4.0 IMPLICATIONS FOR CHRISTCHURCH

4.1 Likely changes to future rates of seismic activity in Canterbury and implications for seismic design

The level of seismic hazard in Canterbury is currently higher than the long-term average, and is likely to stay this way for several decades. This is because shallow crustal earthquakes are always followed by numerous aftershocks, although these do decrease in frequency with time. In addition, there is a possibility that an earthquake of a size comparable to the main shock might be triggered, even if the probability of this remains low. This elevated level of hazard must be considered when reassessing the safety of existing structures and when designing new buildings and infrastructure.

In order to provide seismic design coefficients for the New Zealand Loadings Standard (NZS 1170), we have developed a new seismic hazard model for Canterbury that reflects this increased level of hazard. The model takes account of likely rates of aftershocks, the small likelihood that larger earthquakes may be triggered (clustering of earthquake activity) and, as in earlier New Zealand models, the normal background seismicity and the expectation that large earthquakes will rupture known surface faults in the wider Canterbury region. Since the level of hazard will change with time, the model calculation is for the 50 years from March 2011, as 50 years is the default lifetime for a building. The details of the model and the recommendations for new seismic design coefficients for Canterbury have been provided to the Department of Building and Housing as a GNS Science Report (Gerstenberger *et al.*, 2011).

Aftershocks occur after a large earthquake as small areas of the fault surface that ruptured continue to shift and readjust—the initial rupture never fully relieves the stresses that had accumulated over hundreds or thousands of years. Movement along a fault also piles up additional stresses at the ends of the fault where there has been no slip, causing the aftershock zone to expand to form an elongated cloud as stresses are further redistributed throughout the Earth's crust. These more dispersed aftershocks often do not occur on the main fault, but on smaller pre-existing faults or zones of weakness in the earth's crust. At first, the rate of aftershocks drops off very rapidly after a main shock, but then a long 'tail' of aftershocks continues (Fig. 4.1). In the absence of very large aftershocks (which in turn have their own aftershocks), the decay rate is quite predictable and follows the Omori law (Omori, 1894). The Short Term Earthquake Probability (STEP) model (Gerstenberger *et al.*, 2005) is a model for forecasting the behaviour of aftershock sequences over a short term—periods from days to a few years following an earthquake. The STEP model provides estimates of both future rates for earthquakes of various sizes and their spatial distribution, which is closely related to where aftershocks have occurred already.

In addition to aftershock activity, there is a small chance that large earthquakes may trigger (or bring forward in time) other large earthquakes on faults within distances of tens of kilometres and over timeframes of months to decades. This effect results in a tendency for large earthquakes to occur in clusters (seen in New Zealand's historical large earthquakes; Figure 2.5) and can be represented by the Every Earthquake a Precursor According to Scale (EEPAS) model (Rhoades and Evison, 2004). In this model every new earthquake slightly increases the probabilities of future higher magnitude earthquakes. The model forecasts that these future events will occur within an area centred on the locus of previous activity, but over a broader region than that estimated by STEP.

To calculate the most robust forecast of earthquakes, we have combined the STEP and EEPAS models with both fault-based source models aimed at long-term (decades to centuries) mostly time-independent forecasts and smoothed seismicity source models for decadal scale forecasts (Proximity to Past Earthquakes; PPE). The latter two models are largely equivalent to what has traditionally been used to construct the National Seismic Hazard Model (Stirling *et al.*, 2002) that underpins the New Zealand design standard NZS 1170. As we are introducing time variability into this new model, for consistency we have updated the most active faults that will potentially affect the Christchurch region with conditional earthquake probabilities (i.e. taking account of how frequently and when the last earthquake occurred on a particular fault).

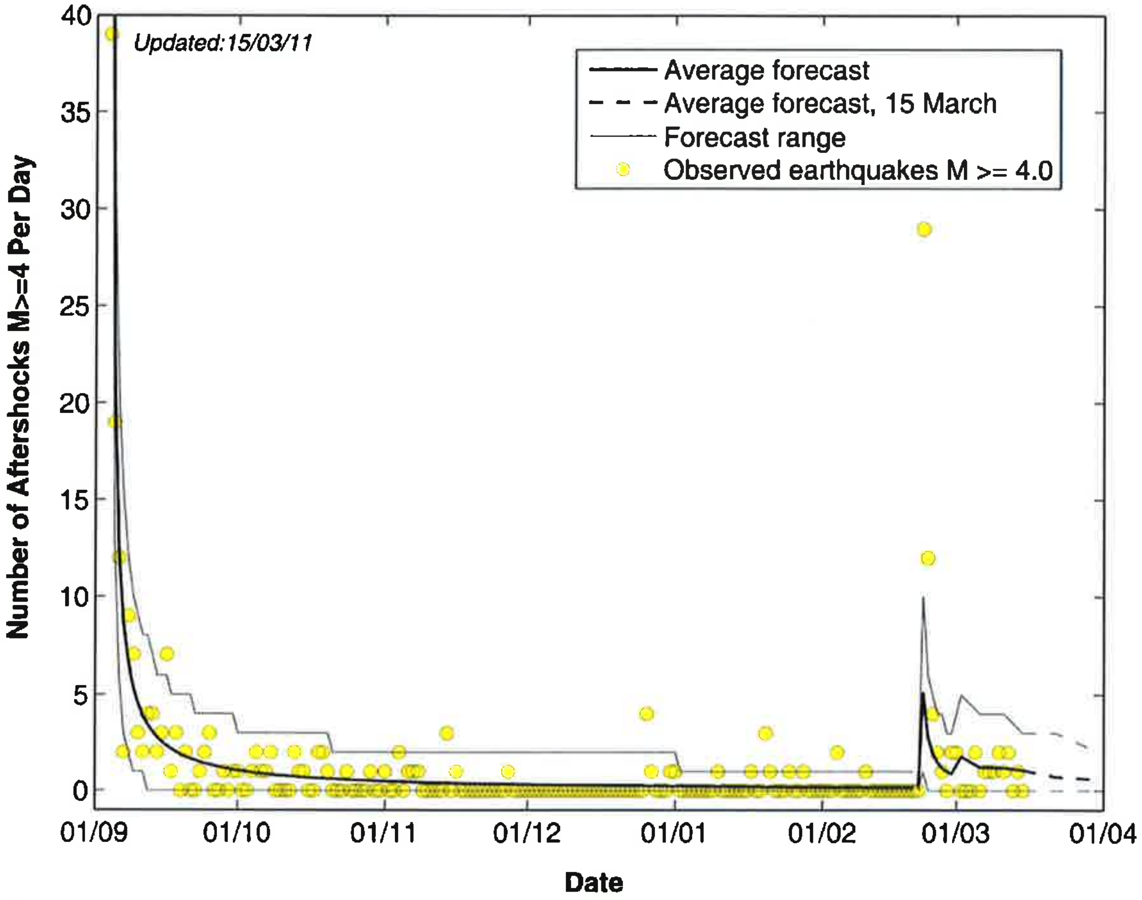

Figure 4.1 Decay of Canterbury aftershocks with time (dd/mm) since September 2010.

We have combined the four source models into a single model for the hazard calculations by taking the average of the models after the first year. In the first year only the STEP model is used, because this model primarily targets the immediate aftershock sequence information, whereas the other models are more focussed on longer term clustering.

Figure 4.2 shows the yearly forecasts for the three seismicity-based models for years 2011–2041. In this figure the sharp decay of the aftershock sequence from the STEP model is apparent, as is the slower response over time of the EEPAS model and the static forecast of the PPE model. The STEP model is initially dominant in all magnitude ranges, with a longer dominance at M7.0–7.9. The EEPAS model then dominates the forecasts until roughly 2025, when the PPE model begins to produce the highest forecast rates.

Ground motion is calculated by taking the output from the source models and using a ground motion attenuation relationship to produce accelerations for each period of ground motion (termed spectral accelerations). In this work we have used the McVerry *et al.* (2006) relationship, as is used in the NSHM.

As mentioned in Section 3.4, the 22 February earthquake radiated more seismic energy (and hence caused stronger ground shaking) than is expected from an average New Zealand M_w6.2 earthquake. This enhanced ground shaking is likely for other Canterbury earthquakes, so it has been incorporated into our calculations of likely future ground shaking using the relationship of Atkinson and Boore (2006). This relationship produces a multiplying factor for the predicted accelerations based on the earthquake magnitude and the ratio of a regional stress drop to an expected average stress drop. In its simplest form, stress drop is directly related to the amount of slip that occurred on a fault compared to the fault length. Based on preliminary work on the Canterbury earthquakes, we have used 150 bars (15 MPa) for the regional (Canterbury) stress drops and 100 bars (10 MPa) for the average stress drop, giving a stress drop ratio of 1.5.

Another factor enhancing shaking from the 22 February earthquake was directivity (Section 3.4). Sites that may have enhanced motions from directivity effects in one earthquake could have reduced motions from another earthquake, where the rupture propagates away from the surface site. Empirical models are available for incorporating the effects of rupture directivity in models, but they require information about the geometry of the fault. The main earthquakes contributing to the estimated PGA hazard for Christchurch do not occur on known faults, so rupture directivity cannot be precisely modelled. In this case, the directivity effects should average out over different earthquakes, but will contribute to the overall variability in expected ground shaking.

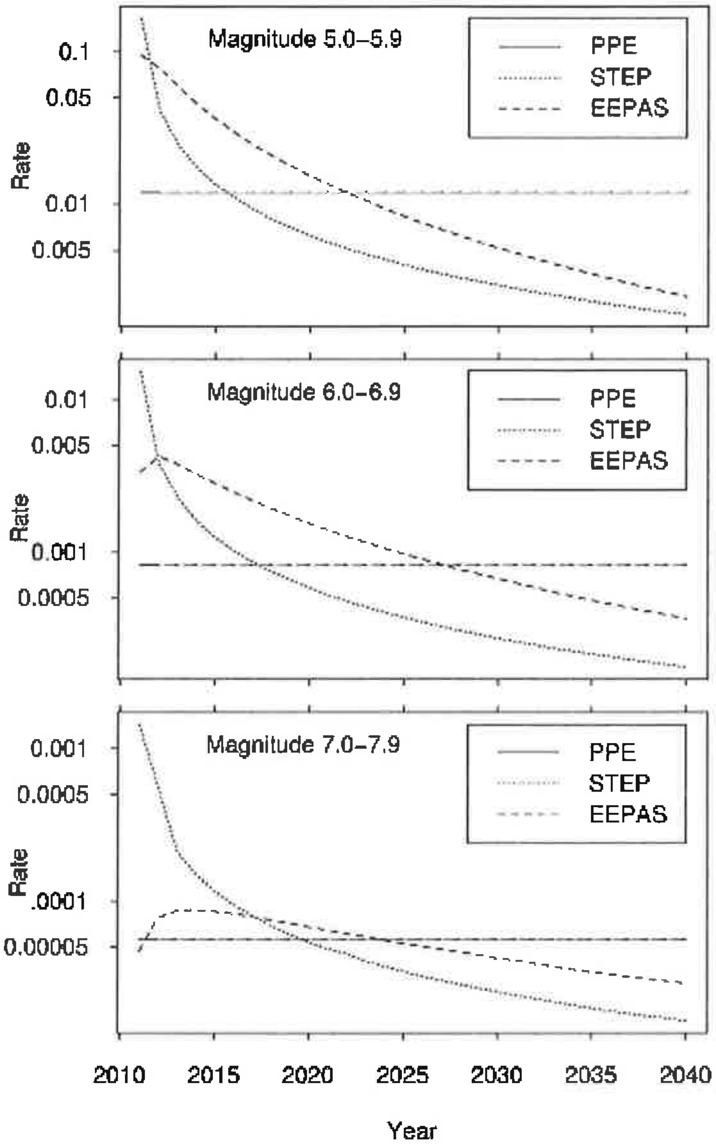

Figure 4.2 Forecast annual earthquake rates for a representative Christchurch location from the three seismicity-based models for M5.0–5.9 (top), M6.0–M6.9 (middle) and M7.0–M7.9 (bottom). The dominance of the higher rates of the STEP model initially can be seen before the EEPAS model takes over at slightly longer time scales. After roughly 20 years, the Proximity to Past earthquakes (PPE) smoothed seismicity model produces the highest rate.

When applying the National Seismic Hazard Model (NSHM) for engineering applications, the forecast ground motions are usually weighted according to the size of the earthquake. Amplitudes of smaller magnitude earthquakes are relatively down-weighted to account for their shorter duration of shaking, which causes less damage to structures than longer duration shaking. A fuller discussion of this and how it has been applied can be found in Appendix 5.

In a typical hazard analysis, the most frequent strong ground shaking is produced by large earthquakes greater than approximately magnitude 7. The earthquakes that produce the majority of the hazard can be separated out for Christchurch city, showing dominant contributions from distant fault sources such as the Alpine Fault and the Porters Pass-Grey Fault (Fig. 4.3a). The time-dependent hazard analysis described here differs from traditional long-term seismic hazard analysis in that the earthquakes that are contributing to the hazard calculations are small (Fig. 4.3b). This is due to the active and on-going aftershock sequence following the Darfield event.

Structures designed in accordance with modern New Zealand standards should not be susceptible to structurally significant damage from small earthquakes. For this reason, when we develop a seismic hazard model we consider only earthquakes larger than a certain minimum magnitude. Typically a minimum magnitude of 5.0 is used in the NZS1170 hazard studies. This is also the usual lower-bound magnitude in probabilistic seismic hazard analysis in the U.S. for similar reasons (e.g. Reiter, 1990). However, in this study the minimum magnitude has been raised from 5.0 to 5.5. This modification was based on engineering advice that structures satisfying modern code requirements performed well in all but the larger events in Christchurch (J. Hare and R. Jury, pers. comm., 2011). This change also served to partly offset the very high rate of small-to-moderate magnitude earthquakes, as it was felt that the combination of the dominance of M5 events with their relatively short duration was over-estimating the hazard in terms of its effect on structural performance.

The seismic design coefficients and spectra that engineers need to meet the requirements of NZS1170 depend on four components:

- The spectral shape factor, which depends on the type of soil or rock present at the site.
- The hazard factor *Z*, which reflects the estimated level of seismic hazard in the region.
- The return period factor *R*, which scales the design levels so that structures that are more important (critical facilities such as hospitals) are built more strongly. This factor is also used to determine the level of design required for a structure to remain serviceable at lower, but more frequent levels of ground shaking.
- The near-fault factor for locations that are closer than 20 km to one of 11 named major active faults in New Zealand. This factor does not affect Christchurch.

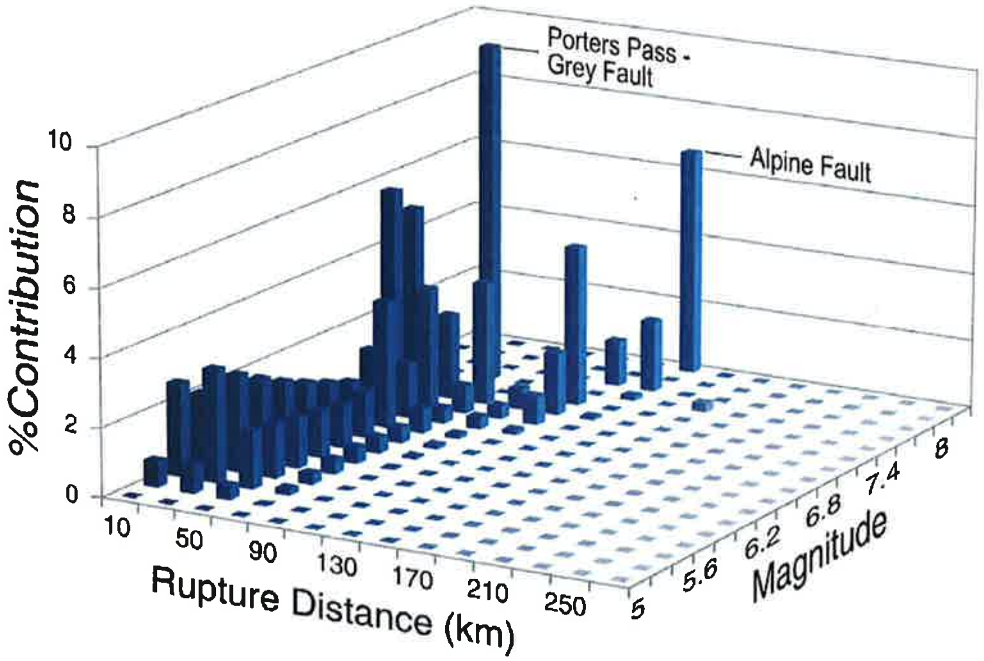

Figure 4.3a Separation of contributions of different fault sources for a representative Christchurch location for spectral accelerations of 0.5 s for 0.6 g for the original New Zealand Seismic Hazard Model. The dominant contribution is from distant fault sources such as the Alpine Fault and the Porters Pass-Grey Fault.

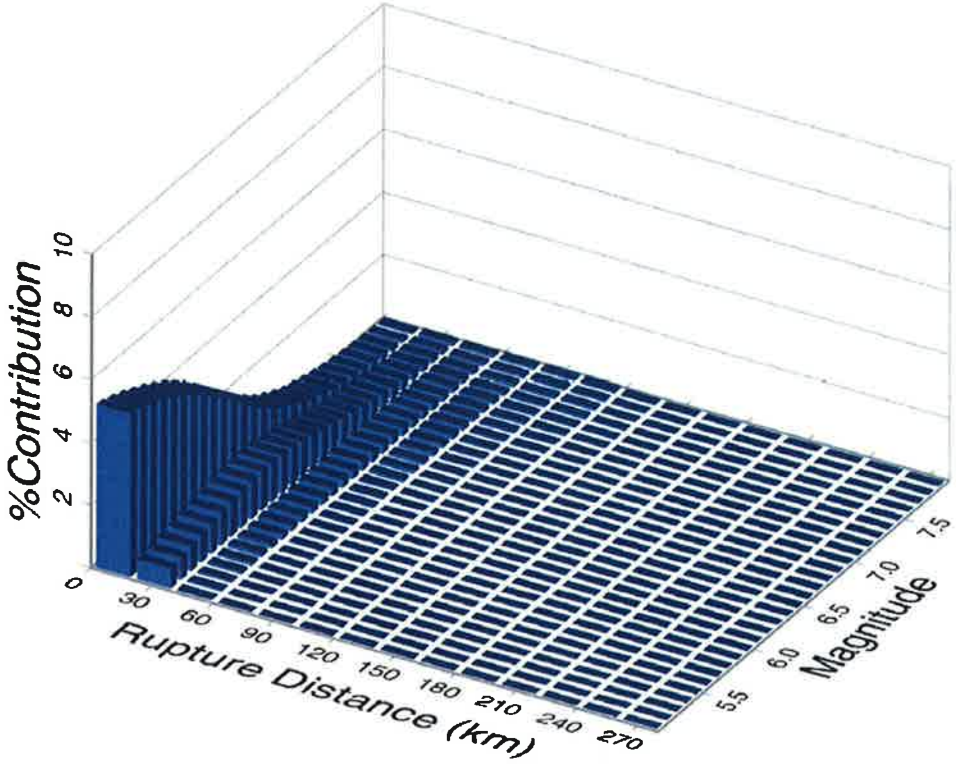

Figure 4.3b Separation of contributions of different fault sources for a representative Christchurch location for spectral accelerations of 0.5 s for 0.6 g in the new model. Note the dominant contribution of events of less than magnitude 6. For the results as presented, magnitudes less than 5.5 were not included.

The new model described here uses new values for the Z factor and the R factors for Canterbury. Figure 4.4 shows the hazard spectrum for NZS1170 Class D Deep or Soft Soil conditions that is estimated to have a 10% probability of being exceeded in the 50 years from March 2011 in Christchurch using the new earthquake source model. In the figure, this spectrum is compared to the NZS1170 Z=0.3 spectrum for this soil class. It can be seen that beyond its short-period plateau (i.e., periods less than 0.5 s), the Z=0.3 spectrum envelopes the '10% in 50 years' spectrum. In general, the NZS1170 spectrum for a site should envelope its '10% in 50 year' hazard spectrum, apart from truncating the peak of the spectrum by up to about 30%. The Z=0.3 spectrum in Figure 4.4 is consistent with this requirement. We have also calculated R factors for the new hazard model for Christchurch and for NZS1170 so that design coefficients can be calculated for structures that need to be built more strongly because of their importance. These values are set out in Gerstenberger *et al.*, (2011).

At the time of writing (July 2011), the new time-dependent seismicity model for Canterbury is still 'work in progress', but due to the urgent need for design parameters, interim results are being used as they become available. For example, two inconsistencies have been found in the calculations used in Gerstenberger *et al.* (2011) compared to those usually used for Z-factor calculations. These inconsistencies have the potential to further increase the Z-factor and are the subject of ongoing discussions.

Future planned work includes modelling the stress changes created by the initial and subsequent earthquakes and using rate and state friction laws to attempt to predict where future activity will occur. Currently we use spatial estimates based on STEP and EEPAS model outputs, which predict that future activity is centred on past activity, but with a broader spatial scale. Other planned work will involve a closer look at how well a range of New Zealand-derived and international relationships we use to predict ground motions from an earthquake of a given size are predicting the shaking produced by the larger Canterbury earthquakes. Finally, an expert elicitation process (a structured approach to using an expert panel) will be used to determine relative weights to be given to alternative models used in building the final hazard estimates.

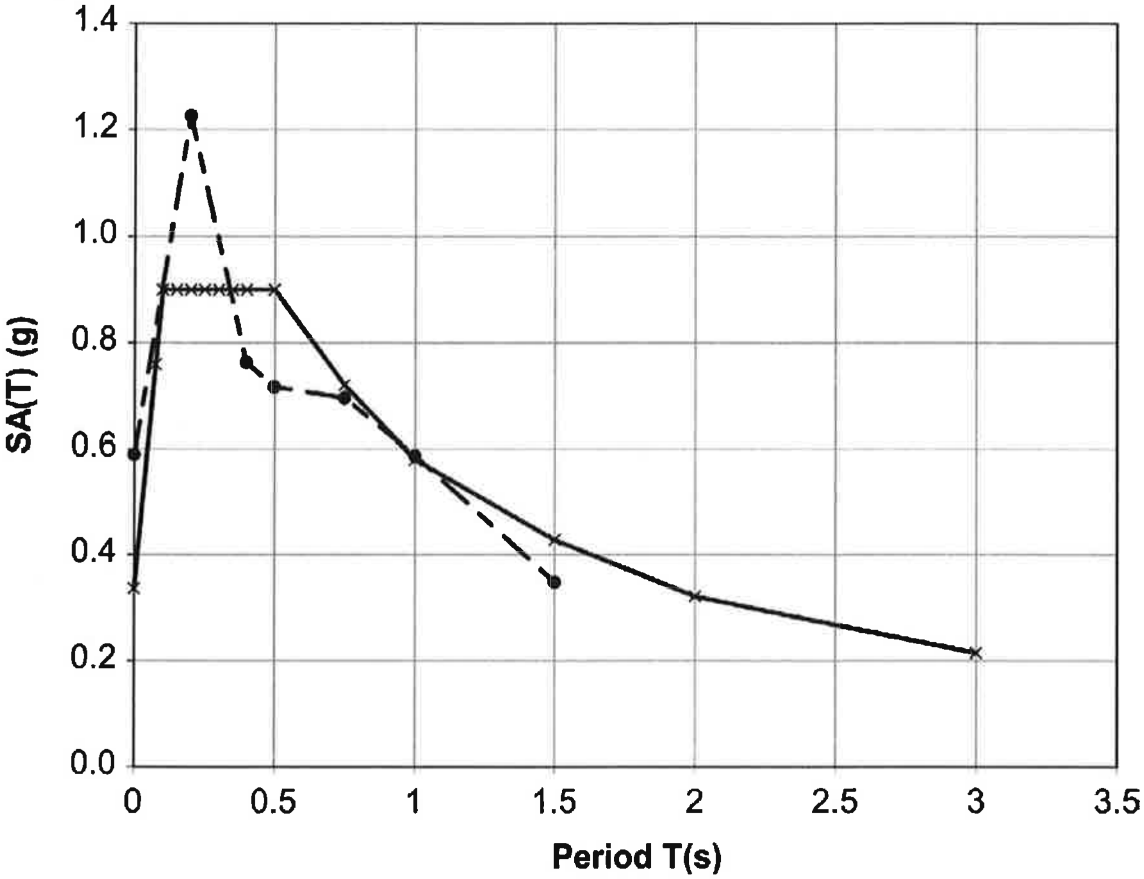

Figure 4.4 Demonstration that the Z=0.3 Class D deep soil spectrum approximately envelopes the hazard spectrum estimated with a 10% probability of being exceeded in the next 50 years, apart from truncation of the peak of the spectrum.

4.2 Potential effect of a future Alpine Fault rupture

The Alpine Fault is a major geological feature in New Zealand—a dextral transform fault separating the Pacific plate on the east from the Australian plate on the west. It is 650 km long and crosses the South Island from northeast to southwest (Fig. 4.5). The Alpine Fault is a potential source of major earthquakes in the South Island. The average return period of the fault is in the range 260–400 years (Berryman *et al.*, 2011), with no major event occurring in the last 294 years and a likelihood of rupture of 30% in the next 50 years. Sutherland *et al.* (2007) suggested that a magnitude M_w>8 earthquake would be a realistic estimate for a future Alpine Fault rupture. The September 2010 and February 2011 Canterbury earthquakes caused widespread damage by ground shaking and sand liquefaction in the Christchurch region. Both earthquakes are a short distance from the Christchurch central business district, but have magnitudes much smaller than that expected from the Alpine Fault. The Alpine Fault is, at its closest, 125 km from Christchurch, thus there is a need to assess the effect of ground shaking in Christchurch from a potential large Alpine Fault event. In some preliminary work described here we have estimated ground motions in Christchurch from a magnitude 8.2 event, with the rupture propagating from south to north. Ground motions were first calculated for a site on bedrock using a specific rupture scenario, and then the effects of very soft ground conditions, as are found in the Christchurch CBD, were added.

The technique for computing ground motion is based on work by Irikura and Miyake (2011), who assume that most of the strong ground shaking is generated by asperities—rough patches with above average slip—rather than uniform rupture of the entire fault. Fault segments with large slip from past events are assumed to be the major asperities (white ellipses on Figure 4.5). The seismograms were calculated using an empirical Green's function approach, in which the ground-motions from segments of the fault are summed according to the formulation of Irikura (1986) and Kamae *et al.* (1998). Local site effects are modelled by using linear methods. In order to consider an extreme shaking scenario, all of the results presented here represent the most conservative (i.e. highest) estimate of ground shaking in Christchurch, within the range of possible fault parameters adopted for this study.

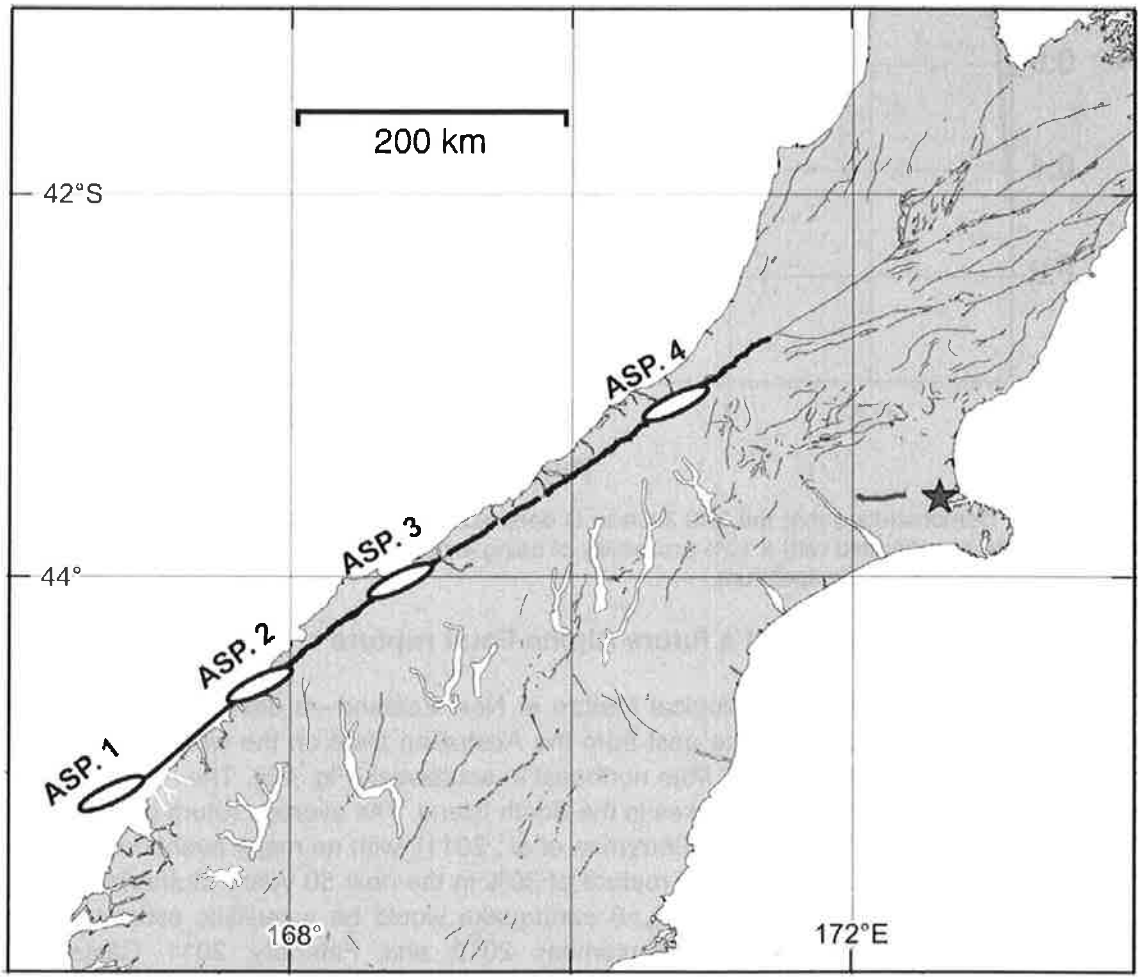

Figure 4.5 Active faults in the South Island. The bold line illustrates a likely Alpine Fault rupture; the grey line west of Christchurch is the fault trace from the Mw 7.1 Darfield earthquake; the white ellipses represent the location and size of the major potential asperities on the Alpine Fault; the grey star is the location where the ground motions are computed.

The ground underlying sites in the Christchurch CBD is at least Class D (deep soils in terms of NZS 1170.5 site class) and those areas with liquefaction would have a site class E if the softest soils are more than 10 m thick. We modelled the effect of various shear-wave velocity profiles for a site in the Christchurch Botanical Gardens (station CBGS in the GeoNet network). A model with a 550 m depth to the bedrock, with a shear-wave velocity of 1200 m/s, produced the largest amplification ratios among all models, for periods up to about

0.7 s. The soil site model amplifies the synthetic rock motions by a factor of 1.7 for the North-South horizontal component and 1.9 for the East-West horizontal component. The PGA amplification ratio is about 1.8 and the largest amplification ratio is 3.8 at 0.54 s. The surface ground motions, the amplification ratios, and the response spectra derived from the synthetic records can be found in Holden and Zhao (2011). The synthetic response spectra are amplified at all spectral periods by the soil column, and the largest response spectrum is about 0.12 g for both horizontal components. Figure 4.6 compares the modelled ground surface motions (in terms of PGA) for the larger of the two horizontal components for a potential Alpine Fault earthquake, with the PGA for the two largest Canterbury events.

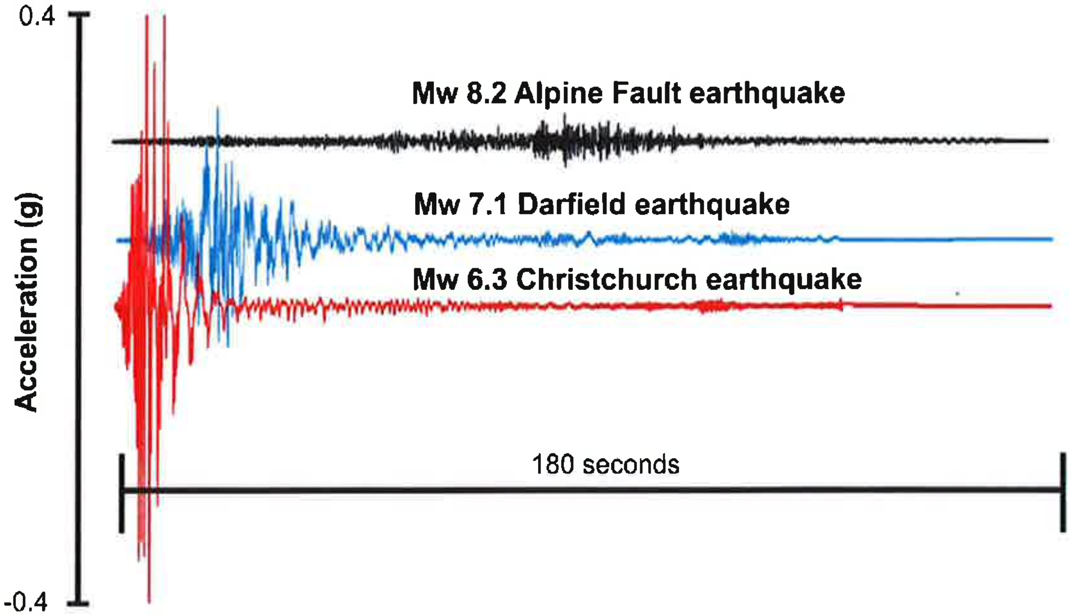

Figure 4.6 Three minutes of synthetic acceleration time histories for the larger of the two horizontal components, in terms of PGA, for a potential Alpine Fault event (black) compared with the accelerations from the M_w 7.1 Darfield earthquake (blue) and the 22 February M_w 6.3 Christchurch earthquake (red) as recorded at the Christchurch Botanical Gardens GeoNet station (CBGS).

The preliminary computed values indicate that the maximum horizontal acceleration would be less than 4% g (0.4 m/s/s), but the computed shaking duration is at least 3 minutes long. These results are in agreement with observations for locations at distances of >150 km from the faults for recent large overseas earthquakes ($M_w > 7$) (Fig. 4.7; Holden and Zhao, 2011), indicating that these preliminary results are reasonable. Further studies will be required to provide detailed analyses, and to assess the sensitivity to some of the specific fault parameters used in this preliminary study.

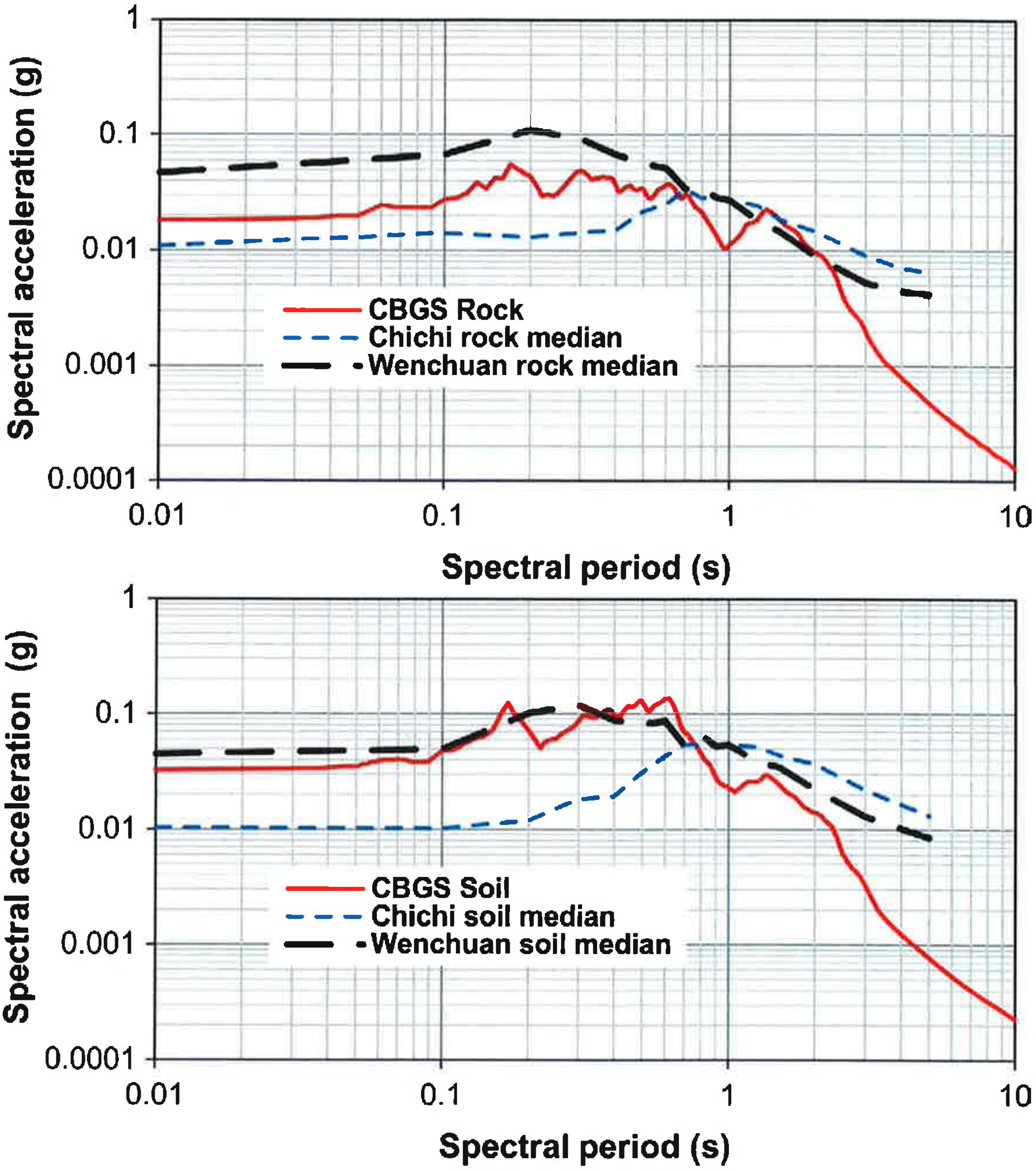

Figure 4.7 Comparison of response spectra for synthetic ground motions at Christchurch Botanical Gardens GeoNet station (CBGS) on rock (top) and on soil (bottom) with the Taiwan M_w 7.6 Chichi earthquake in 1999 and the China M_w 7.9 Wenchuan earthquake in 2008. The spectra represent the average values at a source distance (closest distance to the fault rupture) of 170 km, for two sites with shear wave velocities of (top) 1200 m/s (a rock site) and (bottom) 243 m/s (a soil site).