3.0 THE CANTERBURY EARTHQUAKES

3.1 Introduction

In the early hours of Saturday morning on 4 September 2010, people in Christchurch and the surrounding Canterbury region were jolted awake by a powerful M_W 7.1 earthquake. This was a rare and unexpected event, occurring in an area of New Zealand where previous seismic activity was relatively low. By world standards it was a major earthquake, yet there were no fatalities and just a few injuries. The shaking caused damage in Christchurch to older brick and masonry buildings, and to historical stone buildings and Canterbury homesteads. The earthquake also seriously affected Christchurch's eastern suburbs and Kaiapoi—here layers of the ground liquefied, with silt oozing to the surface. The ground above the liquidised layers spread laterally, cracking the ground, footpaths, roads, and houses. Water and sewer pipes broke and water from broken mains flooded many streets.

The Darfield earthquake occurred on 4 September 2010 at 04:35 NZST (3 September at 16:35 UTC) approximately 40 km west of Christchurch on a previously unknown fault within the Canterbury Plains (see Fig. 3.1). This was a rare event, occurring in an area where previous seismic activity was relatively low for New Zealand. The earthquake caused extensive damage in Christchurch and the surrounding region and left a well-defined surface rupture that has been named the Greendale Fault.

Since the Darfield earthquake, more than 7,000 aftershocks with magnitude (M_w) up to 6.2 (see text box explaining earthquake magnitude) have been recorded by the New Zealand national seismograph network (GeoNet[1]). This sequence of earthquakes is termed the Canterbury earthquake sequence. In the months following the Darfield earthquake, aftershock activity was particularly concentrated at the eastern end of the Greendale Fault. Despite several moderate-magnitude ~5 earthquakes occurring during this time, the number and size of the aftershocks was initially somewhat less than that experienced after other shallow New Zealand earthquakes of similar size.

A notable M_w 4.7 event occurred at 10:30 NZST on 26 December 2010, less than 2 km from the central business district (CBD) of Christchurch. Because it was so close to the city centre, this earthquake (termed the Boxing Day earthquake) caused further damage to buildings there and brought an abrupt halt to one of the city's busiest shopping days.

The most destructive earthquake of the Canterbury sequence occurred at 12.51 NZST on 22 February 2011, five and a half months after the Darfield main shock. This M_w 6.2 aftershock (termed the Christchurch earthquake) occurred toward the eastern end of the aftershock zone and with an epicentre just 6 km southeast of the Christchurch city centre (red star in Figure 3.2).

[1]New Zealand was well-prepared for capturing critical research data and being able to provide rapid earthquake information to the public through having the GeoNet system (www.geonet.org.nz) well-established before these earthquakes. This is largely thanks to the vision of the Earthquake Commission in funding the project since its inception in 2001 and helping to support the associated national research capability.

The Christchurch earthquake was the most deadly since the 1931 Hawke's Bay (Napier) earthquake, with 181 people killed and several thousand injured. About two-thirds of the fatalities were from the collapse of two multi-storey office buildings. Many were killed in the streets by falling bricks and masonry, and in two buses crushed by toppling walls. Five people died in the Port Hills area, killed by collapsing rock cliffs and falling boulders.

Earthquake Magnitude

Numerous magnitude scales are used to describe the 'size' of an earthquake. GeoNet routinely issues M_L, or 'Richter' magnitude, which can be rapidly determined after the earthquake using nearby seismographs. Other magnitude estimates (including M_w and M_e) are calculated after sophisticated processing of the data. Ground shaking is described by Mercalli Intensities derived from initial ground acceleration values and felt reports.

M_L ('Richter' magnitude) is the initial magnitude assigned to an earthquake with routine GeoNet processing. The GeoNet M_L is a modification of the original magnitude scale defined by C.F. Richter in 1935. M_L is derived from measurements of the peak amplitude on seismographs and is thus a preliminary estimate of the amount of energy released by the earthquake. It is measured on a logarithmic scale, so each magnitude increment of 1 represents an order of magnitude increase in the measured amplitude or about 30 times more energy released.

M_w (Moment magnitude) is a measure of the final displacement of a fault after an earthquake. It is proportional to the average slip on the fault times the fault area. M_w is more complicated to determine than M_L, but is much more accurate, although the standard methods used to determine it are valid only for larger earthquakes ($\sim M_w > 4.0$). M_w is a rough proxy for the amount of low-frequency energy radiated by an earthquake and is commonly used worldwide to characterise large earthquakes.

M_e (Energy magnitude) is a measure of the amount of energy released in an earthquake so it is very useful for determining an earthquakes potential for damage. M_e is determined from the amplitude of all frequencies of seismic waves as measured on seismographs (as opposed to just the peak amplitude for M_L) and thus contains more information about the overall energy released in an earthquake and hence its destructive power. Two earthquakes with identical M_w (i.e., identical fault area times average slip) can have differing M_e if the strength of the faults that ruptured is different. Earthquakes on strong faults have relatively high M_e, whereas those on weak faults have relatively low M_e.

Modified Mercalli Intensity scale is a measure of how ground shaking from an earthquake is perceived by people and how it affects the built environment at a particular location. In any given large earthquake, the Mercalli Intensity will depend on the location of the observer and will usually be greatest nearer to the earthquake's hypocentre. This information is complementary to 'static' magnitude estimations (M_L, M_w, M_e) that describe the earthquake source rather than the ground shaking experienced.

The earthquake brought down many buildings previously damaged in the September 2010 earthquake. Many heritage buildings were heavily damaged, including the Provincial Council Chambers, Arts Centre, and both the Anglican and Catholic cathedrals. A number of modern buildings were also damaged beyond repair, including Christchurch's tallest building, the Hotel Grand Chancellor.

Liquefaction was even more widespread than in the Darfield earthquake, occurring in a number of suburbs that had not been affected in September.

Particularly high accelerations were recorded in the Christchurch earthquake, a factor which led to the severe building damage, widespread liquefaction and landslides. The February 22 earthquake led to an increase in aftershock activity, with several strong aftershocks of magnitude > 5.

On 13 June 2011 at 14:20 NZST, an M_w 6.0 earthquake occurred near the suburb of Sumner (blue star in Fig. 3.2). This earthquake resulted in one fatality and caused yet more damage in Christchurch and Lyttelton, causing irreparable damage to many CBD buildings scheduled for repair. The earthquake once again produced high accelerations in the southern and eastern suburbs, causing more widespread liquefaction, and rockfalls from cliffs in Port Hills suburbs.

The earthquakes of the Canterbury sequence were well-recorded by the GeoNet network, providing rare near-fault shaking data of international significance for seismological studies that will result in an improved understanding of near-fault earthquake shaking and how to mitigate its effects on our built environment. In this section we discuss the main features of significant earthquakes of the Canterbury sequence and conclude with a comparison of the main features of the events.

3.2 4 September 2010 Darfield Earthquake

The M_w 7.1 Darfield earthquake was the first earthquake to produce ground-surface rupture in New Zealand since the 1987 M_w 6.5 Edgecumbe earthquake in the North Island. The earthquake ruptured the previously unknown Greendale fault, which was buried beneath post-glacial, alluvial gravel deposited on the Canterbury Plains (Forsyth *et al.* 2008). The east-west striking surface rupture extends for ~29.5 km, mainly across low-relief pastoral farmland. Movement was predominantly right-lateral strike-slip with an average horizontal displacement of ~2.5 m and maximum displacements of ~5 m horizontally and ~1.5 m vertically as measured at the surface (Quigley *et al.* 2010). The rupture is not a continuous line—it has a series of offset fault traces with a maximum stepover (or perpendicular distance between fault segments) of 1 km. The rupture recurrence interval for the Greendale Fault is at least 8,000 years (Villamor *et al.*, 2011).

Information from seismographs, GPS and processed satellite radar (InSAR) data all suggest that the earthquake rupture was in fact a complex process involving rupture of several fault segments (Fig. 3.3; Beavan *et al.*, 2010, Holden *et al.* 2011). Seismological evidence (Holden *et al.* 2011) suggests fault rupture initiated on a blind thrust fault, the Charing Cross Fault (a blind fault is one that does not break the ground surface). The Charing Cross fault is located at the earthquake epicentre and intersects the dominant Greendale Fault surface trace. Rupture then spread in both directions (but dominantly eastwards) along the Greendale Fault. An additional intersecting smaller thrust fault at the western end of the Greendale Fault ruptured later into the earthquake. Both geodetic and seismological models suggest that the dominant fault displacements responsible for the earthquake were very shallow, confined to the upper ~5 km of the crust.

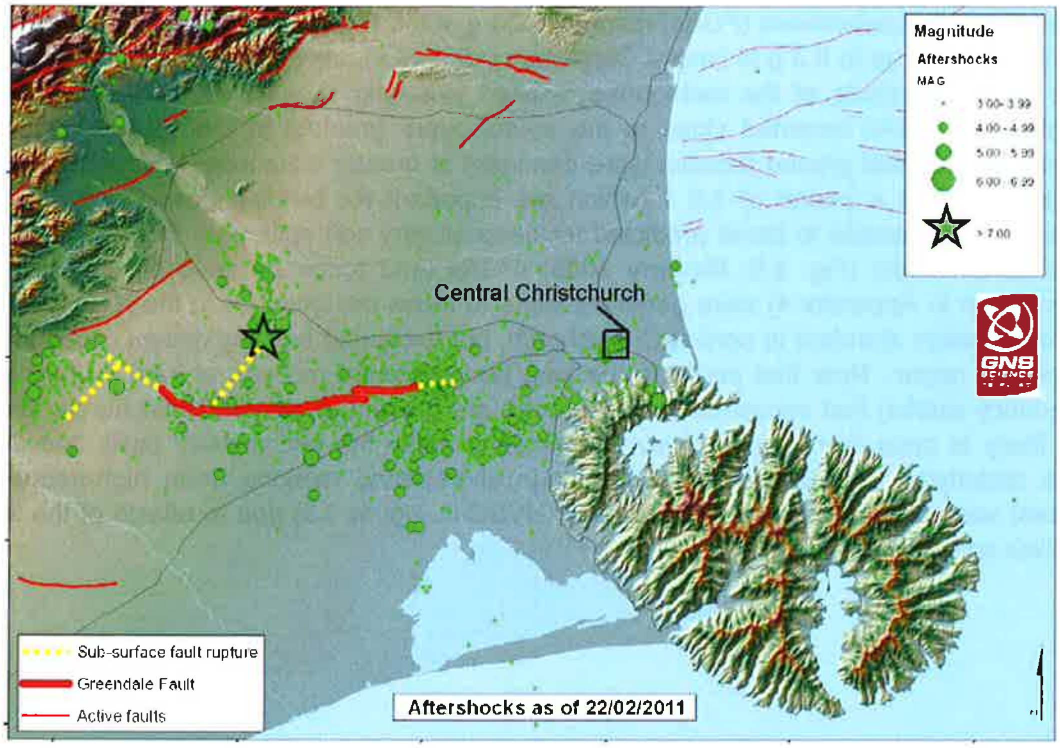

Figure 3.1 Earthquakes of the Canterbury sequence through 21 February 2011. The 4 September 2010 Darfield main shock rupture initiated at the location of the green star. The Boxing Day event occurred in the cluster below central Christchurch.

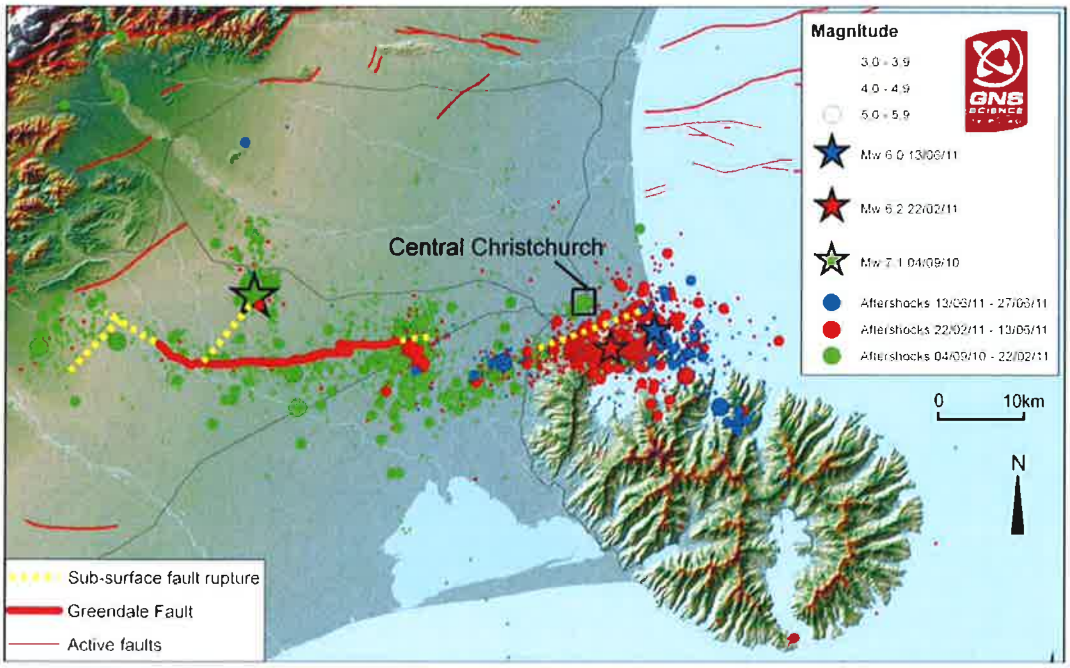

Figure 3.2 Earthquakes of the Canterbury sequence through 27 June 2011. Major earthquakes are shown as stars, including the September 2010 Darfield main shock (green), the February (red) and June (blue) 2011 Christchurch earthquakes.

Peak Ground Accelerations (PGAs) reached 1.26 g at the Greendale seismic station (GDLC in Fig. 3.3) and up to 0.3 g in central Christchurch (Fig. 3.4), over 35 km from the epicentre. The large magnitude of the earthquake resulted in strong shaking over a large area of Canterbury. PGAs recorded close to the source were greatest in the vertical direction, whereas horizontal ground motions were dominant at greater distances. Horizontal ground accelerations at a period of 1.0 s (which are important for building design codes) were generally comparable to those predicted for deep or very soft soils from the New Zealand attenuation model (Fig. 3.5; McVerry 2006). PGAs (and response spectra—see detailed information in Appendix 4) were generally close to those designed for in the New Zealand building design standard in central Christchurch, but exceeded building design codes in the epicentral region. Note that peaks in the long period ground motions at ~2.5 s (from low-frequency waves) that exceeded design spectra are present in central Christchurch. These are likely to arise from complex wave interactions within the sedimentary basin and deep soils underlying Christchurch. Unusually high short-period motions (from high-frequency waves) were observed in Heathcote Valley (HVSC in Figure 3.3) due to effects of the local shallow soils and basin.

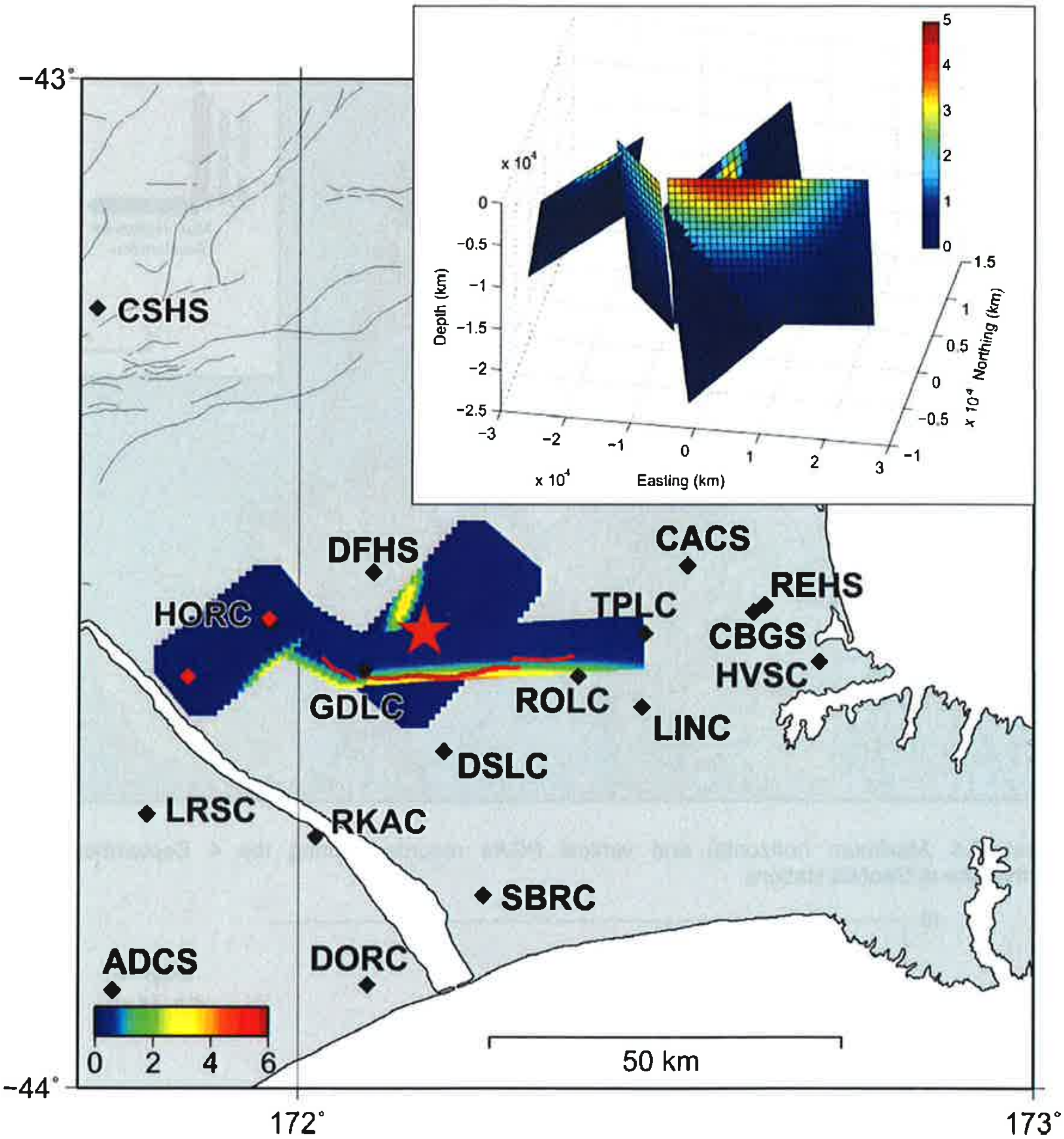

Figure 3.3 This model for the Darfield earthquake based on seismological data shows the complex earthquake rupture (Holden, 2011). The map shows the surface projection of the slip from the 3D fault rupture model, strong motion stations (four-letter labels), the mapped surface trace (red) and the Darfield epicentre (red star). Top right corner: 3D rupture model showing the Greendale Fault plane with the east-west and north striking segments, the reverse fault plane near Hororata to the west, and the Charing-Cross reverse fault near the epicentre. Warmer colours represent increasing slip along the fault plane (given in metres).

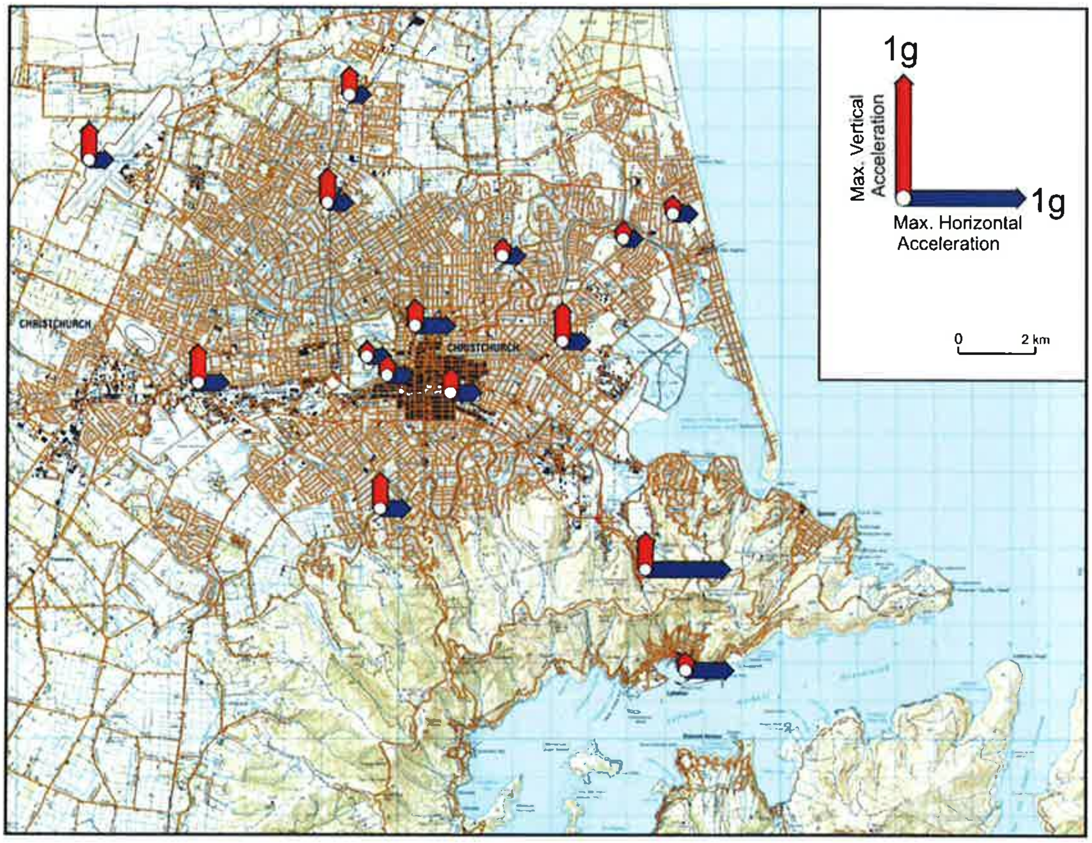

Figure 3.4 Maximum horizontal and vertical PGAs recorded during the 4 September 2010 earthquake at GeoNet stations.

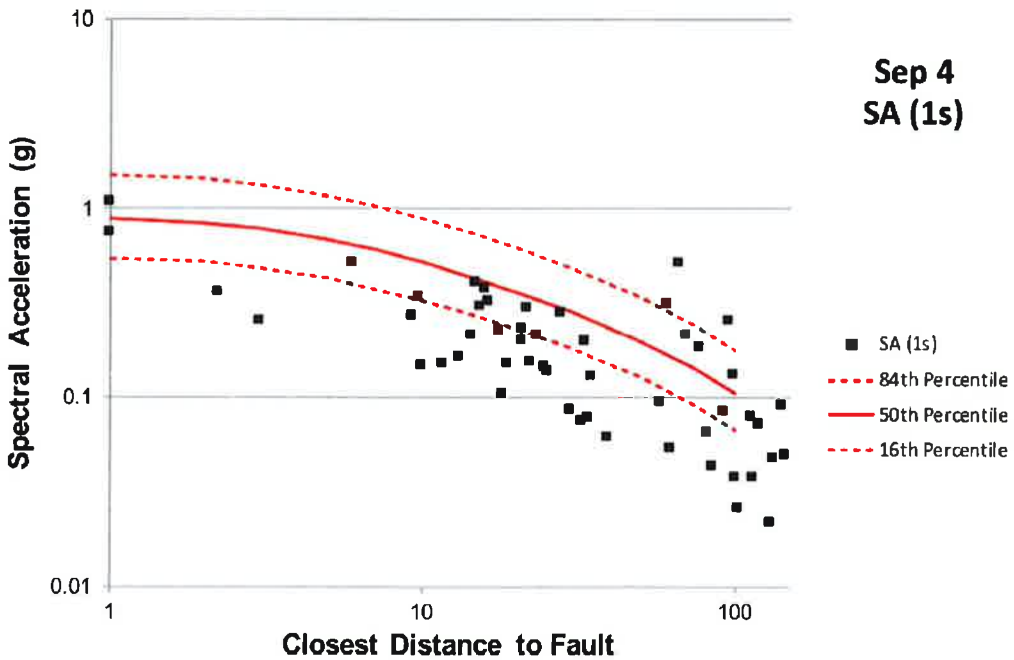

Figure 3.5 Observed spectral accelerations at 1.0 s during the Darfield earthquake (black squares) compared to those predicted from the national attenuation model for deep or very soft soils (solid red line; McVerry *et al.*, 2006).

More than 7,300 felt reports were lodged with GeoNet, with well over 100 reports indicating shaking intensities of MM 8 and some of MM 9. The highest intensities were in the epicentral region and extended east to Christchurch. Most of the reports of heavy damage came from Christchurch city as expected because of the dense population and types of buildings there, although reports of damage came from across the Canterbury region. Liquefaction was widespread in many eastern areas in the Canterbury Plains including Christchurch city's eastern and southwestern suburbs and the town of Kaiapoi, about 17 km north of Christchurch's city centre.

The energy magnitude (M_e, see 'Magnitude' textbox) for this event was very high, at M_e ~8.0, compared to the moment magnitude M_w 7.1 (G. Choy, personal communication; Fry & Gerstenberger 2011). This indicates that a high amount of energy was released for the size of the fault rupture (defined by fault area and average slip). One measure of the energy released in relation to the rupture size is the stress drop—the sudden reduction of stress across a fault during rupture. It can be derived from the M_e and M_w of the earthquake. The high stress drop associated with the Darfield earthquake indicates that the fault was strong, such that the rupture radiated more energy than the average earthquake of its size as defined by M_w. This has commonly been observed for faults in areas of where strain accumulates slowly, so there is a long recurrence interval between major earthquakes.

Because the fault rupture spread eastward, it had 'directivity' effects in the Christchurch area. In seismological terms, directivity is the stacking of energy that results when waves emitted from the starting point of an earthquake are superimposed on waves generated as the rupture progresses. This led to larger seismic waves in the forward direction of rupture towards the eastern end of the Greendale Fault. Christchurch ground motions showed 'polarization' or generally higher amplitudes in the north-south direction (Cousins & McVerry, 2010). Polarization in the direction perpendicular to fault rupture is typically seen in directivity effects for strike-slip faults.

3.3 26 December 2010 Boxing Day Earthquake

Starting on 26 December 2010 a series of shallow aftershocks termed the 'Boxing Day sequence' occurred near to the Christchurch city centre. The sequence began with an M_w 4.7 earthquake on Boxing Day 2010, with magnitude 4.6 and 4.4 events just a few hours later. More than 30 events followed within a relatively small area over the subsequent 3–4 weeks. The initial M_w 4.7 event was the largest and caused a significant amount of damage in the city centre.

Fig. 3.6 shows the locations of earthquakes catalogued by GeoNet that occurred between 25 December 2010 and 5 February 2011 beneath the city. The main cluster of earthquakes lies directly beneath central Christchurch city. Sophisticated earthquake location analyses indicate that the initial Boxing Day M_W 4.7 event was located at ~4.0 km depth with an epicentre 1.8 km NW from Christchurch cathedral (Bannister 2011). Most of the subsequent events occurred at depths between 3.5 and 7 km in a single patch less than 1 km^2 in area, with epicentres ~1 km NE of Christchurch cathedral. Analyses of seismic records indicate that the Boxing Day earthquakes involved right-lateral strike-slip (Ristau 2011) and their distribution (shown in Figure 3.6) is consistent with an east-west fault plane striking at ~74° and dipping steeply.

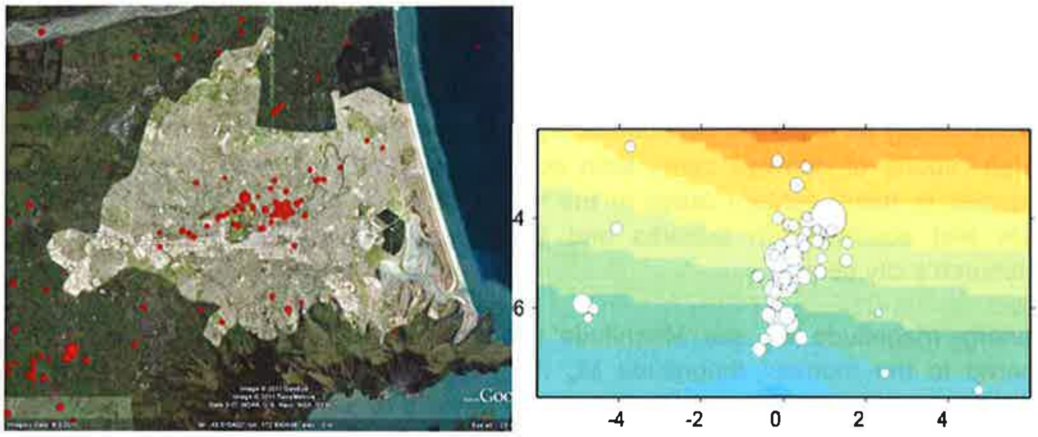

Figure 3.6 Left: Locations of earthquakes (catalogued by GeoNet) that occurred beneath Christchurch city between 25/12/2010 (00:00 UTC) and 5/2/2011 (23:59 UTC). Right: Cross-section showing precise earthquake locations that are clustered around the fault plane of the Boxing Day earthquake (Bannister, 2011).

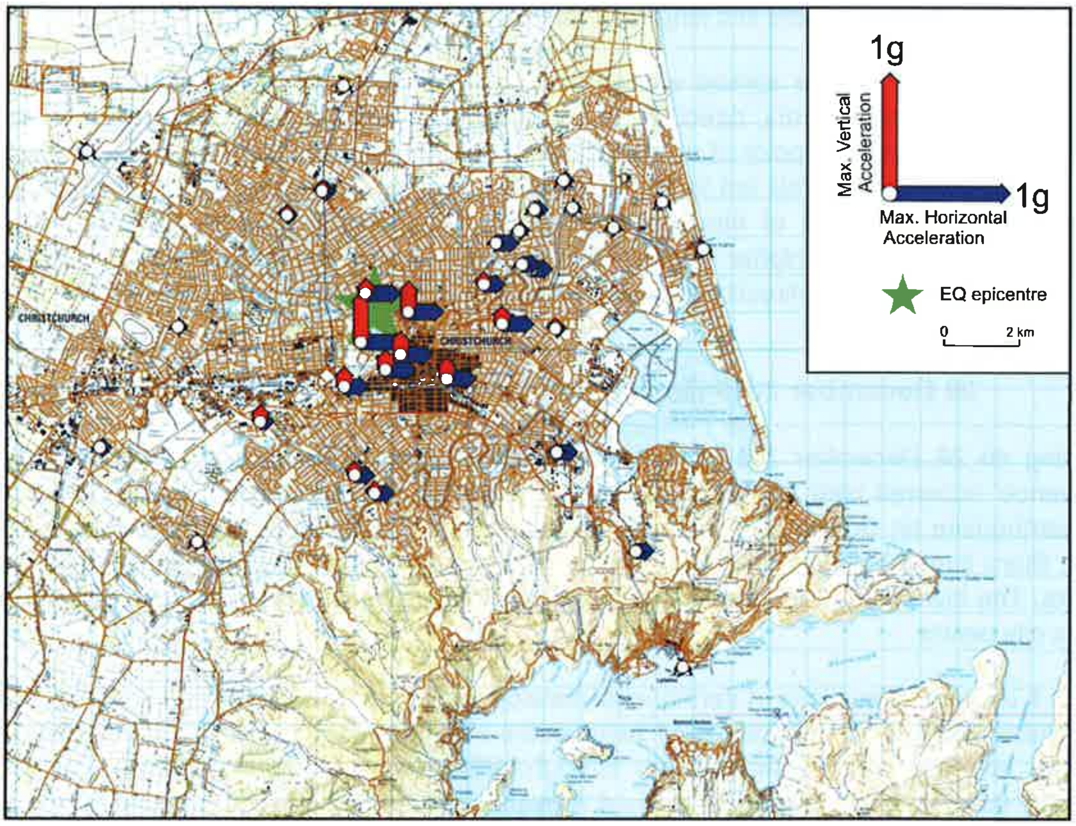

Figure 3.7 Maximum horizontal and vertical PGAs recorded during the 26 December earthquake at GeoNet stations and using temporary low-cost accelerometers (Quake-Catcher Network).

The maximum PGA measured from the M_w 4.7 earthquake was 0.4 g, measured at the Christchurch Botanical Gardens, and over 0.2 g elsewhere in the CBD (Fig. 3.7). Both of these PGA values equate to modified Mercalli intensities of MM7. Felt reports lodged with GeoNet included 8 reports of MM8 and 23 reports of MM7, indicative of damaging or heavily damaging ground motions. However, due to the smaller earthquake size, these high ground motions were confined to the central city area.

Because of the relatively small magnitude of the Boxing Day event, directivity effects were minimal and very local. The relative size of these events also makes determination of a slip distribution difficult. Radiated energies have not yet been determined for these events, but it is expected that they will be consistent with the September, February, and June events, implying relatively high stress drops compared to average New Zealand earthquakes.

3.4 22 February 2011 Christchurch Earthquake

The M_w 6.2 February 22 Christchurch earthquake was by far the most destructive of the Canterbury sequence, with severe ground shaking occurring over much of the city. The earthquake occurred on a northeast-southwest oriented fault at shallow depth. Slip along the fault reached within ~1 km of the surface but did not break the surface. This fault was unknown prior to the Darfield earthquake, but had experienced aftershock activity in the months prior to the Christchurch earthquake. The faulting movement for this earthquake was oblique-reverse (a combination of right-lateral strike-slip and thrust faulting). Based on geodetic and seismological data (Fig. 3.8), the rupture produced maximum slip of 2.5–4.0 m at a depth of 4–5 km on a fault plane dipping ~70° to the southeast (Beavan *et al.* 2011; Holden 2011). However, the geodetic data are better modelled by incorporating a second smaller fault below the Port Hills to the southwest that is oriented ENE-WSW with dominantly strike-slip movement. The seismological evidence is consistent with this hypothesis and suggests the smaller strike-slip patch may have ruptured before the larger oblique-reverse area of slip.

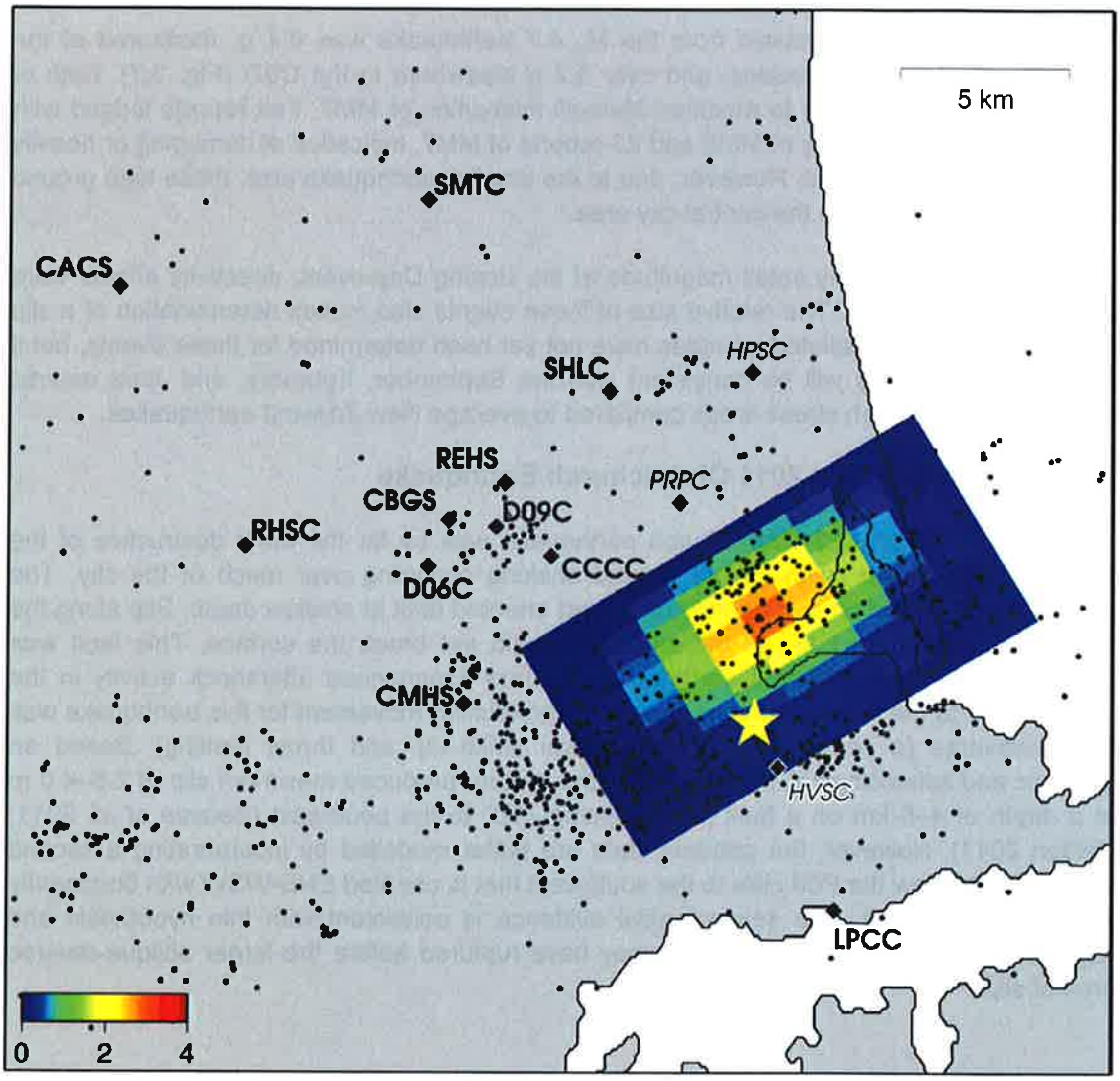

Figure 3.8 This geodetic source model (from Beavan *et al.*, 2011) shows the locations of the two model faults and their slip magnitudes (coloured images), GPS displacements observed (blue arrows) and modelled (red arrows), and aftershocks since September 2010 (crosses).

Ground motions in Christchurch city were extremely high during the February event, reaching 2.2 g in Heathcote Valley near the epicentre and up to 0.8 g in the CBD (Fig. 3.9). In areas close to the fault (less than 5 km away) peak horizontal accelerations were in fact stronger in the Christchurch event than the Darfield main shock (Kaiser *et al.* 2011; Cousins & McVerry 2010). However, the horizontal PGAs at greater distances from the fault plane were stronger in the Darfield earthquake, in keeping with the larger magnitude of that event.

Figure 3.10 shows comparisons of recorded ground accelerations with those estimated for a shallow oblique-reverse earthquake of this magnitude based on the national attenuation model (McVerry *et al.* 2006). At distances within ~10 km of the fault, including central Christchurch, PGAs were considerably higher than those expected from the McVerry *et al.* (2006) model. However, PGAs were somewhat less than expected at distances greater than 10 km.

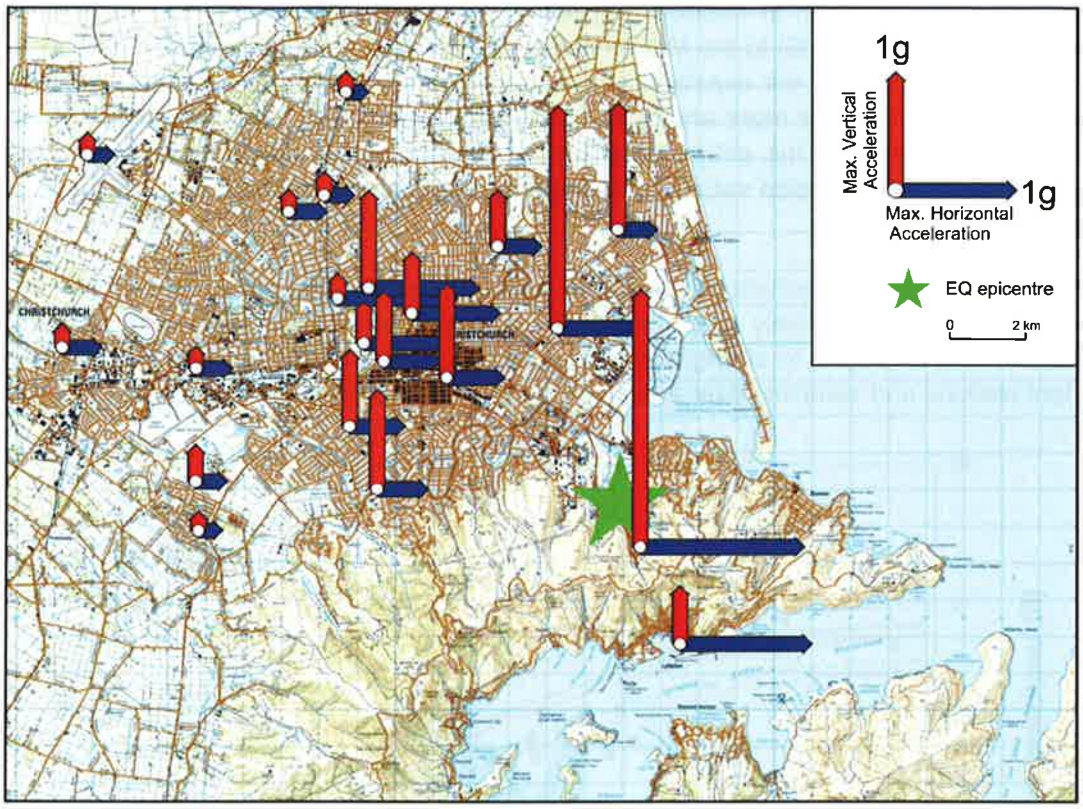

Figure 3.9 Maximum horizontal and vertical PGAs recorded during the 22 February earthquake at GeoNet stations and using temporary low-cost accelerometers (Quake-Catcher Network).

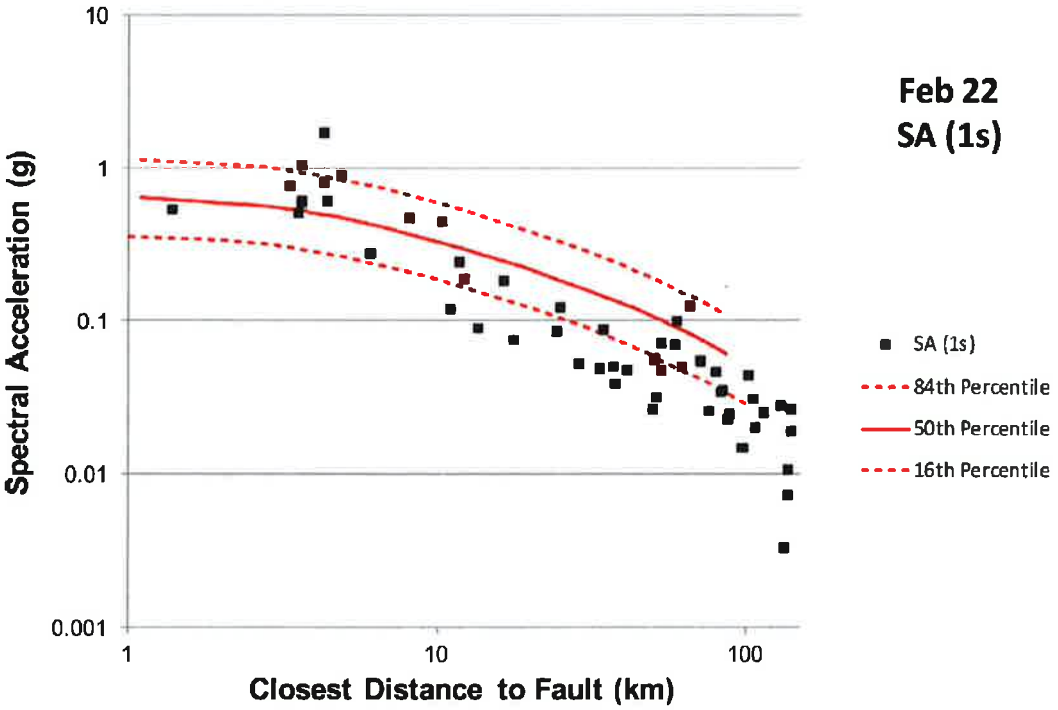

Figure 3.10 Observed spectral accelerations at 1.0 s during the Christchurch earthquake (black squares) compared to those predicted from the national attenuation model for deep or very soft soils (solid red line; McVerry *et al.*, 2006) assuming a crustal oblique-slip source.

In Figure 3.11 we have, in addition, applied a stress drop scaling term as proposed by Atkinson and Boore (2006) to the McVerry *et al.* (2006) relationship. The stress drop scaling is based on the ratio of the expected stress drops of earthquakes across New Zealand to those expected from the more energetic Canterbury events (i.e., 10MPa/15MPa), giving a ratio of 1.5. Even with the enhanced stress drop, most of the observations within 10 km distance exceed the median value, indicating that other factors, such as directivity, are also important.

The sharp decrease in ground motions after about 10 km (resulting in an over-prediction of the ground-motions) is likely to be caused by a biased sampling of data in the near field toward locations subject to strong directivity, with that bias diminishing when including more distant stations and sampling over a much wider area outside of the directivity region.

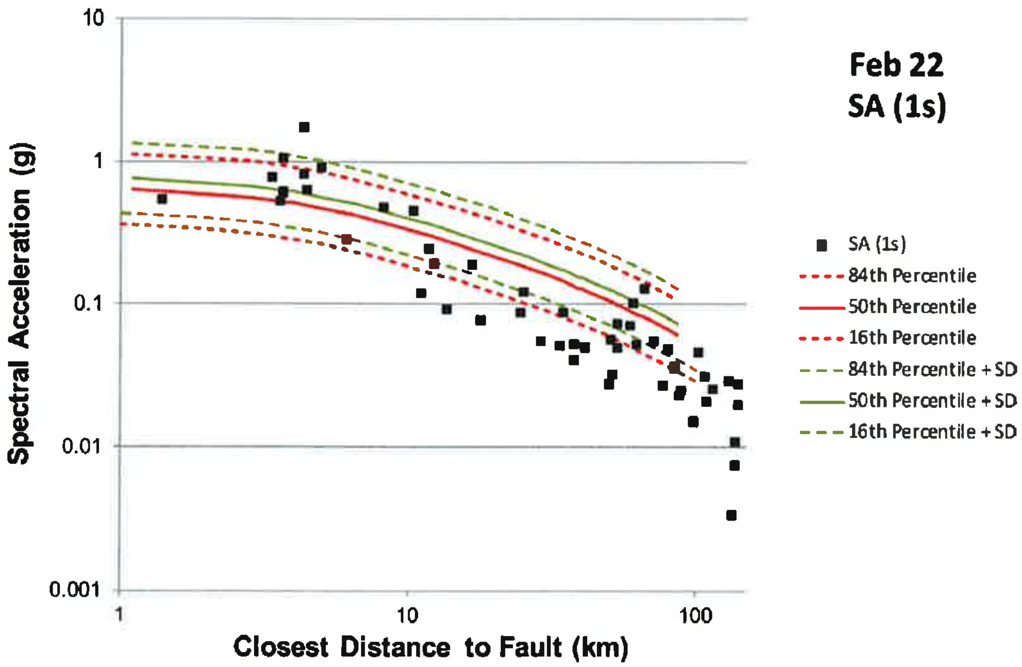

Figure 3.11 Observed spectral accelerations at 1.0 s during the Christchurch earthquake (black squares) compared to those predicted from the national attenuation model for deep or very soft soils (solid red line; McVerry *et al.*, 2006) assuming a crustal oblique-slip source. Also shown is the prediction with stress drop scaling (green solid line). For both predictions, the 16th and 84th percentile motions are also shown in the same color.

In Figure 3.12 we have plotted the median ground acceleration curves at 1.0 s for the 22 February event using the Atkinson and Boore (2006) and Abrahamson and Silva (2008) attenuation relationships. These relationships are known as Next Generation Attenuation (NGA) models and are applicable to parts of the Unites States, but are also likely to be appropriate for parts of New Zealand. Both curves are plotted using a reverse mechanism and assuming a seismic shear wave velocity, Vs30, of 230 m/s, a value determined from the average of two Christchurch GeoNet sites (Perrin, pers. Comm., 2011). For Abrahamson and Silva, we have used parameters based on data from two average sites in Christchurch. The behavior of the models is similar to the McVerry *et al.* (2006) model with under-predictions in the near field and over-predictions beyond 10 km. This confirms that this earthquake is anomalous in terms of the ground shaking produced, rather than this being a problem with New Zealand attenuation models.

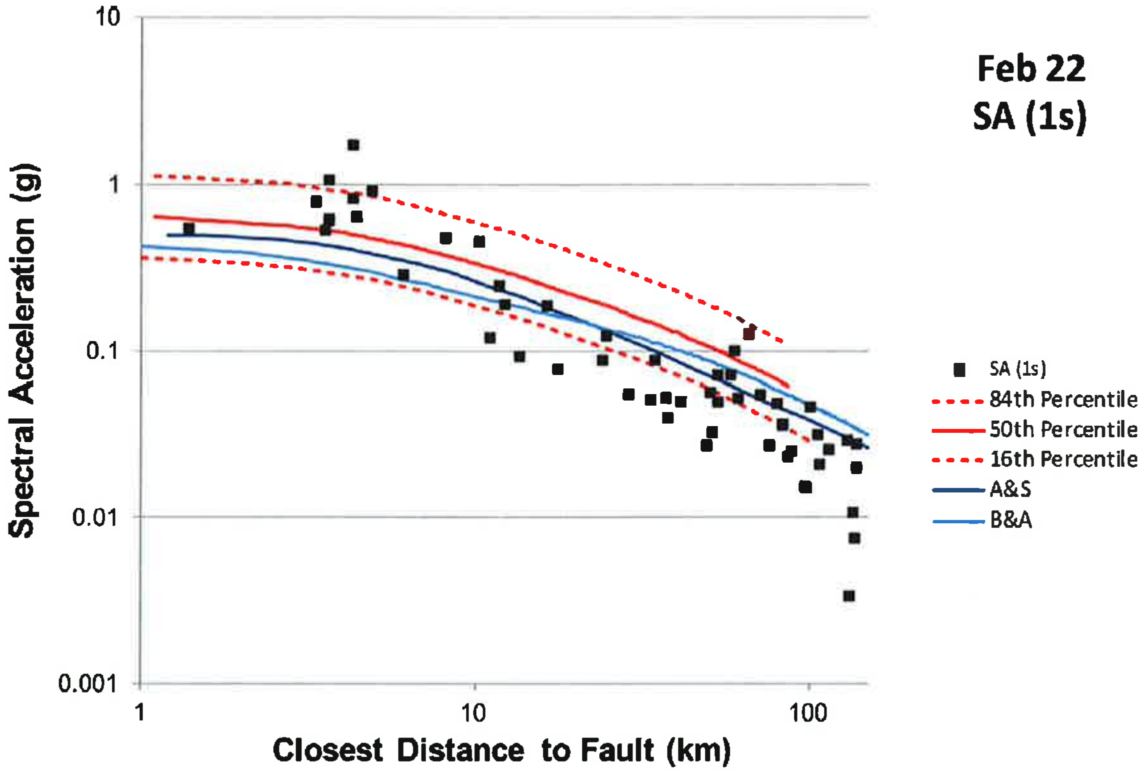

Figure 3.12 Observed spectral accelerations at 1.0 s during the Christchurch earthquake (black squares) compared to those predicted from the national attenuation model for deep or very soft soils (solid red line; McVerry *et al.,* 2006) assuming a crustal oblique-slip source. Also shown are the ground motion predictions from the Abrahamson and Silva (A&S; 2008) and Atkinson and Boore (B&A; 2006) relationships.

Fig. 3.13 compares earthquake response spectra (see textbox below) of recorded horizontal ground motions at four sites within ~1.5 km of the Christchurch CBD with spectra from the New Zealand design standard NZS1170. The New Zealand design standard sets guidelines for the levels of ground motion that are expected to occur at average intervals of 500 years, 1,000 years and 2,500 years for normal use, major use and post-disaster use structures, respectively. The comparison in Figure 3.13 shows that in the CBD, recorded earthquake response spectra (coloured lines) exceeded the 2,500 year return ground motions, especially at long periods, although they are generally somewhat less than these motions at short periods (<0.3–0.4 s). As in the 4 September earthquake, peaks in the response spectra at long periods are present, although at a slightly longer period (3 s) for the February earthquake. More detailed information can be found in Appendix 4).

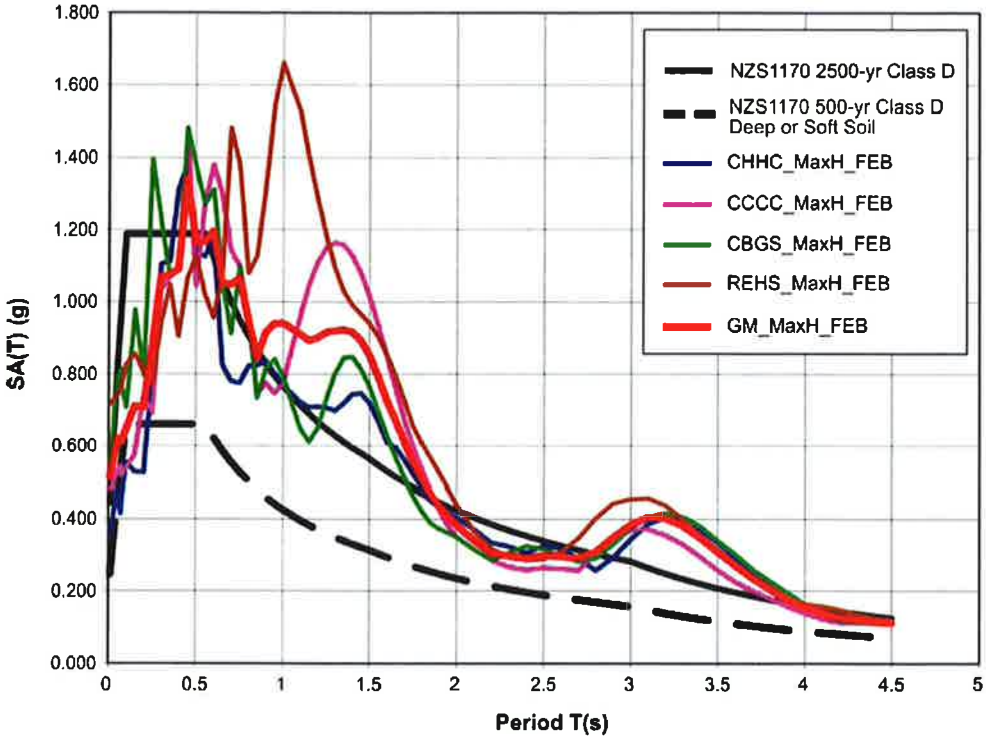

Figure 3.13 Comparison of recorded (5% damped) acceleration response spectra for four sites within ~1.5 km of the CBD (coloured lines) and corresponding spectra from the New Zealand design standard NZS1170 for deep or soft soil sites (black lines). The solid red line is the average of the four central sites; dashed and solid black lines are the NZS1170 spectra expected for 500 and 2,500 year return periods respectively.

Earthquake response spectra

When designing buildings to be resistant to earthquake motions, engineers must take into account the amplitude of seismic waves at different periods (or frequencies). Different types and sizes of buildings respond to the earthquake motions in different ways, and every building has its own resonant behaviour, i.e. it responds most strongly when the input ground shaking is strong at the natural period of the building. Very roughly, a one-storey building will respond most strongly to ground accelerations with a 0.1 second period, a ten-storey building to 1 second accelerations (i.e. 10 times the period of a 1-storey building), and a 20-storey building to 2 second accelerations, etc.

To create an earthquake response spectrum, a large set of very simple building models with different resonant periods and a specified level of damping are exposed to a complete earthquake recording, and the peak responses of the models are estimated, and plotted as a function of their period. Note that, for building design, engineers generally use the spectra of horizontal (rather than vertical) ground motions.

A number of factors are thought to have contributed to the high accelerations experienced in Christchurch city during the 22 February event (Fry *et al.* 2011a; Reyners 2011). Firstly, because the earthquake was close to the city and at a shallow depth, ground shaking was high compared to September, as the energy of seismic waves reduces very rapidly away from where the fault rupture occurred. Secondly, the energy magnitude (Me) of the Christchurch earthquake was 6.75 (compared to the moment magnitude of 6.2), indicating that, as for the 4 September Darfield earthquake, this was a high stress drop event that radiated more energy than average for an earthquake of this size. Thirdly, seismological and geodetic modelling shows that the maximum fault displacement was shallow and the direction of rupture was in a northwestward direction and upwards towards Christchurch city. Therefore stacking of energy in the direction of earthquake rupture (or directivity effects) is likely to have further enhanced ground motions within 10 km of the fault.

Other site, basin and topographical effects will also have contributed to the strong ground shaking in Christchurch. Of particular note was that vertical accelerations were greater than horizontal accelerations near the fault source (Fig. 3.9). This can be partly attributed to the rupture directivity, but local site conditions are also thought to contribute. Striking differences in the frequency characteristics of seismic waves in the horizontal and vertical directions were observed at many Christchurch stations. Vertical accelerations near the fault were rich in high-frequency (short period) energy, in marked contrast to the dominant lower frequency energy (longer period) generally observed for the horizontal components. The water table under many Christchurch stations on the plains may have affected accelerations as the water table is quite high, reaching close to the surface. High-frequency near-surface reflections off the water table are likely to amplify vertical accelerations, whereas high-frequency horizontally polarised energy is likely to be attenuated in the shallow subsurface within saturated or liquefied material (Fry *et al.* 2011b). In addition, a 'trampoline' effect involving complex behaviour of near-surface unconsolidated soil may have increased accelerations in the 'upwards' direction at stations near the fault source (Fry *et al.* 2011b). This effect has only previously been observed in a small number of earthquakes worldwide with very large accelerations (e.g. Aoi *et al.*, 2008; Yamada *et al.*, 2009). Complex wave interactions due to the shape of the basin and deep soils below Christchurch are likely responsible for the peaks in ground acceleration at longer periods (or lower frequencies).

3.5 13 June 2011 Christchurch Earthquake

The epicentre of the Mw 6.0 earthquake on 13 June 2011 was located close to the eastern suburb of Sumner (Fig. 3.14). The June 13 earthquake was preceded around an hour before by a significant foreshock of M_L 5.7 in a similar location.

The June earthquake accompanied a rupture of a right-lateral strike-slip fault. Initial source data suggest there are two possible orientations for the fault plane (NNW-SSE or ENE-WSW). Geodetic and strong motion studies of the source mechanism are under way and will resolve the fault plane orientation with more certainty in the coming months. Preliminary results indicate that there were two distinct patches of slip that occurred either on intersecting fault planes or on a single fault oriented NNW-SSE. In either case, directivity effects due to the direction of rupture are expected to have been smaller in the central city area during the June event than in the February earthquake (although they may have been concentrated further to the east in the June earthquake).

The effects of the earthquake were most strongly felt in the southern and eastern suburbs, where Modified Mercalli Intensities were above MM8. Further damage to vulnerable structures occurred in the CBD, and there was further cliff collapse and rockfalls on slopes in the southern Port Hills. Liquefaction was once again widespread in the southern and eastern suburbs.

As in the February 22 earthquake, PGAs in Christchurch were again very high during the June event, reaching 2 g in Sumner and 0.4 g in the CBD (see Appendix 4 and Fig. 3.14).

The energy magnitude (M_e) of 6.7 indicates that energy released during the June earthquake was again high, as in the September and February events, indicating a high stress drop and the radiation of higher-than-average levels of seismic energy.

As previously stated, many of the high PGAs during the February earthquake were measured in the vertical direction. Conversely, horizontal PGAs were dominant in the June event (particularly near the source fault in the Port Hills). It is likely that the different fault movement of the two events (strike-slip in June; oblique-reverse in February) contributed to these dominant polarisations of the PGAs. The extremely high accelerations at the Sumner station (which is on rock) may also have been influenced by a degree of amplification of seismic waves due to the shape of the topography at the surface. For many Christchurch stations on the plains, energetic high-frequency waves were recorded on the vertical component of seismograms, but were significantly weaker on the horizontal component due to shallow site effects (including liquefaction), as discussed for the February earthquake.

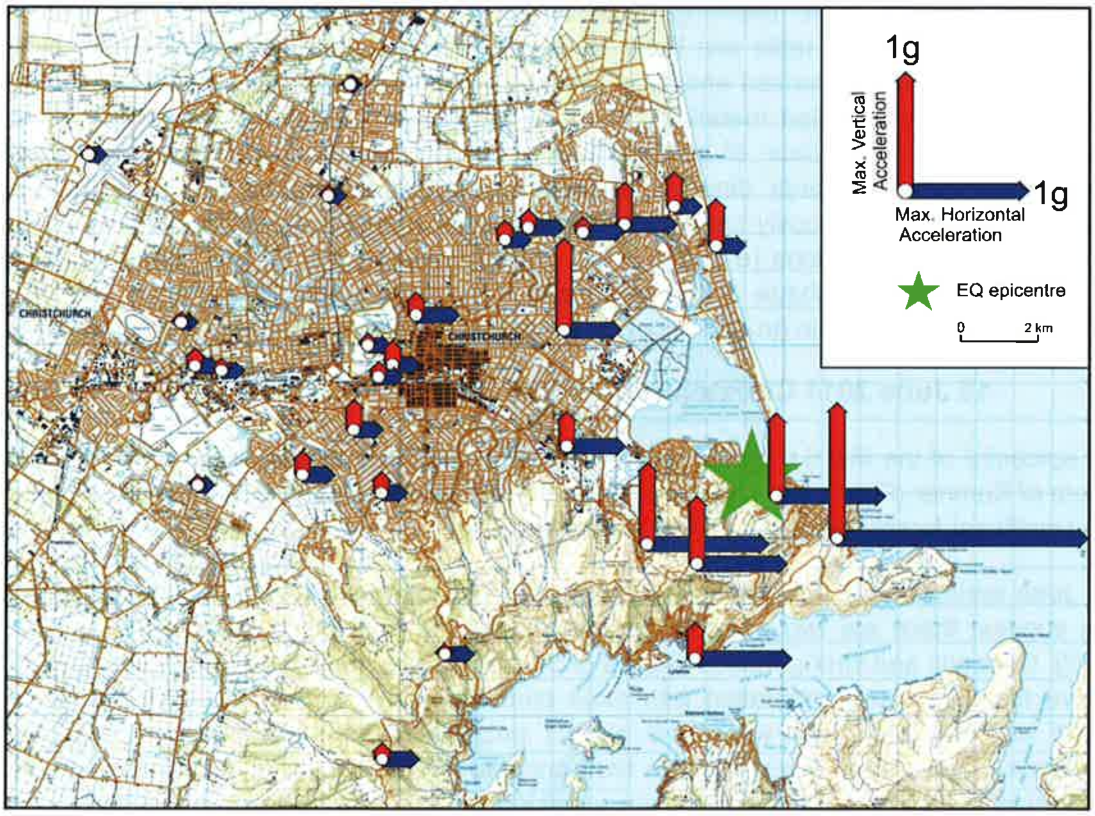

Figure 3.14 Maximum horizontal and vertical peak ground accelerations (PGA) recorded during the 13 June 2011 earthquake at GeoNet stations and using temporary low-cost accelerometers (Quake-Catcher Network).

Figure 3.15 shows the ground acceleration plot at 1.0 s for 13 June 2011 earthquake. Fault rupture models for this rupture are still preliminary and will likely introduce errors of a few kilometers into the distance calculations. We have therefore used the epicenter of the relocated main shock (Bannister *et al.*, 2011) projected to 1 km depth (the estimated top of the rupture). The distances are likely to be over-estimated. For the June earthquake, similar trends are seen as to the February event with high accelerations within 10 km of the source and a steep decrease of accelerations at distances greater than that.

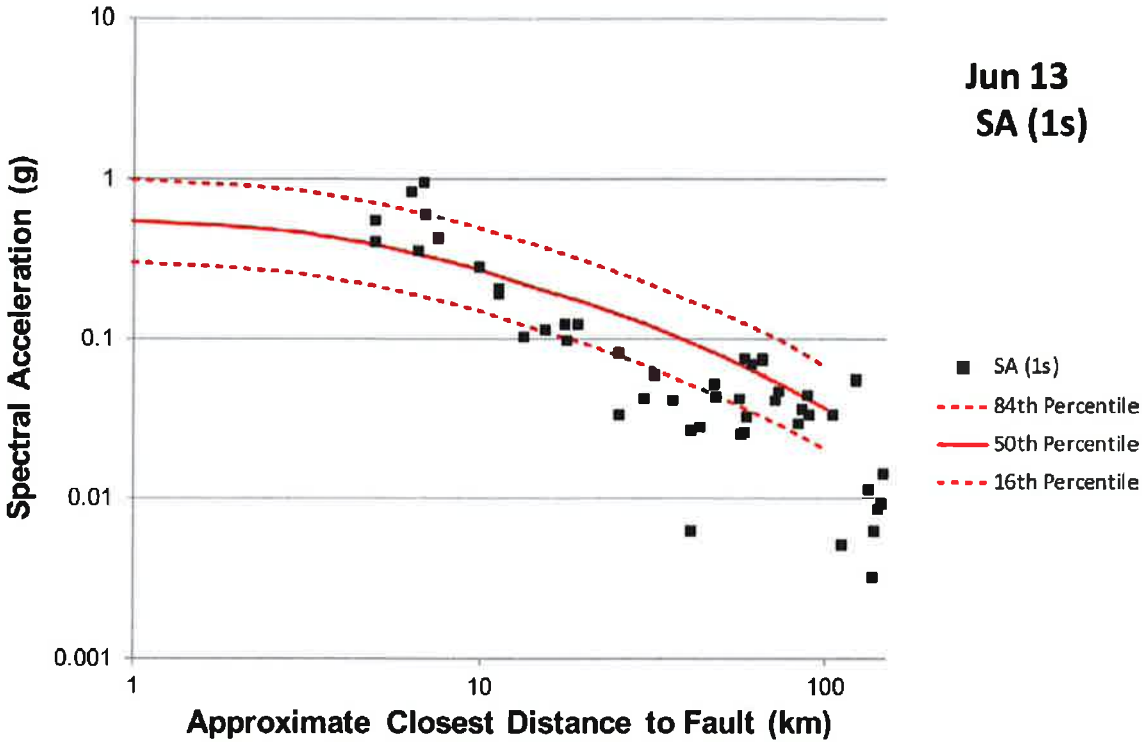

Figure 3.15 Observed spectral accelerations at 1.0 s during the 13 June 2011 Christchurch earthquake (black squares) compared to those predicted from the national attenuation model for deep or very soft soils (solid red line; McVerry *et al.*, 2006) assuming a crustal strike-slip source.

3.6 Comparisons of earthquake characteristics

The main features of the four Canterbury earthquakes discussed above are summarized in Table 3.1. The Canterbury earthquake sequence has included a mixture of strike-slip and reverse faulting at shallow depths on previously unidentified faults in the Canterbury area at varying distances from the Christchurch CBD. Distance from the fault rupture is a principal factor in determining how much shaking will be experienced at a site.

All of the three largest events have high energy magnitudes (M_e) compared to their moment magnitude (M_w), so have radiated above-average amounts of seismic energy. We thus infer that these earthquakes have high stress drops, meaning that the rupture plane area is relatively small for the amount of energy released, implying that the faults were very strong. The reasons for this and the implications for the rest of New Zealand are discussed in Section 5.1.

Directivity effects arising from the direction of rupture along the fault have likely increased the severity of ground motions experienced in central Christchurch during the February and also the September earthquakes, but are not thought to have played a strong role in the Boxing Day or June earthquakes for the CBD area.

Overall there is a good match between the amounts of damage caused by the earthquakes and the horizontal PGAs. Recordings of particular interest were those from sites close to the CBD (Fig. 3.16). It is clear that, in the CBD, the peak horizontal accelerations during the 22 February event were approximately twice as strong as during the other three earthquakes. Although the 4 September 2010 earthquake was significantly larger than the other events, its epicentre was > 35 km from the CBD. Consequently, ground accelerations at this distance were reduced. However, displacements (as opposed to accelerations) were by far the greatest during the 4 September 2010 earthquake (see Appendix 4; displacements are another important ground motion measure for building design, especially in the case of tall buildings). Furthermore, longer durations of shaking such as experienced during the 4 September 2010 earthquake can further exacerbate building damage and liquefaction.

Table 3.1 Summary of the main features of significant earthquakes in the Canterbury sequence. Distances are distance from the fault trace where available, but those marked with an asterisk (*) are taken from the earthquake epicentre. Duration is defined by the approximate length of record containing accelerations over 0.1 g.

Earthquake		**4 Sep**	**26 Dec**	**22 Feb**	**13 Jun**
Magnitude	M_w	7.1	4.7	6.2	6.0
	M_L	7.1	4.9	6.3	6.3
	M_e	8.0	not known	6.75	6.7
Source fault	Rupture	Complex	Strike-slip	Oblique-reverse	Strike-slip
	Orientation	E-W surface rupture	E-W	NE-SW	under investigation
Max. PGA recorded	Horiz.(g)	0.8	0.4	1.7	2.0
	Vert. (g)	1.3	0.5	2.2	1.1
	Dist. (km)	1.3	~2*	2	3*
Max. PGA recorded in CBD	Horiz. (g)	0.3	0.4	0.7	0.4
	Vert. (g)	0.2	0.4	0.8	0.2
	Dist. (km)	20-22	~2 – 3*	5 - 9	9 – 11*
Duration of shaking >0.1g in CBD (s)		8 - 15	1 – 1.7	8 - 10	6 – 7.5

The lower plot in Figure 3.16 shows a comparison of response spectra in the Christchurch CBD during each earthquake. Each coloured line is an average of the strongest responses calculated from horizontal ground motions from all CBD sites. Houses and other low-rise buildings (1 to 3 storeys) will usually have response periods in the range 0.1 to 0.3 s. Hence Figure 3.16 suggests that the damage potential of the four earthquakes for houses and low-rise buildings, is in order from worst to least, 22 February, 26 December, 4 September and 13 June. In contrast, most of the medium to high-rise buildings in Christchurch, 4 to 10 storeys, will usually have response periods in the range 0.4 to 1.0 s. For them the 22 February earthquake had by far the most damage potential, followed by the 4 September and 13 June events, and with the 26 December event having the least potential for damage. Interestingly, at 2 seconds period (the approximate resonant period for a 20-storey building), the three largest earthquakes had a similar damage potential. The small 26 December event had very little damage potential beyond about 1 second period (i.e. that would affect buildings roughly 10-storeys and higher).

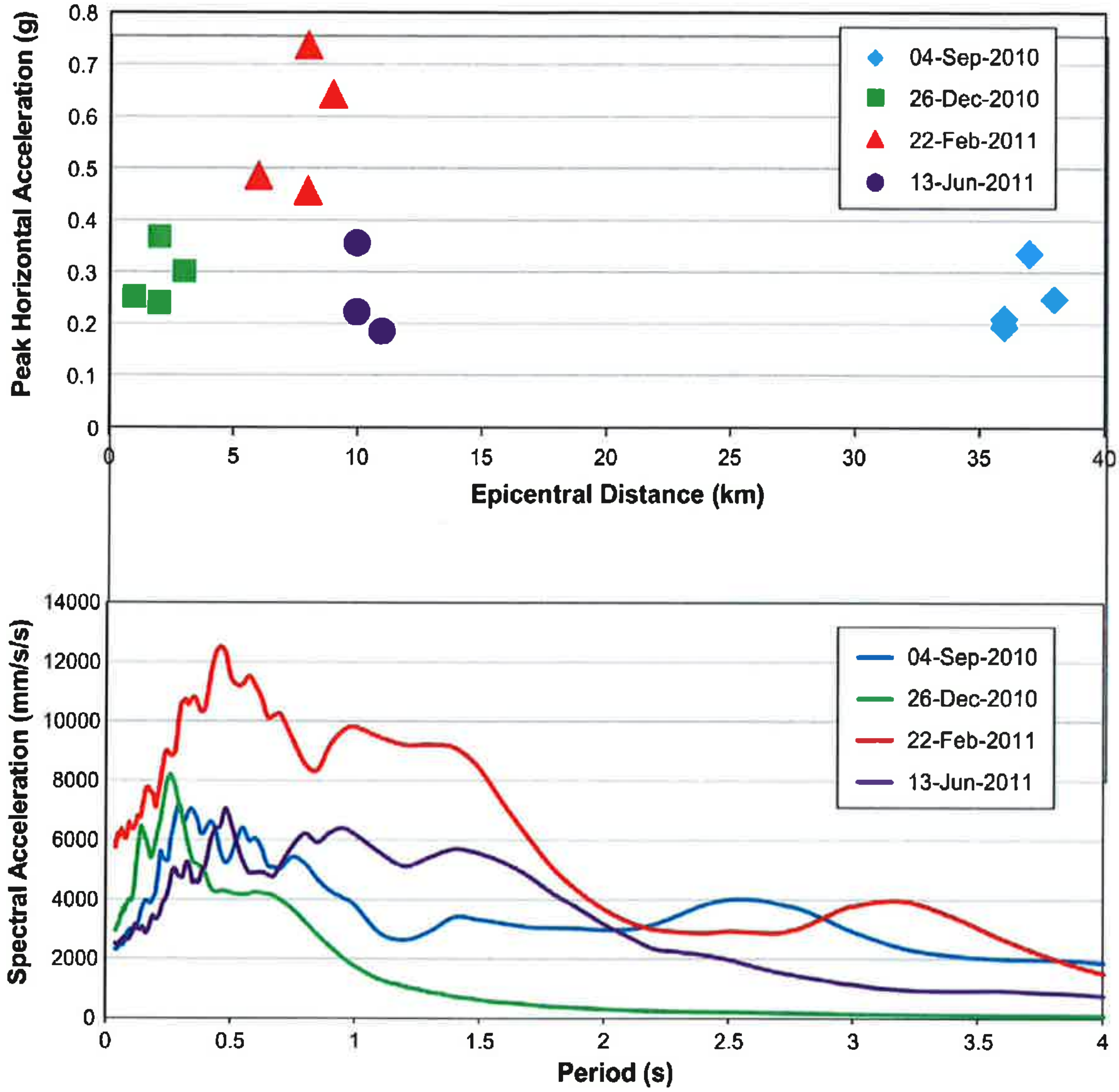

Figure 3.16 Top: Peak horizontal ground accelerations recorded at CBD stations. Recording locations include CBGS (Botanic Gardens), REHS (Resthaven), CHHC (Christchurch Hospital) and CCCC (Catholic Cathedral College). The June 13 earthquake was not recorded by the CCCC site. Bottom: Peak response-spectral accelerations averaged over the CBD recording sites.