio. Predictions are for soft/firm soil conditions.

Figure 8 shows the inter-event residuals (similar to average model bias) associated with the A05 and BC04 SA_v models when compared to the observations from both the Darfield and Christchurch earthquakes. Figure 8a, which illustrates the A05 model, makes an obvious statement that the Christchurch earthquake was more underpredicted than the Darfield earthquake as the corresponding inter-event residuals are much larger than those of the Darfield earthquake for each respective period. Many of the other models also suffer from this shortfall. There are multiple factors which may have contributed to this result, but primarily is the result of the Christchurch earthquake having a greater number of near-source recordings than the Darfield earthquake, making it appear to be more underpredicted (due to poor model performance for near source distances). On the contrary, Figure 8b shows the inter-event residuals for the BC04 SA_v model which is the only SA_v GMPE which did not exhibit the aforementioned trend, and it can be subsequently seen that the inter-event residuals are essentially the same for both earthquake events.

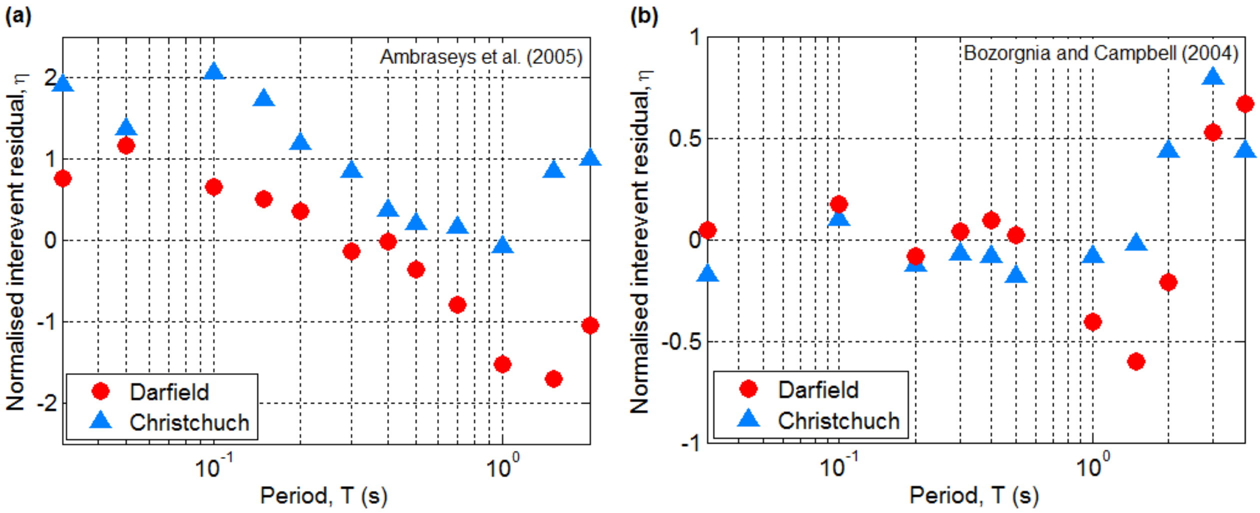

Figure 8. Inter-event residuals of SA_v for the Darfield and Christchurch earthquakes for: (a) Ambraseys et al. (2005); and (b) Bozorgnia and Campbell (2004).

4 CONCLUSIONS

The large amount of strong vertical ground motions recorded throughout the Canterbury earthquake sequence provided a unique opportunity to investigate current methods of predicting vertical ground motion. Such observations provide clear evidence that the NZS1170.5:2004 code prescription is insufficient with multiple instances of observed vertical ground motion exceeding the prescribed V/H ratio of 0.7. Numerous ground motion prediction equations (GMPEs) for vertical response spectra were examined and compared with observations from the two major earthquakes from the Canterbury earthquake sequence. These comparisons illustrated two important trends: Firstly, despite a favourable comparison at source-to-site distances greater than 10km, the short period and near-source vertical spectral amplitudes were generally underpredicted by the existing models; Secondly, models which predict SA_v directly, as opposed to the prediction of V/H ratio which then must be multiplied by the predicted horizontal spectra, tend to be more accurate and precise.

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