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Probabilistic Response Spectra for Christchurch CBD Ground Motions Incorporating Amplification Factors Derived from the 2010-2011 Canterbury Earthquake Sequence

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ABSTRACT

A probabilistic seismic hazard analysis was performed for the Christchurch Central Business District (CBD). A component of the time varying model of Gerstenberger et al. (2014) that reflects the increased likelihood of aftershocks in the Christchurch region was considered in the analysis; the long term component of that model representing spatial and temporal clustering of large earthquakes over future years and decades was not included. The seismic hazard analysis used the ground motion prediction model of Bradley (2013a) with adjustments for local site conditions in the CBD (Bradley, 2013b). We made additional adjustments to the 5% damped response spectra to include the long period plateau that was recorded in the CBD during the 2010 Darfield and 2011 Lyttelton earthquakes but not fully represented in the Bradley (2013b) site-specific amplification factors. The significant difference between the resulting spectra and the NZ 1170.5 code spectra, which are based on the full time-varying model, suggests that the long term component of that model makes a large contribution to the seismic hazard in the Christchurch CBD.

Introduction

This paper describes the use of probabilistic seismic hazard analysis to develop estimates of strong ground motions in the Christchurch Central Business District (CBD) for representative site conditions. Several special circumstances were taken into consideration. First, ground motions at design ground motion levels were recorded in the Christchurch CBD close to the Hospital site in the 2010 Darfield and 2011 Lyttelton earthquakes. We made use of ground motion prediction models (Bradley, 2013a,b) that have taken account of the special ground motion effects that were recorded in these events, including long period peaks in their response spectra, as they are highly relevant to the ground motion conditions expected at the site. Since the Bradley (2013a,b) ground motion models are for the geometric mean component, additional modifications were made according to Bradley (2013c) to represent the stronger component. The resulting probabilistic response spectra were further modified to incorporate a long period plateau in the response spectra recorded in the CBD in the 2010 Darfield and 2011 Lyttelton earthquakes. Second, a component of the time varying hazard model of Gerstenberger et al. (2014) that reflects the increased likelihood of aftershocks in the Christchurch region was taken into account in the seismic hazard analysis.

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Earthquake Source Model and Time-Dependent Aftershock Model

We used the GNS (Stirling et al, 2012; Litchfield et al., 2014) earthquake source models for New Zealand. These models include the Greendale fault on which the 2011 Darfield earthquake occurred. McVerry et al. (2012) and Gerstenberger et al. (2014) describe a time-varying seismic forecast model for the Canterbury earthquake sequence. The component of that model that reflects the increased likelihood of aftershocks in the Christchurch region was taken into account in our seismic hazard analysis. The long term component of that model, which relates to the spatial and temporal clustering of large earthquakes over future years and decades, was not included because it is not currently standard practice to include this feature in probabilistic seismic hazard analyses, and because it was not available at the time of preparation of this paper. The aftershock model yielded an increase in seismicity of a factor of 1.9 averaged over the 50 years beginning in 2012. Two years later, in 2014, the model yielded an increase of a factor of 1.5, about 25% lower, for the 50 years beginning in 2014. The 2014 spectra, which we show in this paper, are about 9% lower than the 2012 spectra.

Ground Motion Prediction Models

In selecting the set of ground motion prediction equations (GMPE's) for use in the seismic hazard analysis, we considered the degree to which the available ground motion prediction equations provide an adequate representation of the ground motion effects that were observed in Christchurch during the Canterbury earthquake sequence. We also considered the systematic local site amplifications that were observed from the Canterbury earthquake sequence in the Christchurch CBD.

Bradley (2010; 2013a) analyzed the Next Generation Attenuation (NGA) GMPE's (summarized by Abrahamson et al., 2008) and found that the Chiou and Youngs (2008) NGA GMPE provided the best fit to the New Zealand strong motion data set (prior to the inclusion of the Canterbury Plain events). Based on the New Zealand strong motion data set, he used the functional form of the Chiou et al., (2010) model to develop a ground motion model for application in New Zealand, modifying some of the coefficients and adopting the remaining ones from that model.

Bradley (2013a) demonstrated that his model provides a better fit to the Canterbury Plain data than the McVerry et al. (2006) model. The Bradley model has the advantages of (a) being based on a large global data set, (b) of having been calibrated to optimally fit New Zealand data (pre Canterbury), and (c) of being compatible with the Canterbury data. The scaling requirements of NZS 1170.5, Section C5.5.2 state that the design spectrum should represent the stronger of the two orthogonal horizontal components. Since the Bradley (2010,2013a) ground motion model is for the geometric mean component, additional modifications were made using Bradley (2013c) to represent the larger horizontal component.

Bradley (2013b) studied the systematic region-specific local site effects in the Canterbury earthquakes and derived a non-ergodic empirical modification that can be applied to the median and its standard deviation values of the Bradley (2010) ground motion prediction model. The Bradley (2013b) empirical modification model was derived from 10 selected events and for specific Christchurch areas including the CBD area. The modification leads to improved spectral acceleration predictions taking into account the long period amplification effects that were observed in the four CBD recording stations as well as at other recording stations in the period range of 1s<T<2s. This model is only applicable to the Bradley (2013a) ground motion prediction model, and is not applicable to other ground motion prediction models.

Based on these considerations we selected the Bradley (2010,2013a) ground motion prediction model with the incorporation of the Bradley (2013b) region-specific non-ergodic empirical modification factors for the CBD area and the Bradley (2013c) modification factors to give the larger horizontal component as the only ground motion model used in the PSHA calculations. We consider that the advantages of using the basic model of Bradley (2013a) together with the region-specific non-ergodic modification outweigh those of using multiple ground motion prediction models such as the NGA West models (Abrahamson et al., 2008) to represent epistemic uncertainty in the ground motion predictions.

Downhole measurements of shear wave velocity at strong motion recording sites in Christchurch are described by Wood et al. (2011). We adopted the Vs30 value of 220 m/sec as representative value for the Christchurch Central Business District. We assumed that Z2.5, the depth to a shear wave velocity of 2.5 km/sec, could be estimated from the depth to the volcanic basement, which is about 400 m (Lawton et al., 2012) based on a seismic reflection survey. We estimated Z1.0, the depth to a shear wave velocity of 1.0 km/sec, to be 100m.

Probabilistic Seismic Hazard Results

The results of the probabilistic seismic hazard are summarized in Figure 1. Figure 1 shows the 5% damped response spectra for return periods of 500, 1,000, 2,500, 5,000 and 7,500 years. The deaggregation of the hazard by earthquake source is shown for ground motion periods of 0.75 and 3.0 seconds in Figure 2. For 0.75 seconds, the largest contributor to the hazard at all five of the above return periods is the background source in which the site lies. However, the Porters Pass fault, located about 40 km northwest of Christchurch, makes an almost equally large contribution, especially at the shorter return periods. For 3.0 seconds, the background source and the Porters Pass fault make similar contributions at return periods up to 5000 yrs. For longer return periods the background source dominates the hazard at this site. The contribution of the Porters Pass fault is evident on the deaggregations by earthquake magnitude and distance shown in Figure 3 for return periods of 1,000 years and 2,500 years. However, larger earthquakes on the more distant Alpine fault, located about 160 km northwest of Christchurch, make the largest contribution to the hazard at 3.0 seconds period.

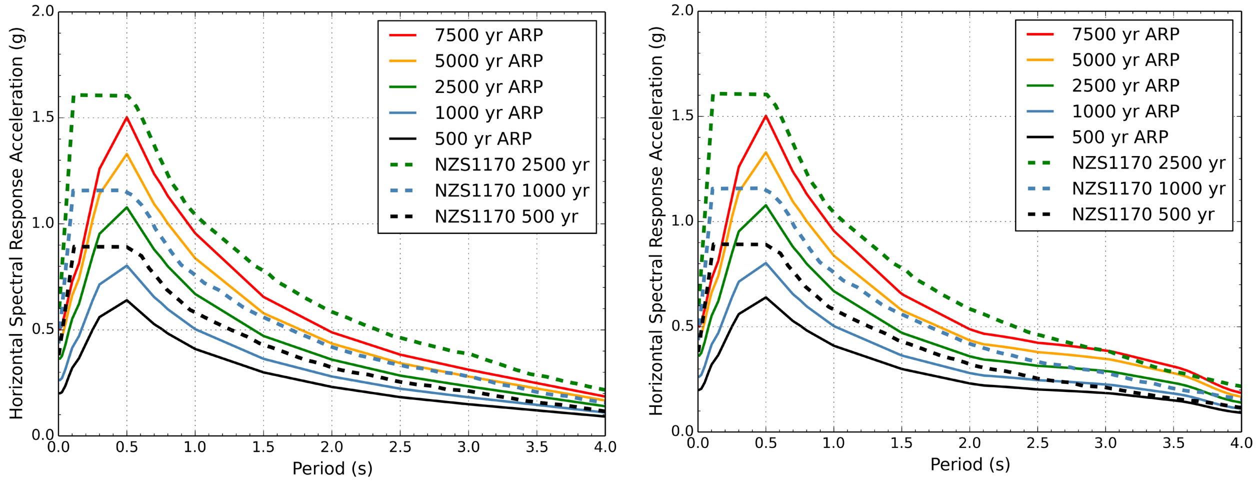

Figure 1. Response Spectra for the 50 years beginning in 2014: left: prior to the long period adjustment; right: after the long period adjustment. The dashed lines correspond to the NZS1170 spectra for return periods of 500, 1,000, and 2,500 years.

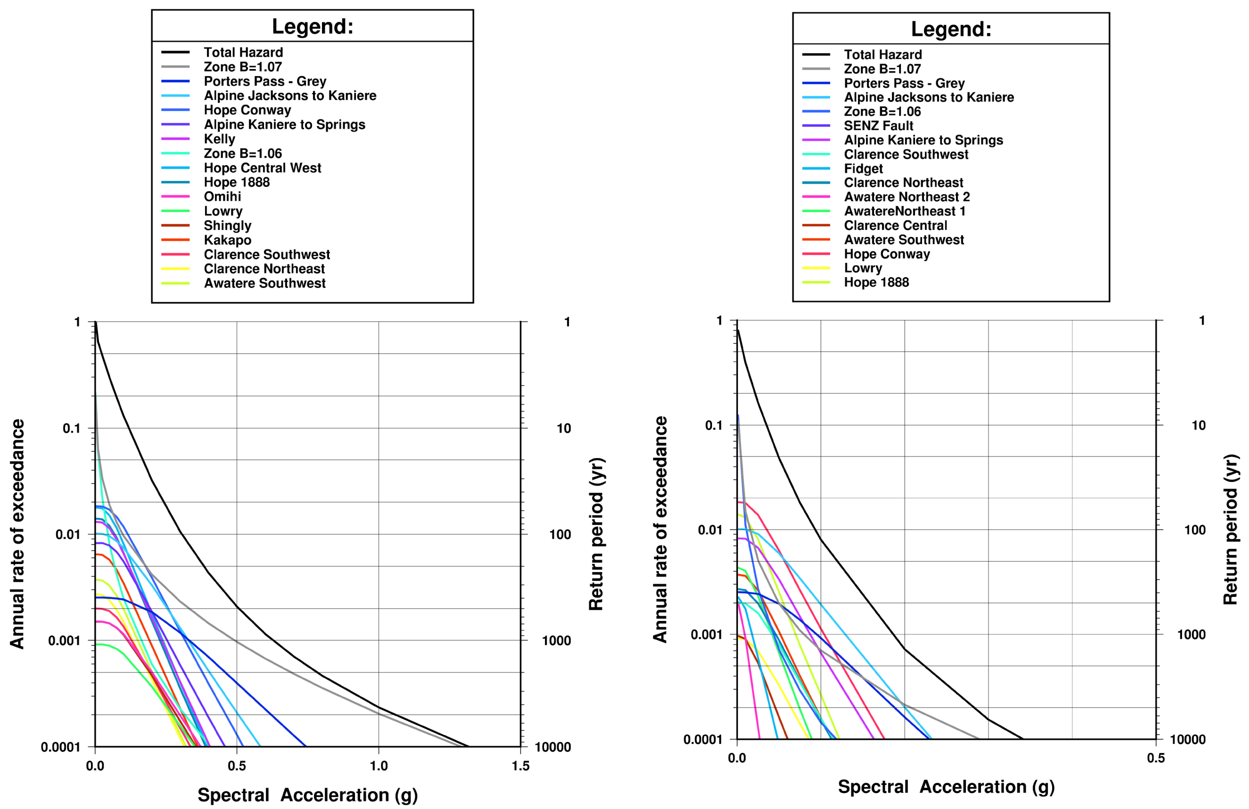

Figure 2. Mean seismic hazard curve for 0.75s response spectral acceleration (left) and 3 second spectral acceleration (right) showing deaggregation of the hazard by source zones. The top curve (black line) shows the total hazard, the second curve (green line) shows the contribution from the areal source with b=1.07 and the contributions of other zones are shown with the different colors.

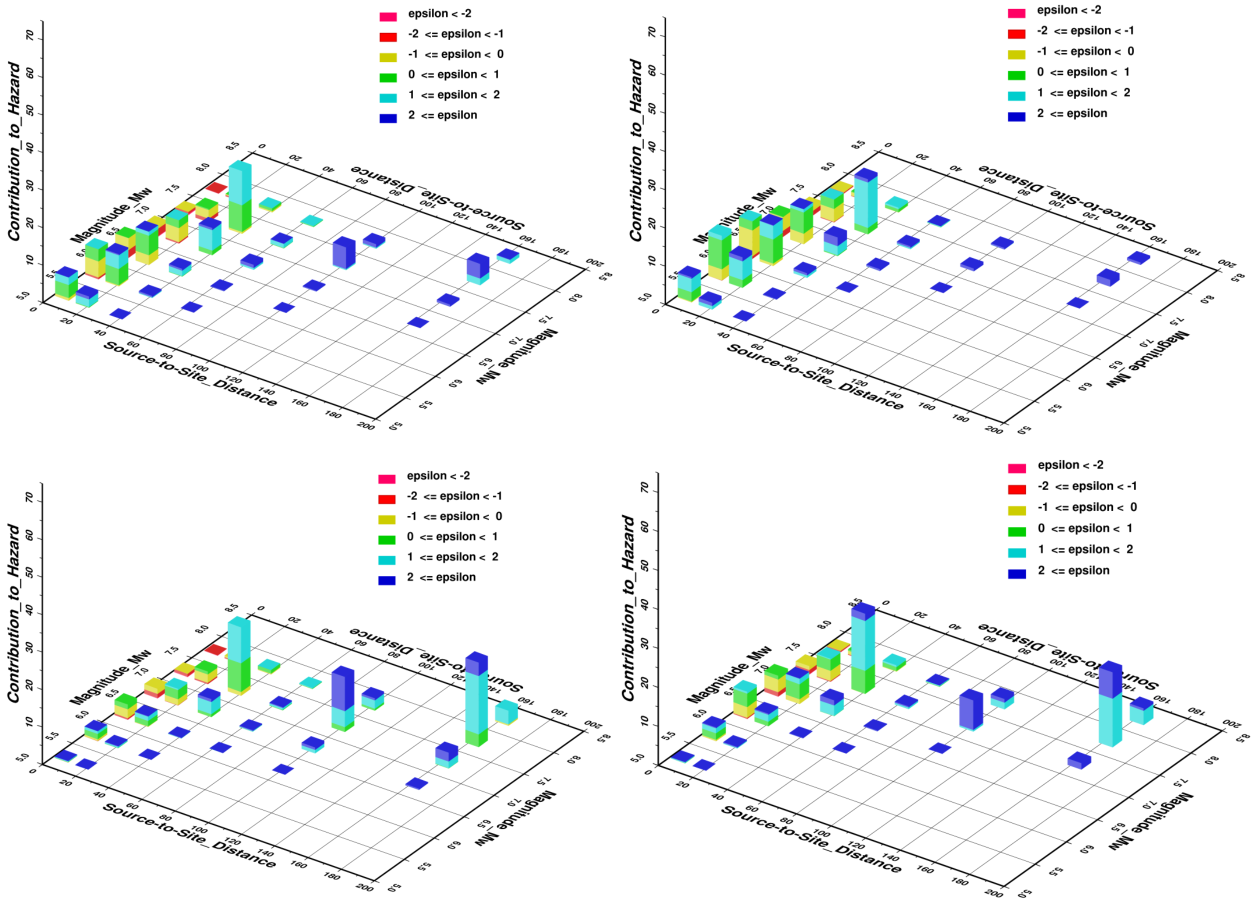

Figure 3. Deaggregation of hazard for 0.75s (top) and 3.0s (bottom) response spectral acceleration for 1,000 year (left) and 2,500 year (right) average return period (ARP).

Christchurch CBD Ground Motion Amplification Effects

The evaluation of the probabilistic ground motions is done in the unusual situation in which ground motions at design ground motion levels were recorded nearby in two earthquakes. As described above, we used a site-specific modification (Bradley, 2013b) of the Bradley (2010) ground motion model to represent the recorded ground motion amplification effects in the CBD, and these effects are incorporated in the probabilistic response spectra shown in Figure 1. Nevertheless, these spectra do not have the plateau in the period range of about 2 to 4 seconds, as seen in the average spectra recorded in the Christchurch CBD during the 2010 Darfield and 2011 Lyttelton earthquakes (Figure 4). Based on judgment, the response spectra were increased in the period range of 2 to 4 seconds to introduce this plateau in order to accommodate these large long period ground motions, as shown on the right side of Figure 1. The largest increase is 25%. These modified spectra are therefore no longer uniform hazard response spectra, but are conservative representations of the uniform hazard response spectra in the period range of 2 to 4 seconds.

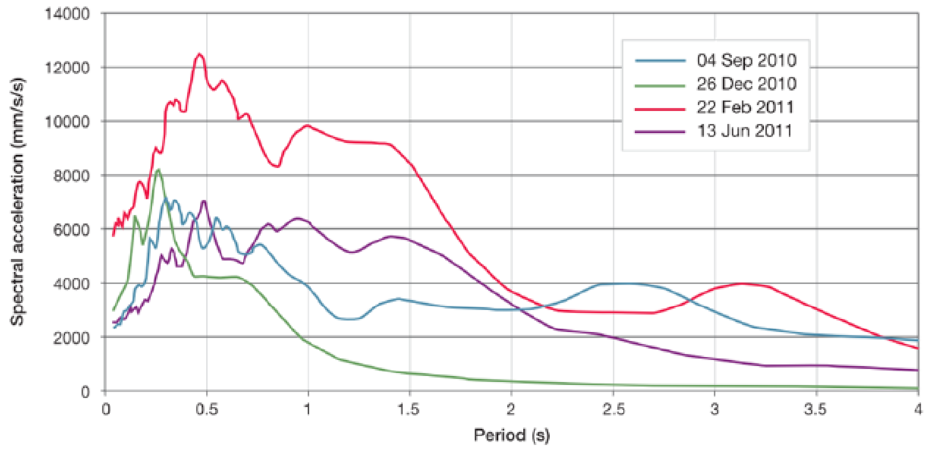

Figure 4. Response spectra from four NZ earthquakes averaged over four CBD recording sites: blue: Darfield earthquake; red: Lyttelton earthquake (from Figure 9, Royal Commission Report).

Rupture Directivity Effects and Comparison with Code Spectra

The response spectra of the strong ground motions recorded in the Christchurch CBD, shown in Figure 4, have a long period plateau that has been attributed to a combination of basin and near fault rupture directivity effects (Bradley, 2012). We therefore consider that the site-specific response spectra, with the adjustment described above, include near fault rupture directivity effects. The faults on which the Lyttelton and Darfield earthquakes occurred are thought to have long recurrence intervals, so in the probabilistic seismic hazard calculation they do not make a significant contribution to the hazard in Christchurch.

The NSZEE 1170.5 code spectra for return periods of 500, 1,000 and 2,500 years are shown in Figure 1, which also shows the corresponding site-specific response spectra. The code spectra are significantly larger than the site-specific spectra at all periods. The 1,000 year code spectrum has a peak acceleration of 0.775 g, much larger than the site-specific value of 0.263 g and the average value of about 0.25 g recorded at the four CBD sites during the Darfield earthquake (Figure 4, blue line). The 2,500 year code spectrum has a peak acceleration of 0.776 g, much larger than the site-specific value of 0.364 g and the average value of about 0.6 g recorded at the four CBD sites during the Lyttelton earthquake (Figure 4, red line).

One contributor to the difference between the site-specific response spectra and the code spectra is that the latter were based on the time-varying hazard model described by McVerry et al. (2012) and Gerstenberger et al. (2014). The site-specific spectra do not include the long term component of the time-varying hazard model whereas the code spectra are based on the full time-varying hazard model. Incorporation of the long term component in the site-specific results is expected to bring them into closer agreement with the code spectra.

Conclusions

This paper describes the use of probabilistic seismic hazard analysis to develop estimates of strong ground motions in the Christchurch Central Business District (CBD) for representative site conditions. Several special circumstances were taken into consideration. First, ground motions at design ground motion levels were recorded in the Christchurch CBD close to the Hospital site in the 2010 Darfield and 2011 Lyttelton earthquakes. We made use of ground motion prediction models (Bradley, 2013a) that have taken account of the special ground motion effects that were recorded in these events, including long period peaks in their response spectra, as they are highly relevant to the ground motion conditions expected at the site. The resulting probabilistic response spectra were further modified to incorporate a long period plateau in the response spectra recorded in the CBD in the 2010 Darfield and 2011 Lyttelton earthquakes. Second, a component of the time varying hazard model of Gerstenberger et al. (2014) that reflects the increased likelihood of aftershocks in the Christchurch region was taken into account in the seismic hazard analysis. The long term component of that model, which represents spatial and temporal clustering of large earthquakes over future years and decades, was not included because it is not currently standard practice to include this feature in probabilistic seismic hazard analyses, and because it was not available at the time of preparation of this paper. The significant difference between the site-specific spectra and the NZ 1170.5 code spectra, which are based on the full time-varying model, suggests that the long term component of the time-varying hazard model makes a large contribution to the seismic hazard in the Christchurch CBD.

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