The Canterbury Earthquake sequence and implications for Seismic Design Levels

T. H. Webb (Compiler)

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T. H. Webb (Compiler)
J. Beavan
H. Brackley
B. Fry
C. Holden
E. McSaveney
J. Pettinga
D. Rhoades
M. Stirling
P. Villamor
J. Zhao
S. Bannister
K. Berryman
J. Cousins
M. Gerstenberger
A. Kaiser
G. McVerry
M. Reyners
P. Somerville
R. Van Dissen
L. Wallace

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NOTE

This report has been commissioned by the Canterbury Earthquakes Royal Commission to provide information on seismicity. The report includes commentary on seismic hazard models. These models are mathematically based statistical models that produce probabilities as to ground shaking from future earthquakes. Although all reasonable effort is made to construct robust models there is uncertainty inherent within the nature of natural events. For this reason, neither GNS Science nor the University of Canterbury can accept responsibility for any actions taken based on the modelling and excludes liability for any loss, damage or expense in any way resulting from those actions.

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[1]GNS Science, PO Box 30368, Lower Hutt
[2]Department of Geological Sciences, University of Canterbury, PO Box 8140 Christchurch
[3]URS Corporation, 915 Wilshire Boulevard, Suite 700, Los Angeles, CA 90017-3437, USA

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EXECUTIVE SUMMARY

New Zealand straddles the boundary zone between the Australian and Pacific tectonic plates, which are moving relative to each other at 35–45 mm/yr. In the North Island, the plates are converging, and the relatively thin ocean crust of the Pacific Plate dives down westward beneath the eastern North Island just offshore of the east coast. Similarly offshore of Fiordland the thin ocean crust of the Australian Plate is diving eastward beneath Fiordland.

In the central and northern South Island, however, the crust of both the Pacific and Australian plates is very thick, so one cannot be driven beneath the other. Here the plates collide, with 75% of the motion between the plates being built up and then released during major earthquakes along the Alpine Fault. To the east of the Alpine Fault, the remaining 25% of the plate motion occurs through occasional earthquakes on a complex web of active faults This motion extends all the way to the east coast, where faults such as those beneath the Canterbury Plains accommodate 1–2 mm/yr of the overall plate motion. It is inevitable that this steady build-up of deformation across the Canterbury Plains will occasionally be released as earthquakes.

Because it straddles a major plate boundary, New Zealand has a long history of earthquakes ranging from tiny tremors detectable only by sensitive instruments to violent earthquakes causing major damage and many fatalities. The more powerful earthquakes have occurred at irregular intervals, separated by relatively quiescent periods. Since European settlement of the Canterbury Plains began in 1853, Christchurch has experienced intermittent damage from earthquake shaking on about 10 occasions. However, before the earthquakes in 2010 and 2011, few of these damaging earthquakes were local—more frequently, damage was caused by shaking from large earthquakes on more distant faults.

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 magnitude 7.1 earthquake (the Darfield earthquake). 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 earthquake occurred on a previously unknown fault within the Canterbury Plains and left a well-defined surface rupture that has been named the Greendale Fault. This was a rare event, occurring in an area where previous seismic activity was relatively low for New Zealand. Since the Darfield earthquake, more than 7,000 aftershocks with magnitudes up to 6.2 have been recorded. These earthquakes are termed the Canterbury earthquake sequence.

A magnitude 4.7 event occurred 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.

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 magnitude 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.

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. 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 ground accelerations were recorded in the Christchurch earthquake, a factor which led to the severe building damage, widespread liquefaction and landslides. Notable were the strong vertical accelerations that exceeded the horizontal motions at some locations. The February 22 earthquake led to an increase in aftershocks, with four of magnitude 5 or more occurring that day.

On 13 June 2011 a magnitude 6.0 earthquake occurred near the suburb of Sumner. 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 Canterbury earthquake sequence has included a mixture of sideways (strike-slip) and vertical (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 has been a principal factor in determining how much shaking has been experienced. All of the three largest events have released high levels of energy for their size. It is thought that this is because the faults involved slip very occasionally and so are very strong.

Focussing of the seismic shaking, arising from the direction of rupture along the fault (known as directivity), is thought to have increased the severity of ground motions experienced in central Christchurch during the September and February earthquakes, but did not play a strong role in the Boxing Day or June earthquakes for the CBD area.

Overall there is a close match between the amounts of damage caused by the earthquakes and the horizontal ground shaking. Recordings of particular note were those from sites close to the CBD where 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 over 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 (displacements are another important ground motion measure, especially in the case of tall buildings).

At certain recording sites in the Christchurch CBD, shaking from the three largest earthquakes exceeded both the 500-year and more stringent 2,500-year design levels in the New Zealand Loadings Standard for certain frequencies of shaking.

The level of seismic hazard in Canterbury is currently higher than normal because of the numerous aftershocks that are occurring. In addition, there is a slight possibility that an earthquake of a size comparable to the main shock might be triggered. This elevated level of hazard needs to be considered when reassessing the safety of existing structures and when designing new buildings and infrastructure. In order to provide appropriate seismic design coefficients, a new seismic hazard model has been developed for Canterbury that reflects this increased level of hazard, taking into account likely rates of aftershocks, the small likelihood of larger earthquakes and the normal background seismicity and fault sources. The enhanced ground shaking observed from the February and June 2011 earthquakes has also been incorporated. The new model (which is still being developed) raises the Z factor (or regional design level) from 0.22 to 0.3 for Christchurch (Wellington's value is 0.4).

The Alpine Fault is a major geological feature in New Zealand, being 650 km long and crossing the South Island from northeast to southwest. The average return period of the fault is in the range 260–400 years, with no major event occurring in the last 294 years. It is a potential source of earthquakes up to magnitude 8.2. An Alpine Fault earthquake, however, would be at its closest 160 km from Christchurch. Some preliminary work to estimate the ground motions in Christchurch from such an event is presented here. These motions were calculated for very soft ground conditions, as are found in the Christchurch CBD and indicate that the maximum horizontal acceleration would be less than 0.04 g (compared to 0.4–0.8 g in February), but the duration of shaking could be at least 3 minutes.

The National Seismic Hazard Model for New Zealand is used to predict likely long-term rates of ground shaking to inform the Loadings Standard used in engineering design. Key components of this model are the earthquake sources (where earthquakes are likely to happen) and the ground motions that those earthquakes are likely to produce. In light of the lessons from Christchurch, the next update to this model will need to assess the importance of such factors as unknown faults close to major cities, enhanced ground shaking from a given earthquake and directivity in the ground shaking produced.

For evaluating the risk of earthquakes occurring close to cities, it is impossible to identify all active faults in a region because the relatively small faults associated with magnitude 6 earthquakes often have no surface expression so are particularly difficult to find. For this reason, the national model uses additional background earthquake sources of up to magnitude 7.2 to supplement existing active fault information. This assumes that an earthquake of up to magnitude 7.2 could occur on an unrecognized fault nearly anywhere in New Zealand, although the likelihood of this happening in low seismicity areas of the country is very small. Given this uncertainty, we need to be sure that the shaking from such earthquakes is correctly accounted for.

The unusually strong shaking observed from some of the larger Canterbury earthquakes can be allowed for in hazard models, providing we can anticipate where such events will occur. Current thinking is that they are likely to occur in areas with a low deformation rate, where faults seldom rupture and, as a result, are strong.

Fault directivity effects are already incorporated in the national hazard model (and building designs) for some of our major active faults. However, if directivity is shown to have been a major factor in enhancing the shaking produced by the 22 February 2011 earthquake, consideration will need to be given to including directivity for smaller earthquakes. Directivity effects can also be included in building design if sufficient variability in shaking is allowed for. In the light of the extreme vertical accelerations that were generated by the 22 February 2011 earthquake, the approach to designing for vertical motions in the Loadings Standard also needs to be re-evaluated.

1.0 INTRODUCTION

The Canterbury Earthquakes Royal Commission is inquiring into the performance of buildings within the Christchurch CBD, and the adequacy of the current legal and best practice requirements for the design, construction, and maintenance of buildings in CBD's in New Zealand to address the known risk of earthquakes. The Commission has requested GNS Science to provide a report on the seismicity of the Canterbury region, as background information for their inquiry. This report has been prepared jointly by GNS Science and the University of Canterbury and includes input from GNS Science earthquake specialists, Jarg Pettinga from the University of Canterbury and Paul Somerville from the URS Pasadena office. The report also draws on the work of many other scientists and this is cited in the appropriate places in the text.

The scope of this report is firstly to provide background information on New Zealand and, more specifically, Canterbury earthquakes by describing plate tectonic process, rates of deformation of the earth, types of earthquake faulting that occurs and, as a consequence, significant historical earthquakes that have affected New Zealand and Christchurch.

We then look in detail at the four principal earthquakes from the Canterbury earthquake sequence, starting with the magnitude 7.1, 4 September 2010 event, then the M4.7 Boxing Day event, the devastating M 6.3, 22 February 2011 event and finally the M 6.0, 13 June 2011 event. For each event we examine the nature of the fault rupture, likely recurrence intervals, extent and severity of ground shaking, and how the ground shaking measurements fit with current models used to inform engineering design.

Next we look at two specific implications for Christchurch, namely the current level of seismic hazard due to aftershocks and the likely ground motions from a future Alpine Fault earthquake.

Finally, we look at the national implications of the Canterbury earthquake sequence in terms of where else such unexpectedly damaging earthquakes could occur and how large they could be. We then consider the implications for the National Seismic Hazard Model that underpins New Zealand building codes, and hence the engineering design of all major structures.

In general we have tried to make this report intelligible to the lay reader, but as this is a specialised and, at times, complex subject, we have used Appendices for more detailed or more complex topics. In the main body of the text we use numerous references to published scientific papers, which are more relevant to technical readers. Three of these papers deserve specific mention, and should be regarded as companion papers to this report. Firstly, Stirling *et al.* (2011) describe in detail the most recent update to the National Seismic Hazard Model, an earlier version of which underpins the current New Zealand Loadings Standard NZS 1170. Secondly, a GNS Science Report by Gerstenberger *et al.* (2011) describes the basis for an initial change to construction standards for Christchurch in light of the increased seismic hazard due to aftershocks. Finally, a GNS Science Report by Holden and Zhao (2011) describes recent modelling of an Alpine Fault rupture and the likely shaking it will produce in Christchurch.

Much of what is presented here should be regarded as 'work in progress'. It will take a number of years for earthquake scientists to analyse and fully understand the implications of all the data collected in the aftermath of the Canterbury earthquake sequence, whereas the Royal Commission has to report on a much tighter timeframe. What we present here must thus be regarded as preliminary findings that will be subject to change as the results from more analysis and detailed peer review prior to publication become available.

2.0 BACKGROUND

2.1 New Zealand—where two tectonic plates meet

The outermost layer of the Earth is called the 'crust' and it varies in thickness from ~10–50 km. Like a cracked eggshell, the crust is broken into several large segments, or tectonic plates, which are continually moving relative to each other. At the edges of these tectonic plates, they either pull apart (in 'rift' areas), slide past each other laterally (known as a 'strike-slip' plate boundary), or the plates can converge (in 'subduction' or 'collision' areas). Most of the world's earthquakes and volcanoes occur along the boundaries of these tectonic plates. The largest and fastest-moving major tectonic plate on Earth is the Pacific Plate, and its boundary, the Pacific Rim (also known as the 'Ring of Fire'), is well-known for its earthquake and volcanic activity. The earthquake and volcanic activity we experience in New Zealand results from the Pacific Plate grinding into the adjacent Australian Plate as the two plates continue their steady and inexorable march across the Earth.

New Zealand straddles the boundary zone between the Australian and Pacific Plates, which are moving relative to each other at 35–45 mm/yr (Fig. 2.1). In the North Island, the plates are converging, and the relatively thin ocean crust of the Pacific Plate dives down or 'subducts' westward beneath the eastern North Island along the Hikurangi Trough just offshore of the east coast. Subduction also occurs offshore of Fiordland, except here the thin ocean crust of the Australian Plate is diving eastward beneath Fiordland along the offshore Puysegur Trench.

In the central and northern South Island, however, the crust of both the Pacific and Australian plates is very thick, so one cannot be driven beneath the other. Here the Australian and Pacific plates meet in a glancing collision, so the continuous movement of the plates must be 'accommodated'—the rock moving toward the plate boundary must have somewhere to go. This occurs in two ways. One way is by sideways slip along the boundary, with the west coast moving north-eastward relative to the rest of the South Island at a rate of ~30 mm/yr. In addition to this sideways movement, the Pacific and Australian plates collide head-on at ~5–10 mm/yr (Beavan *et al.*, 2002). Unable to move directly forward, the edge of the Pacific Plate is being forced upward, leading to the growth of the Southern Alps over the last few million years. Repeated GPS measurements of plate tectonic movement throughout New Zealand (from the 1990's to present) show that most of the South Island is being continually contorted as it is forced southwestward into the Australian Plate (Fig. 2.2).

In the central South Island most (~75%) of the 35–45 mm/yr of motion between the Australian and Pacific plates occurs during major earthquakes along the Alpine Fault (Berryman *et al.*, 1992; Norris and Cooper, 2001). However, the land to the east of the Alpine Fault is also broken up into a complex web of active geological faults—here the remaining 25% of the plate motion occurs through occasional earthquakes on these faults. For example, along the eastern foothills of the Southern Alps and within the Southern Alps themselves there are a number of faults that may accommodate up to ~20% of the plate boundary deformation (Cox and Sutherland, 2007; Pettinga *et al.*, 2001, Wallace *et al.*, 2007).

The collision between the Australian and Pacific Plates is so intense in the central South Island that the slow tectonic deformation it causes penetrates all the way to the east coast of the South Island. GPS measurements suggest that faultlines beneath the Canterbury Plains region are accommodating ~5% of the overall Pacific/Australia plate motion, ~1-2 mm/yr on average (Wallace *et al.*, 2007). It is inevitable that this steady build-up of ground deformation across the Canterbury Plains will occasionally be released as earthquakes.

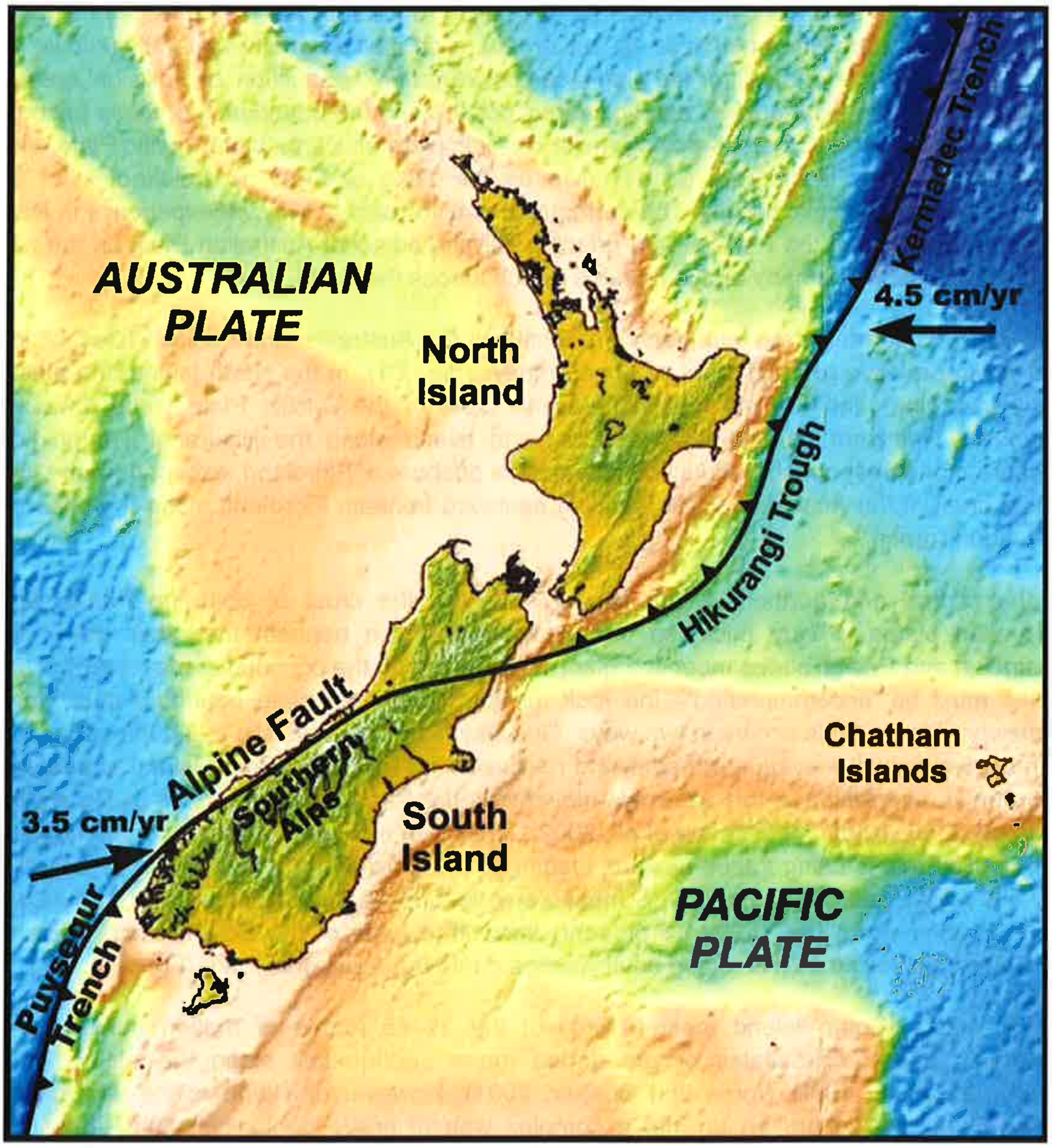

Figure 2.1 Plate tectonic setting of New Zealand. The westward pointing arrow in the upper, right corner shows movement of the Pacific Plate towards the Australian Plate in northern New Zealand, while the north-eastward pointing arrow in the lower left shows the movement of the Australian Plate relative to the Pacific Plate in southern New Zealand.

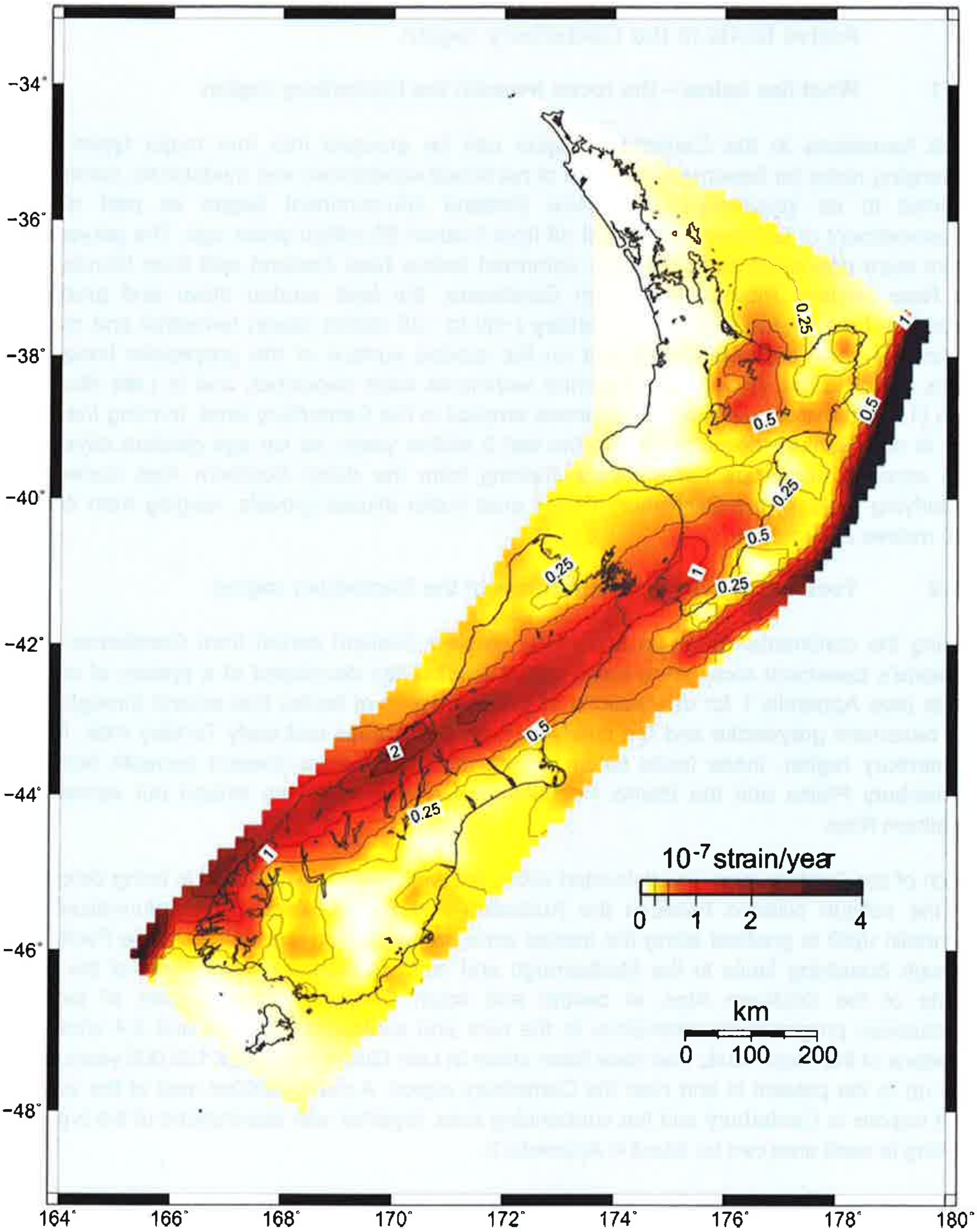

Figure 2.2 Over the last 15 years it has become possible to measure the deformation (strain) occurring in New Zealand directly by satellite surveying using GPS. The dark to red areas have the highest rates of deformation, while the land in the yellow to orange areas are deforming at relatively lower rates. Accumulation of strain in the New Zealand crust will eventually result in earthquakes, so areas with a high strain rate tend to have more earthquakes. Major faults such as the Alpine Fault have extremely high strain rates.

2.2 Active faults in the Canterbury region

2.2.1 What lies below – the rocks beneath the Canterbury region

Rock formations in the Canterbury region can be grouped into four major types. The underlying rocks (or basement) is made of hardened sandstones and mudstones, commonly referred to as 'greywacke'. The New Zealand sub-continent began as part of the supercontinent of Gondwana and split off from it about 85 million years ago. The greywacke rocks were deposited and complexly deformed before New Zealand split from Gondwana. As New Zealand moved away from Gondwana, the land eroded down and gradually subsided. Late Cretaceous to mid-Tertiary (~80 to ~25 million years) terrestrial and marine sediments were deposited; they rest on the eroded surface of the greywacke basement rocks. Later in the Tertiary more marine sediments were deposited, and in Late Miocene time (11 to 6 million years ago) volcanoes erupted in the Canterbury area, forming the area that is now Banks Peninsula. During the last 2 million years, as ice age glaciers advanced and receded numerous times, rivers draining from the rising Southern Alps buried the underlying rocks of the Canterbury Plains area under alluvial gravels, ranging from 200 to 600 metres in thickness.

2.2.2 Tectonic activity and fault zones of the Canterbury region

During the continental break-up and rifting as New Zealand parted from Gondwana, New Zealand's basement rocks were being pulled apart. They developed of a system of normal faults (see Appendix 1 for descriptions of different types of faults) that extend through both the basement greywacke and the overlying Late Cretaceous and early Tertiary rock. In the Canterbury region, these faults today are an inherited feature present beneath both the Canterbury Plains and the Banks Peninsula volcanoes, and they extend out across the Chatham Rise.

Much of the Canterbury region is located within the wide zone in which land is being deformed by the oblique collision between the Australian and Pacific plates. The deformation and mountain uplift is greatest along the narrow zone on and just to east of the Alpine Fault, and through branching faults in the Marlborough and north Canterbury areas. East of the main divide of the Southern Alps, in central and south Canterbury, the amount of tectonic deformation progressively diminishes to the east and southeast. Figs 2.3 and 2.4 show the locations of the major faults that have been active in Late Quaternary (past 125,000 years) time and up to the present in and near the Canterbury region. A more detailed map of the various fault regions in Canterbury and the surrounding area, together with descriptions of the types of faulting in each area can be found in Appendix 2.

An *active fault* is one that is likely to move within a period of concern to society. For the Canterbury region, a fault is considered active if there is evidence it has moved within the last 125,000 years. More than one hundred such active fault structures are recognised in the Canterbury region. Details of all known faults considered as possible earthquake sources are included in the GNS Science active fault database.

2.2.3 The spread of faulting into the Canterbury Plains

In the eastern foothills of the Southern Alps and North Canterbury hill country, NE-SW oriented faults and folds have been active over the last ~5 million years (e.g., Springbank and Hororata faults, Fig. 2.4). However, the zone of deformation at the Australia-Pacific plate boundary has been progressively widening during the last 1–2 million years and current activity indicates that this spread is continuing today. Across the Canterbury Plains and offshore regions, faults running broadly E-W indicate that current plate movement is re-activating the inherited subsurface faults. New surface faults have developed, such as the Ashley and Greendale faults. Since September 2010, patterns of aftershocks, including the February and June 2011 earthquakes, have revealed the existence of further previously unrecognized subsurface faults, including faults extending under Banks Peninsula and into Pegasus Bay.

However, because the alluvial gravels of the Canterbury Plains have remained largely undisturbed until the September 2010 Darfield earthquake, it can be inferred that movements along the inherited faults under the Canterbury Plains causing large earthquakes are generally rare and separated in time by long periods of quiescence extending over thousands of years.

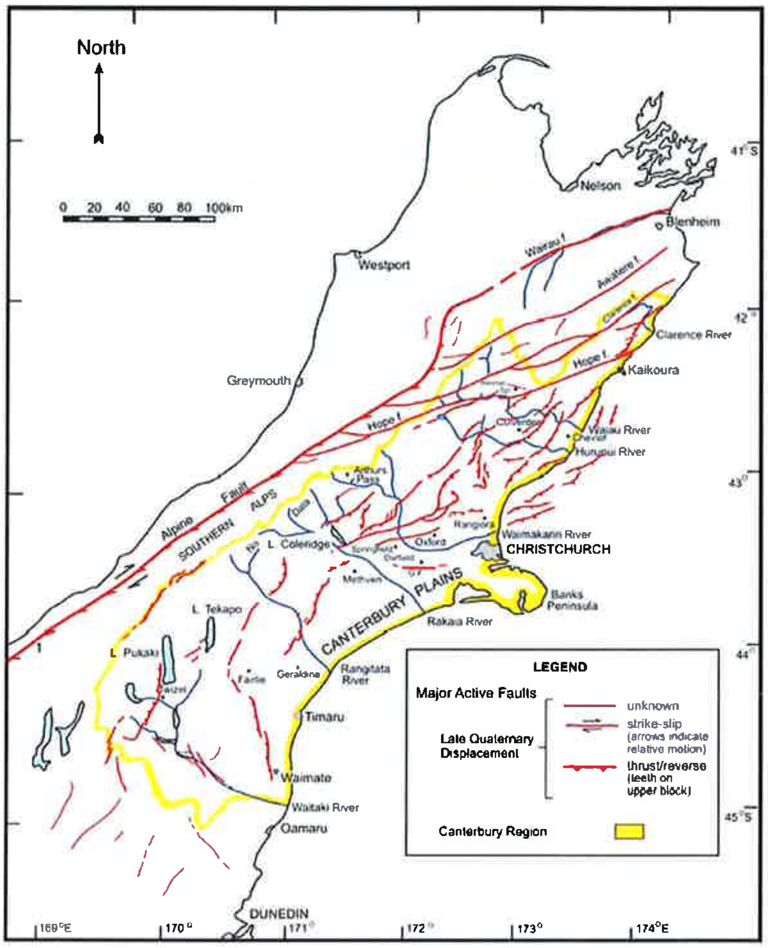

Figure 2.3 Map of the known active faults in the Canterbury region, including the recently formed Greendale fault (G.F.). Figure modified from Pettinga *et al.* (1998).

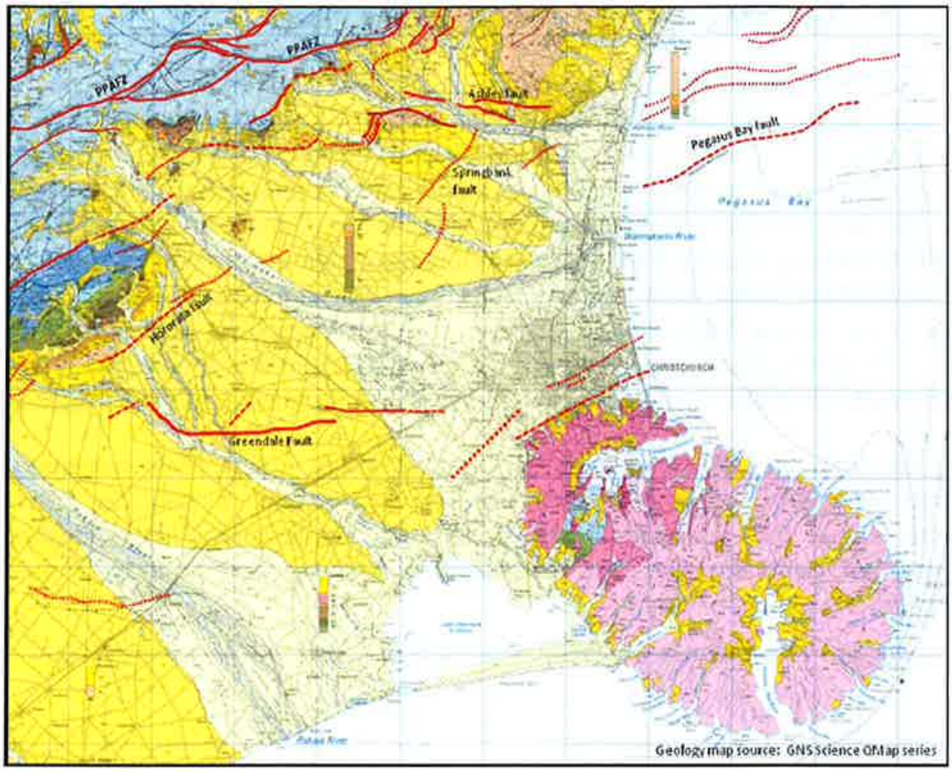

Figure 2.4 General geological setting of the northern Canterbury Plains. Active faults are shown in red (PPAFZ - Porters Pass-Amberley fault zone). The faults shown by dashed/dotted lines are uncertain in location or extent because they do not reach the surface. Base geological map from Forsyth *et al.* (2008).

2.3 Previous major earthquakes in New Zealand history

Because it straddles a major plate boundary, New Zealand has a long history of earthquakes ranging from tiny tremors detectable only by sensitive instruments to violent earthquakes causing major damage and many fatalities. Fig. 2.5 shows the distribution of earthquakes of magnitude 6.5 or greater, from the beginning of European settlement to the present time. These more powerful earthquakes have occurred at irregular intervals, separated by relatively quiescent periods. Brief summaries of many of the major earthquakes during this period can be found in Appendix 3.

Māori oral history includes accounts of large earthquakes, and arriving European colonists soon found that New Zealand was disturbingly shaky. Between 1840 and 1904 there were at least seven earthquakes of magnitude 7 or greater. One of them, the magnitude 8.2 Wairarapa earthquake in 1855, still ranks as New Zealand's most powerful earthquake in recorded history.

Few damaging earthquakes of magnitude 7 or greater occurred between 1905 and 1928. The years from 1929 to 1947, however, were marked by a substantial increase in earthquake activity, including a cluster of five magnitude 7 earthquakes in the three-year period from 1929 to 1931. Two of these earthquakes were responsible for a number of fatalities—17 people died in the 1929 Buller (Murchison) earthquake and 256 people in the 1931 Hawkes Bay (Napier) earthquake.

The latter half of the twentieth century in New Zealand was once again a relatively quiet period for earthquake activity, with just a few large magnitude earthquakes, most too far offshore to cause much damage. The beginning of the 21st century, however, has seen an increase in the number of magnitude 7 earthquakes, including several in the remote Fiordland area. The September 2010 Canterbury earthquake was magnitude 7.1, but the February 2011 magnitude 6.3 Christchurch earthquake caused considerably more damage.

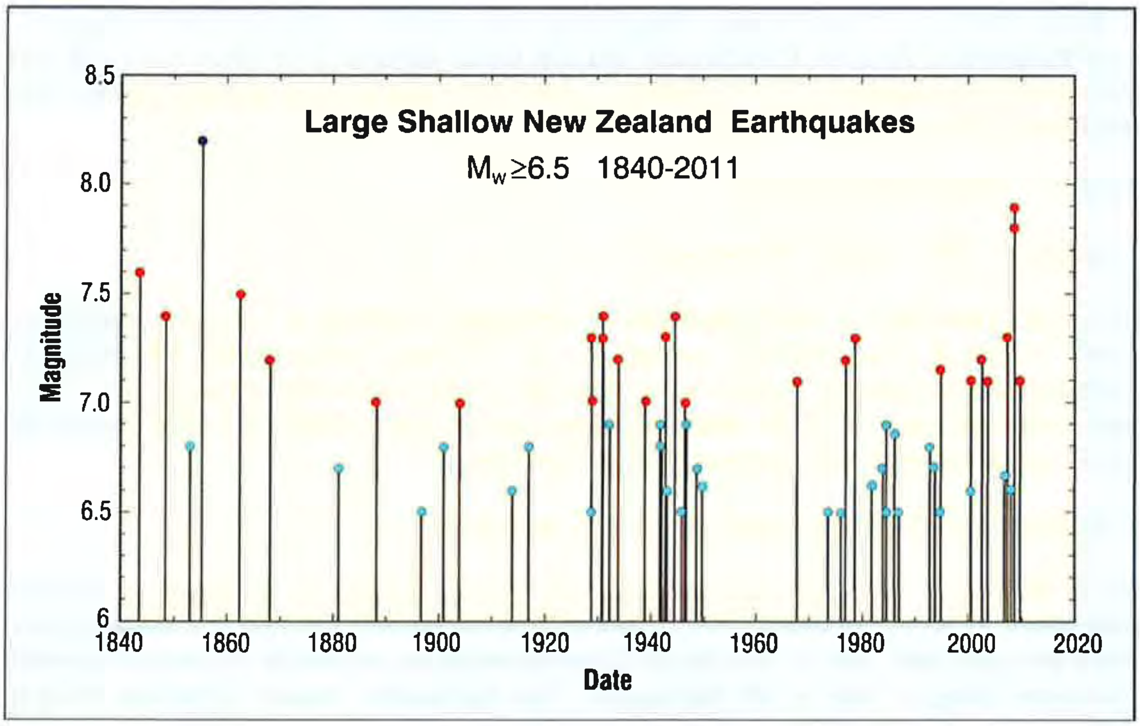

Figure 2.5 Diagram showing the distribution of earthquakes of magnitude 6.5 or greater from 1840 to the present. Some of the large earthquakes occurred too far offshore to cause any damage on land.

2.4 Previous earthquakes affecting Christchurch

Since organised European settlement of the Canterbury Plains began in 1853, Christchurch has experienced intermittent damage from earthquake shaking. However, before the earthquakes in 2010 and 2011, few of these damaging earthquakes were local—more frequently, damage was caused by shaking from large earthquakes on more distant faults.

2.4.1 Local earthquakes

The two earliest damaging earthquakes experienced in Christchurch, in 1869 and 1870, had epicentres in the local region.

5 June 1869 – Christchurch earthquake

On 5 June 1869, Christchurch settlers were shaken by an earthquake centred beneath the city, probably around the Addington-Spreydon area, with a magnitude of about 4.7–4.9. The earthquake was shallow, with most damage in the CBD, and nearby Avonside, Linwood, Fendalton and Papanui. There was minor damage to stone buildings and the tower of St John's Church on Latimer Square, and many fallen chimneys. The quake may have caused some ground settlement in the Heathcote Estuary, as the tide was described as running higher up the Heathcote River afterward.

31 August 1870 –Lake Ellesmere earthquake

On 31 August 1870 the Canterbury region was shaken by an earthquake with an estimated magnitude of 5.6–5.8, at shallow depth (< 15 km), centred near Lake Ellesmere, southwest of Banks Peninsula. It was felt over a larger area than the 1869 earthquake, with damage to brick buildings in Temuka. Christchurch had just minor damage, with fallen chimneys and minor structural damage to a few buildings. Lyttelton and Akaroa were strongly shaken, with rocks falling from cliffs around Lyttelton Harbour.

2.4.2 Distant earthquakes

5 December 1881 – Castle Hill earthquake

On 5 December 1881 an earthquake with an estimated magnitude of 6.0 shook the central South Island; it was probably centred in the Torlesse Range-Castle Hill area. In Christchurch, the shaking caused minor damage to stone and brick buildings, and there were broken windows and a few fallen chimneys. The spire of Christchurch Cathedral had its first recorded damage, losing some pieces of stonework.

1 September 1888 – North Canterbury (Amuri) earthquake

On 1 September 1888, the northern South Island was shaken by a magnitude 7.0–7.3 earthquake in North Canterbury Amuri District. The earthquake resulted in surface rupture along the Hope fault—one of the first documented examples worldwide of horizontal ground movement along a fault in an earthquake. The earthquake caused extensive building damage, landslides and liquefaction of river terrace sediments in the Amuri District. In Christchurch, the top 8 metres of the stone spire of Christchurch Cathedral collapsed during the quake. There was some damage to stone buildings and chimneys, and minor rock-falls occurred around Lyttelton Harbour.

16 November 1901 – Cheviot earthquake

On 16 November 1901 an earthquake centred near Cheviot, with an estimated magnitude of 6.8, struck the Canterbury area. Most brick and sod buildings in Cheviot collapsed. Christchurch had many broken windows, cracked stonework and toppled chimneys, and Christchurch Cathedral lost the top 1.5 metres of its spire. The quake also caused some liquefaction in Kaiapoi, affecting 2-3 town blocks.

25 December 1922 – Motunau earthquake

Remembered for many years as the Christmas Day Earthquake, a magnitude 6.4 earthquake occurred on 25 December 1922 near Motunau. The earthquake damaged many chimneys from Cheviot to Christchurch and caused minor structural damage. The large stone cross on Christchurch Cathedral spire fell to the ground, breaking some slate roof tiles. Liquefaction was described at Waikuku and Leithfield beaches.

9 March 1929 – Arthur's Pass earthquake

On 9 March 1929, the Arthur's Pass National Park area was shaken by a magnitude 7.0 earthquake along the Poulter fault. The earthquake caused many landslides and closed the main highway to the West Coast for several months. In Christchurch damage was very minor, with some damage to the north wall and oriel window of the Provincial Council Chambers.

16 June 1929 – Buller (Murchison) earthquake

The Buller earthquake, centred near Murchison, had a magnitude of 7.3 and was one of the stronger earthquakes in New Zealand history. It was far enough away to cause only minor damage to a few chimneys and windows in Christchurch.

9 March 1987- Pegasus Bay earthquake

On 9 March 1987, a magnitude 5.2 earthquake centred out in Pegasus Bay about 50 kilometres northeast of New Brighton damaged some chimneys in North Canterbury and cracked paving in the New Brighton area.

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.

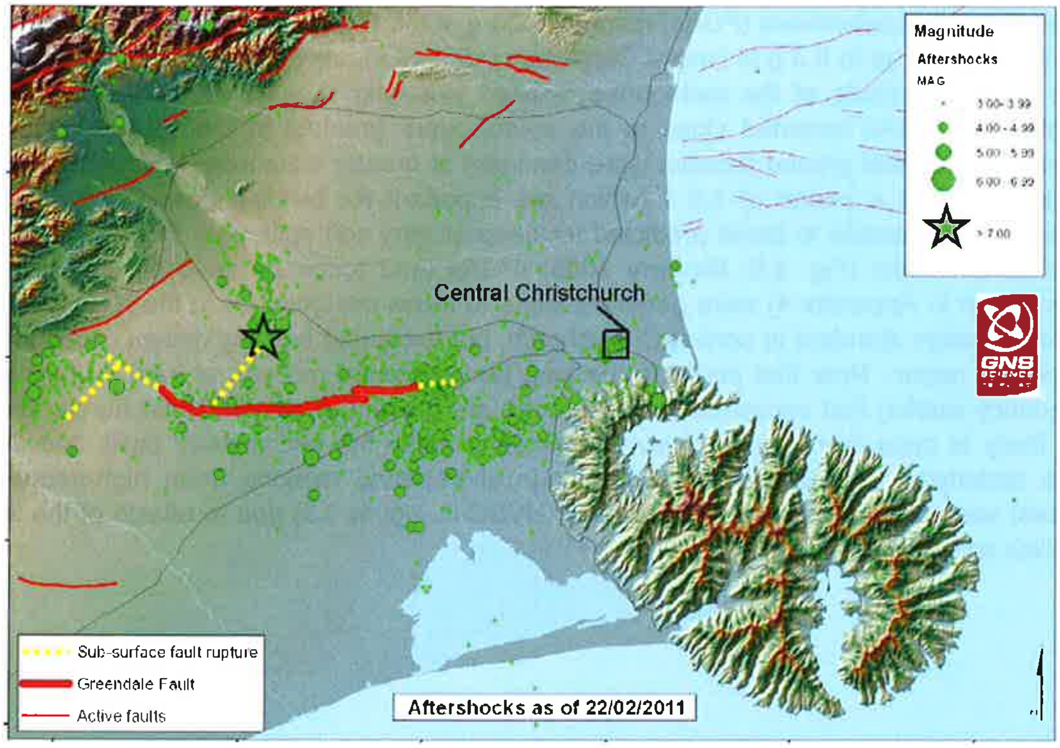

Figure 3.1 Earthquakes of the Canterbury sequence through 21 February 2011. The 4 September 2010 Darfield main shock rupture initiated at the location of the green star. The Boxing Day event occurred in the cluster below central Christchurch.

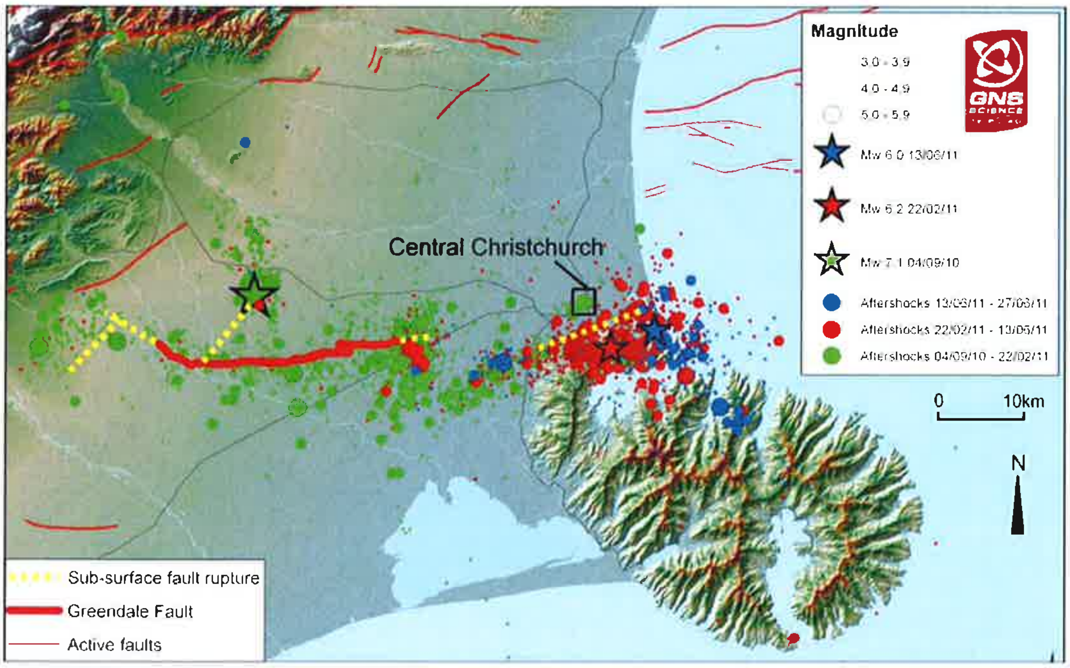

Figure 3.2 Earthquakes of the Canterbury sequence through 27 June 2011. Major earthquakes are shown as stars, including the September 2010 Darfield main shock (green), the February (red) and June (blue) 2011 Christchurch earthquakes.

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.

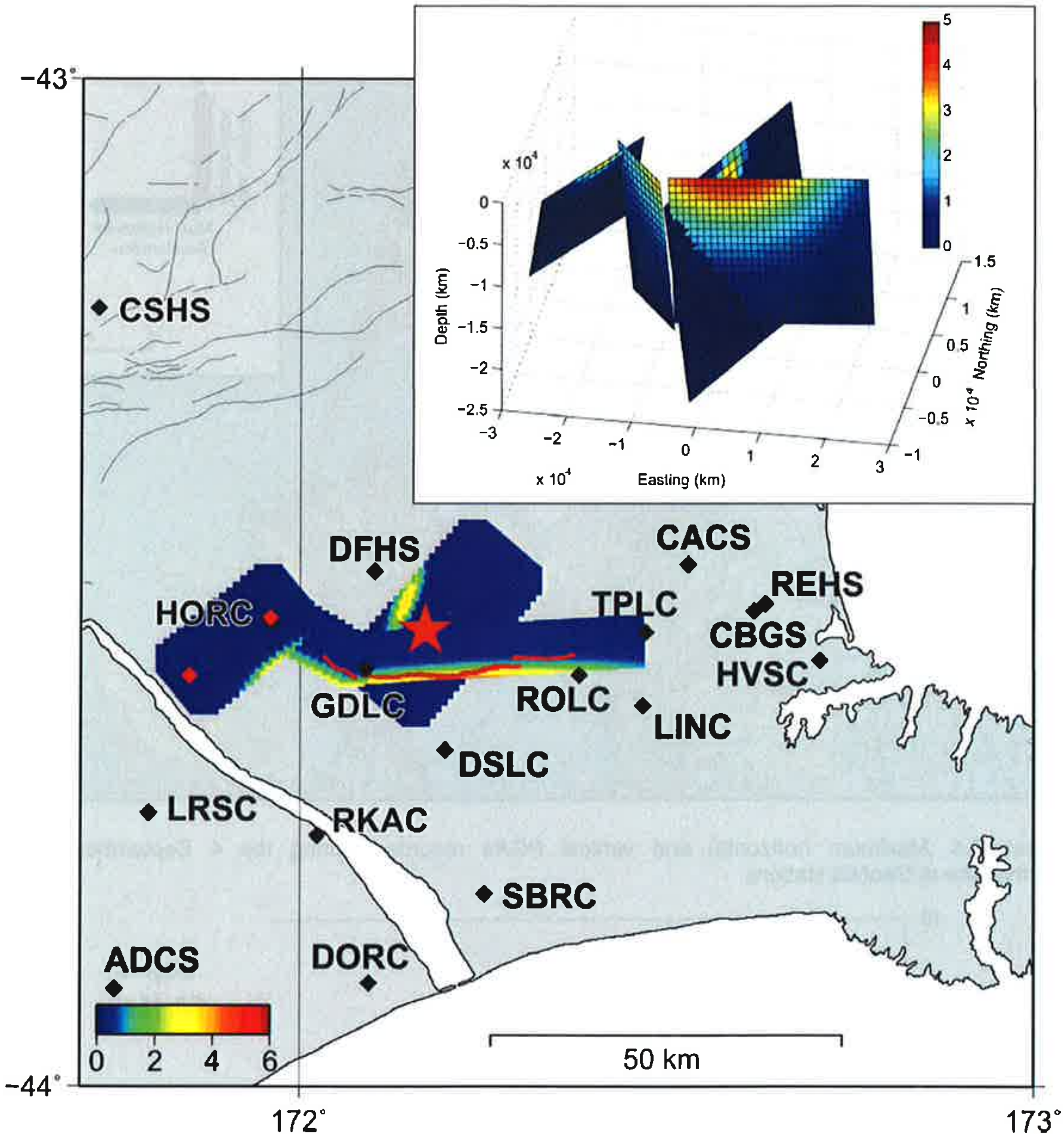

Figure 3.3 This model for the Darfield earthquake based on seismological data shows the complex earthquake rupture (Holden, 2011). The map shows the surface projection of the slip from the 3D fault rupture model, strong motion stations (four-letter labels), the mapped surface trace (red) and the Darfield 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).

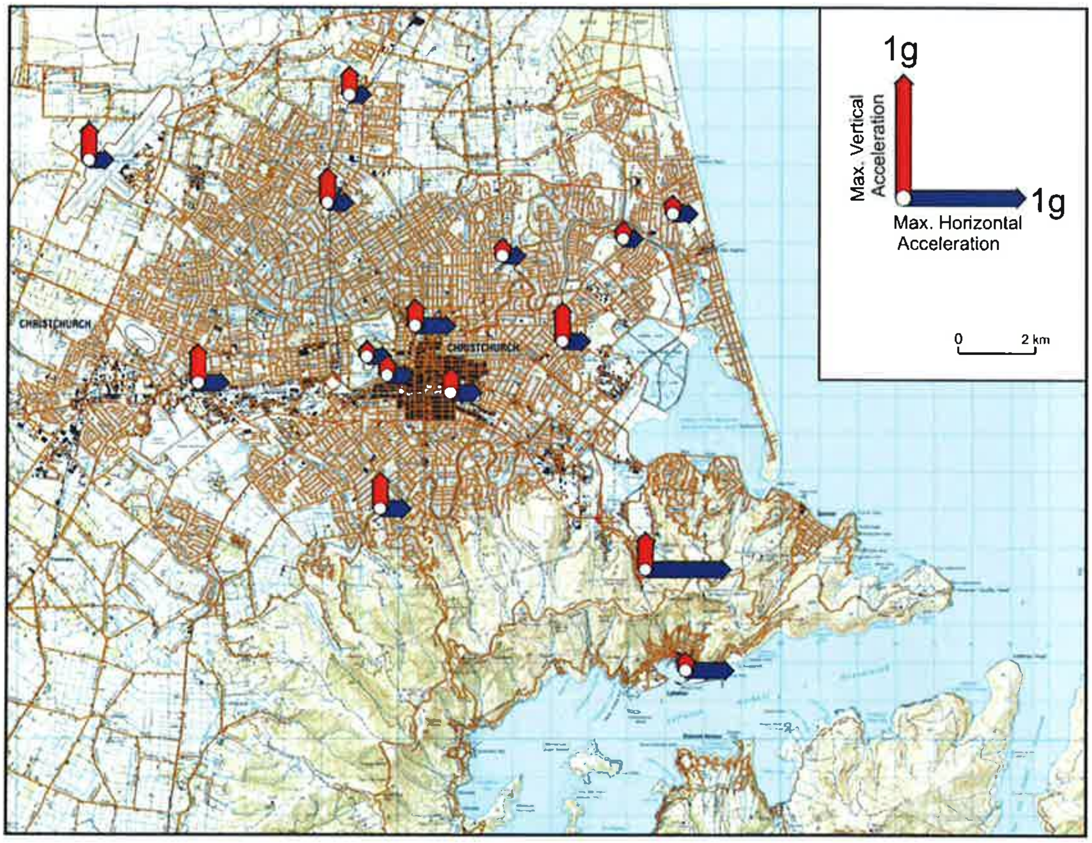

Figure 3.4 Maximum horizontal and vertical PGAs recorded during the 4 September 2010 earthquake at GeoNet stations.

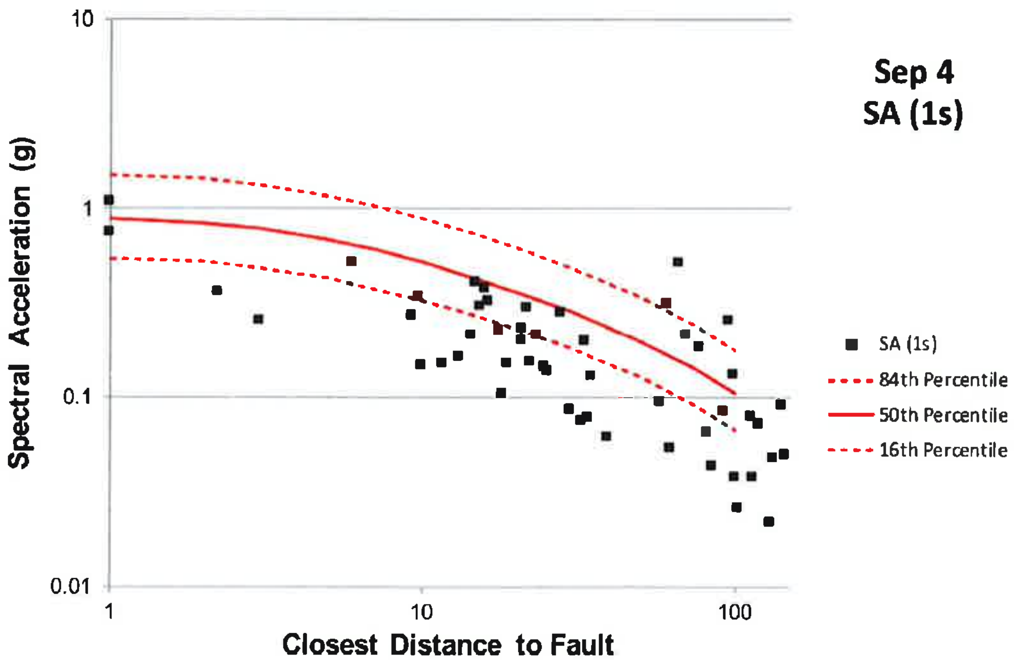

Figure 3.5 Observed spectral accelerations at 1.0 s during the Darfield earthquake (black squares) compared to those predicted from the national attenuation model for deep or very soft soils (solid red line; McVerry *et al.*, 2006).

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.

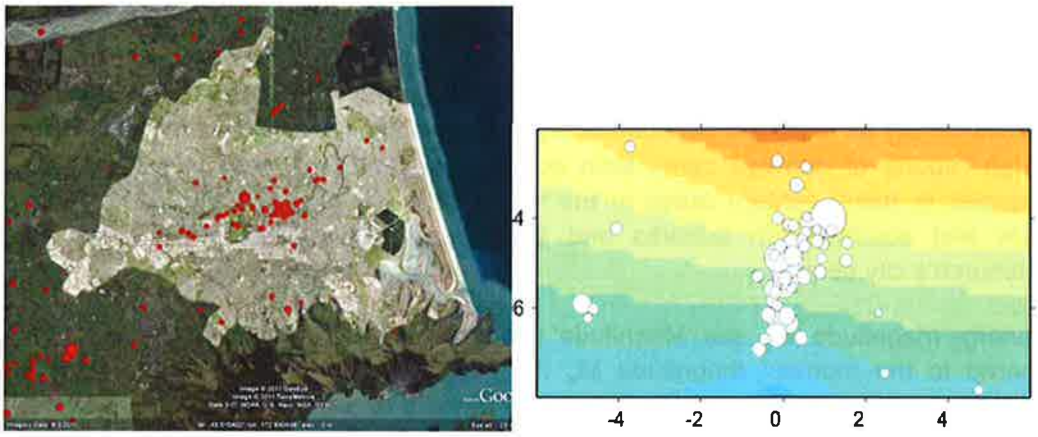

Figure 3.6 Left: Locations of earthquakes (catalogued by GeoNet) that occurred beneath Christchurch city between 25/12/2010 (00:00 UTC) and 5/2/2011 (23:59 UTC). Right: Cross-section showing precise earthquake locations that are clustered around the fault plane of the Boxing Day earthquake (Bannister,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

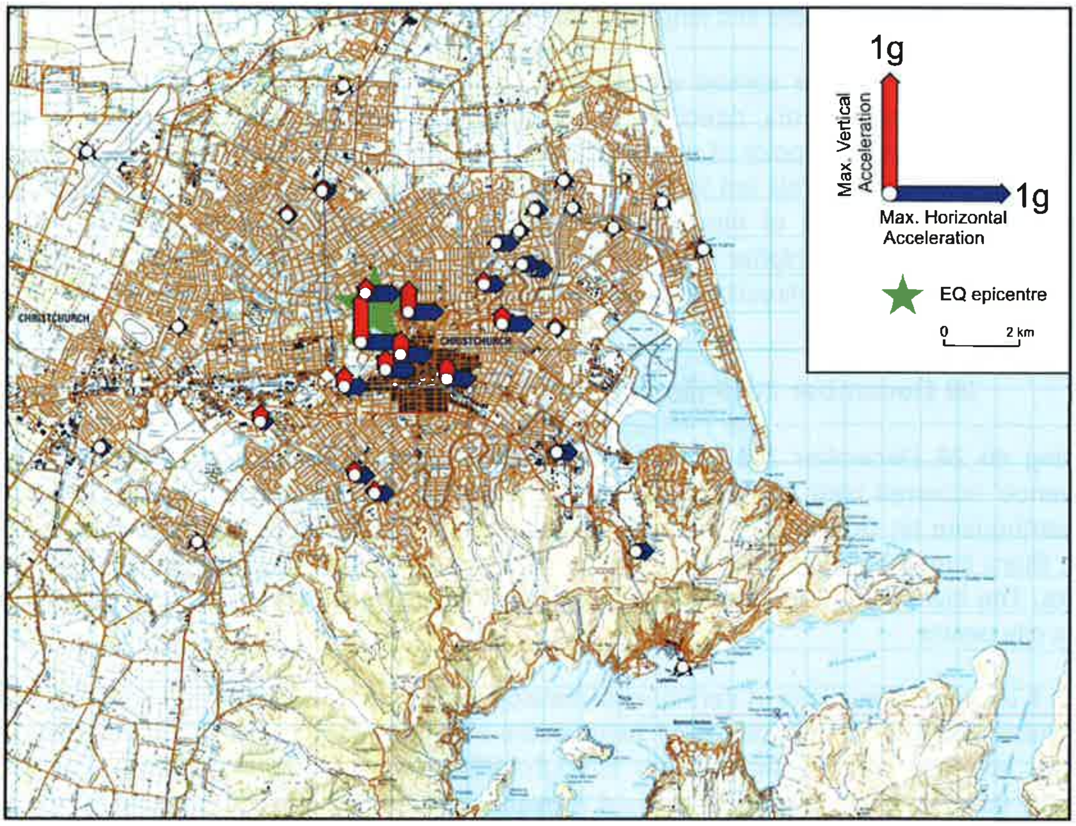

Figure 3.7 Maximum horizontal and vertical PGAs recorded during the 26 December earthquake at GeoNet stations and using temporary low-cost accelerometers (Quake-Catcher Network).

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.

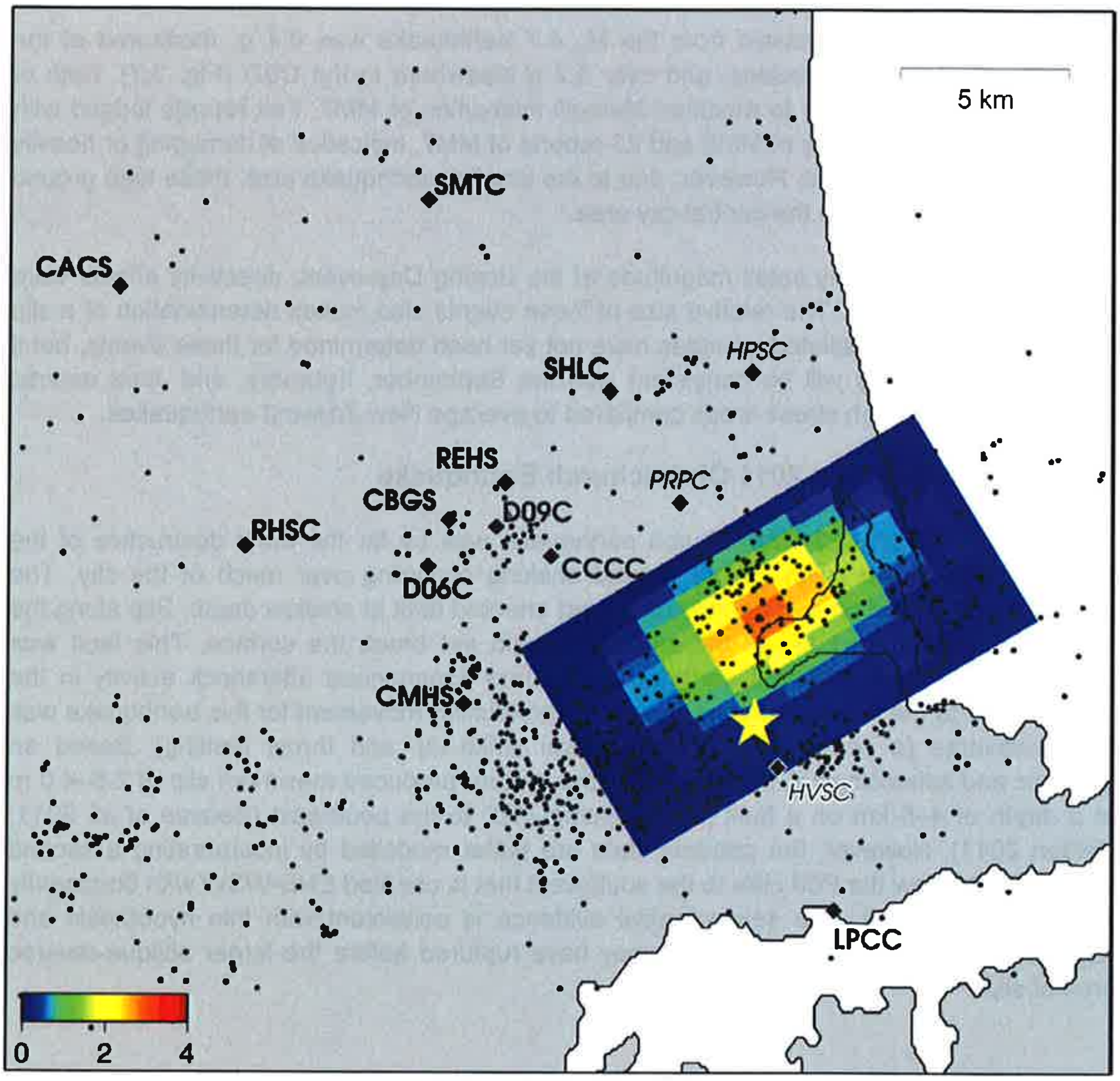

Figure 3.8 This geodetic source model (from Beavan *et al.*, 2011) shows the locations of the two model faults and their slip magnitudes (coloured images), GPS displacements observed (blue arrows) and modelled (red arrows), and aftershocks since September 2010 (crosses).

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.

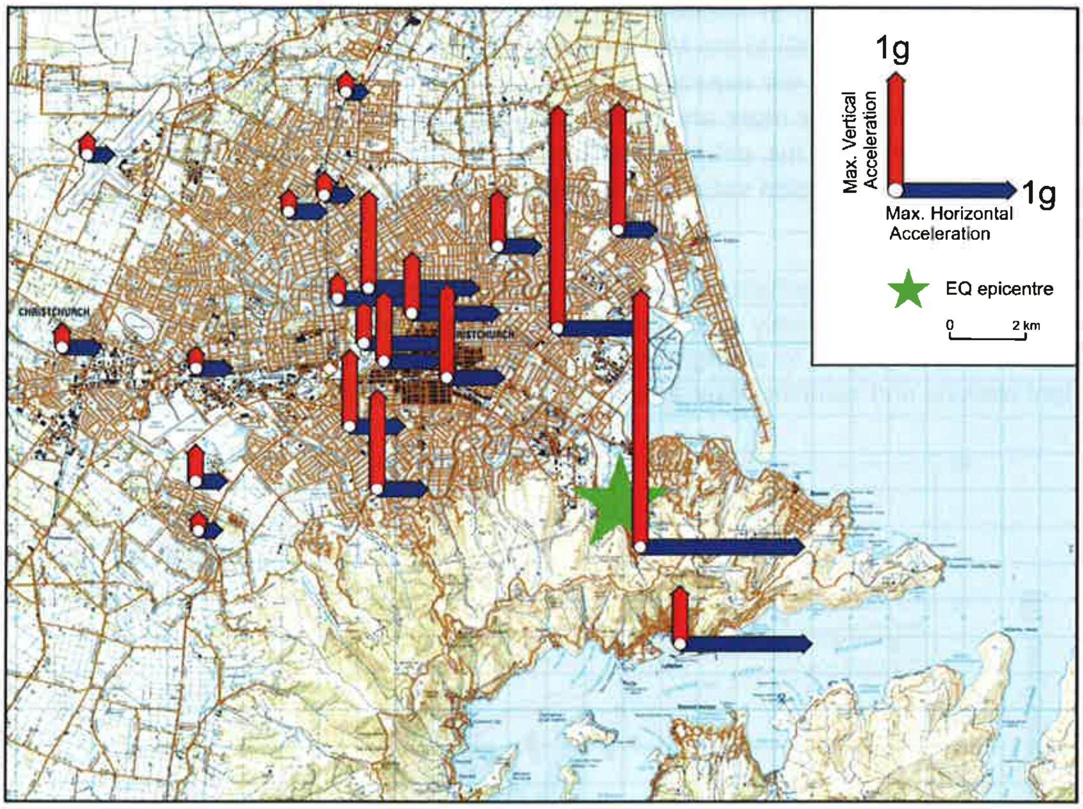

Figure 3.9 Maximum horizontal and vertical PGAs recorded during the 22 February earthquake at GeoNet stations and using temporary low-cost accelerometers (Quake-Catcher Network).

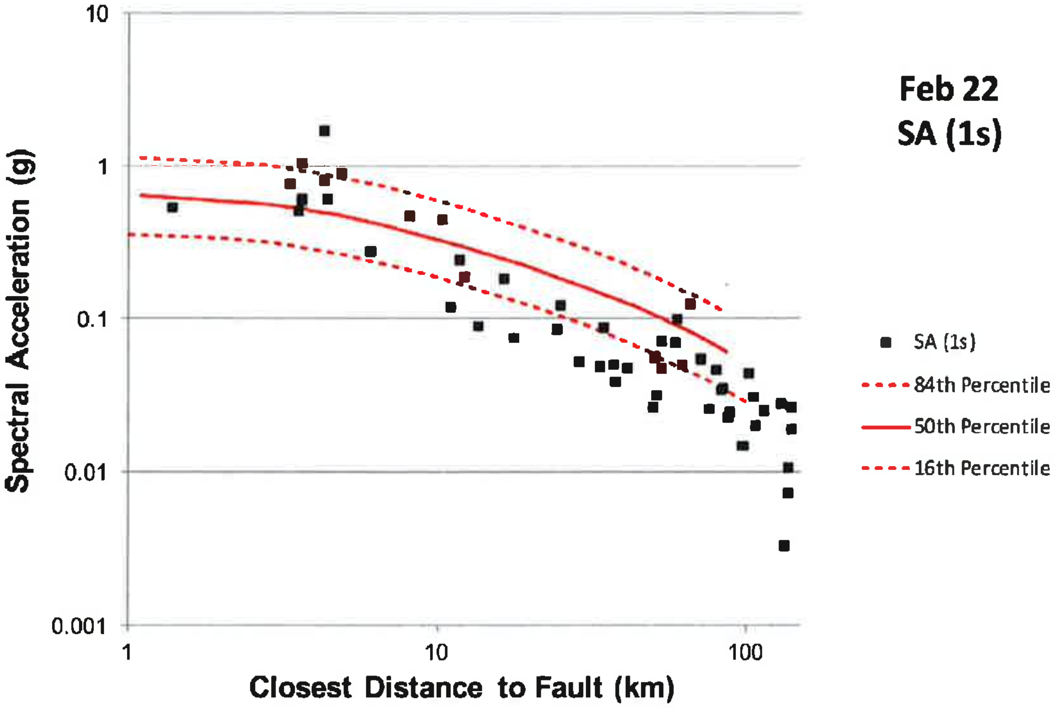

Figure 3.10 Observed spectral accelerations at 1.0 s during the Christchurch earthquake (black squares) compared to those predicted from the national attenuation model for deep or very soft soils (solid red line; McVerry *et al.*, 2006) assuming a crustal oblique-slip source.

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.

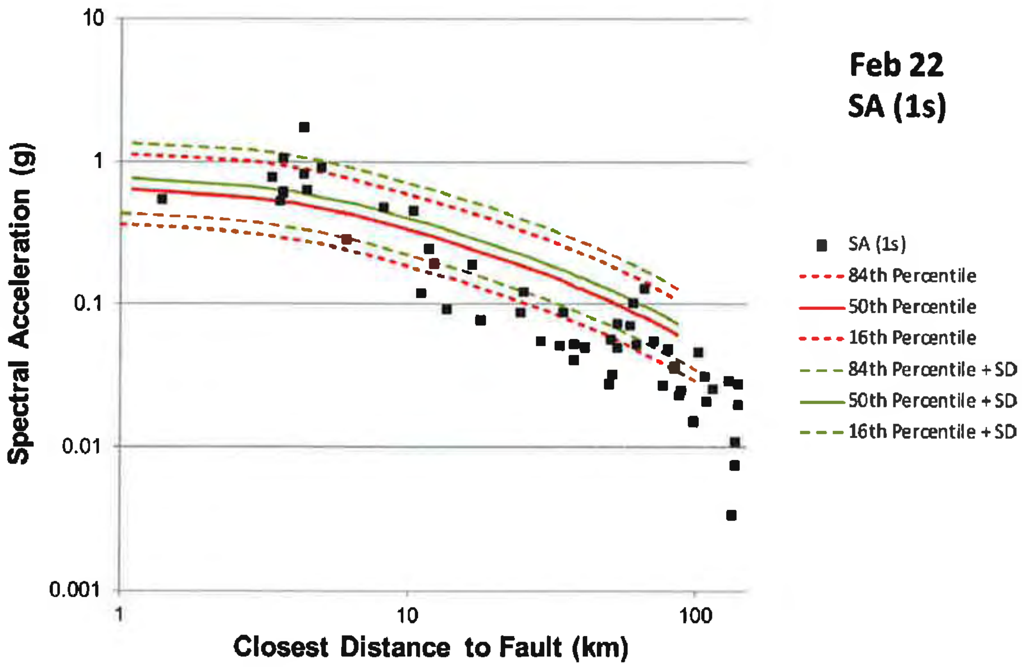

Figure 3.11 Observed spectral accelerations at 1.0 s during the Christchurch earthquake (black squares) compared to those predicted from the national attenuation model for deep or very soft soils (solid red line; McVerry *et al.*, 2006) assuming a crustal oblique-slip source. Also shown is the prediction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

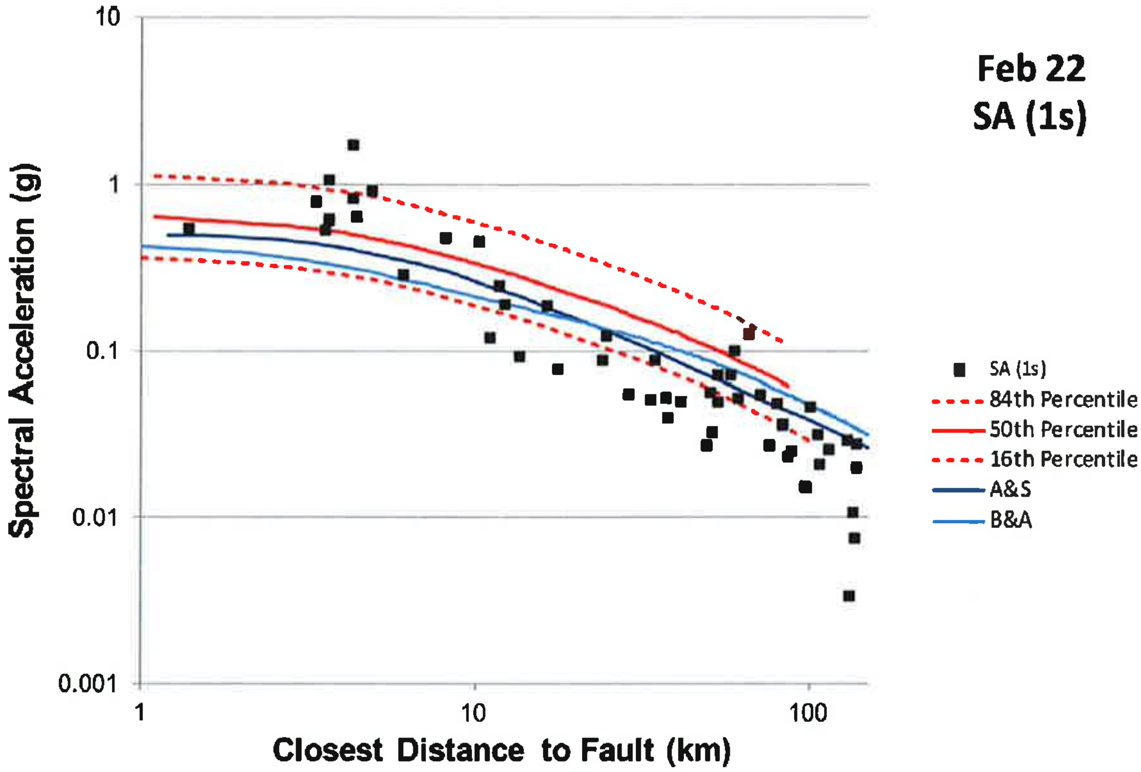

Figure 3.12 Observed spectral accelerations at 1.0 s during the Christchurch earthquake (black squares) compared to those predicted from the national attenuation model for deep or very soft soils (solid red line; McVerry *et al.,* 2006) assuming a crustal oblique-slip source. Also shown are the ground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

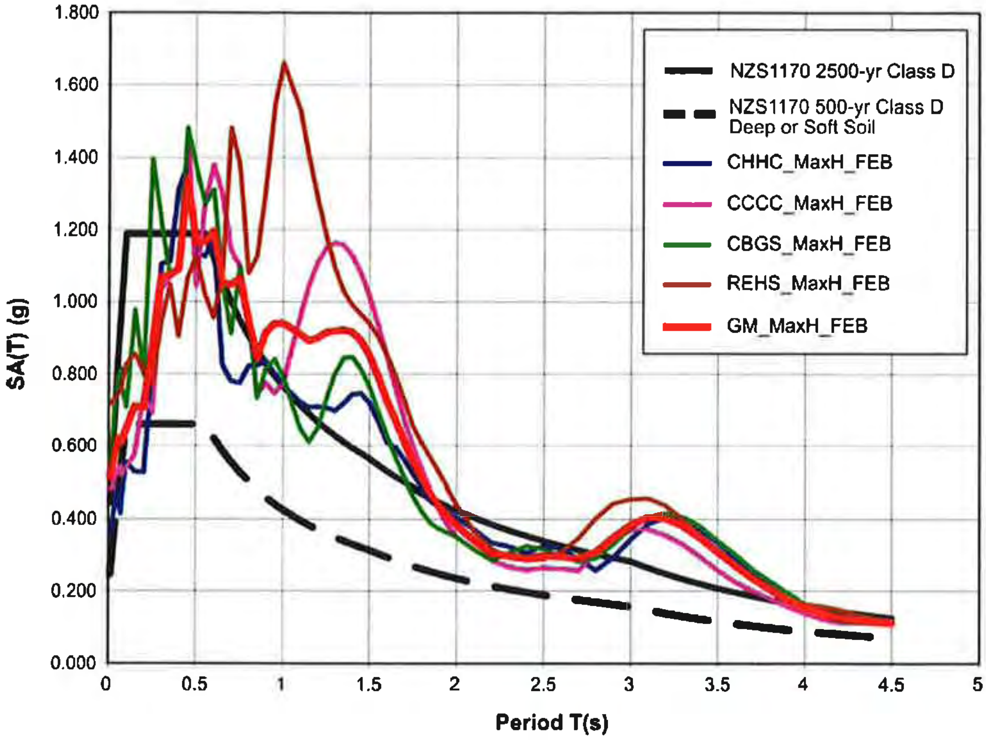

Figure 3.13 Comparison of recorded (5% damped) acceleration response spectra for four sites within ~1.5 km of the CBD (coloured lines) and corresponding spectra from the New Zealand design standard NZS1170 for deep or soft soil sites (black lines). The solid red line is the average of the four central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

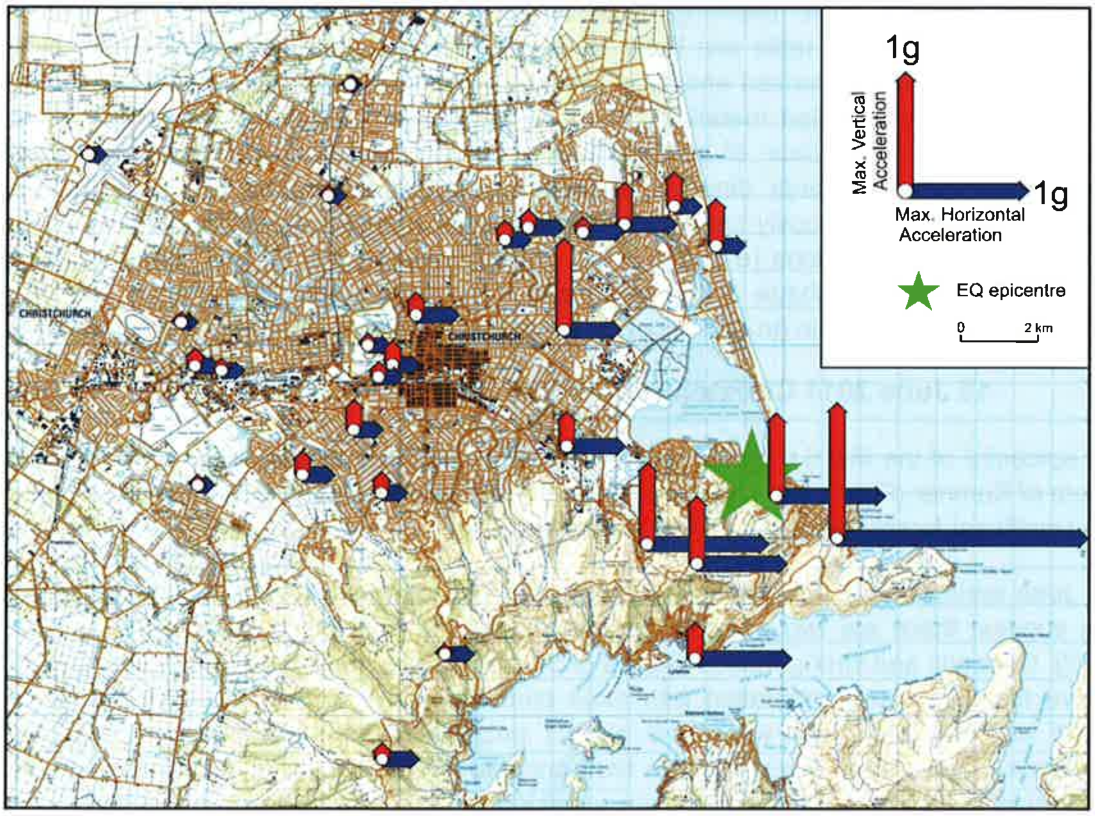

Figure 3.14 Maximum horizontal and vertical peak ground accelerations (PGA) recorded during the 13 June 2011 earthquake at GeoNet stations and using temporary low-cost accelerometers (Quake-Catcher Network).

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.

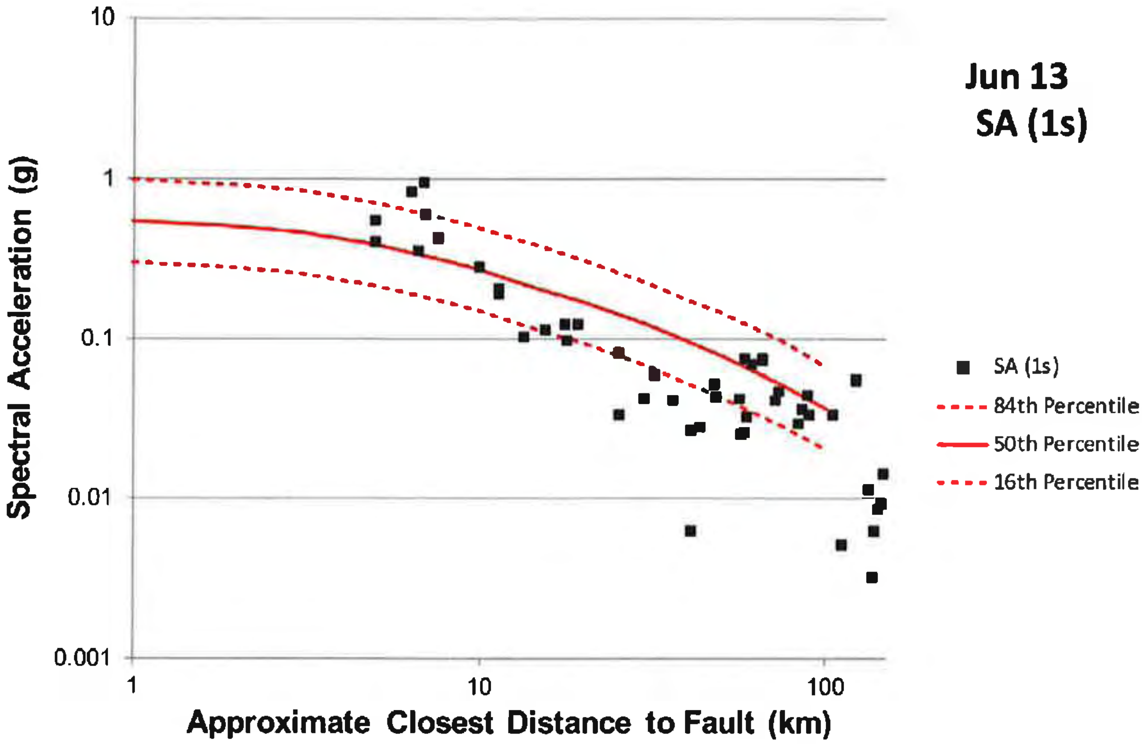

Figure 3.15 Observed spectral accelerations at 1.0 s during the 13 June 2011 Christchurch earthquake (black squares) compared to those predicted from the national attenuation model for deep or very soft soils (solid red line; McVerry *et al.*, 2006) assuming a crustal strike-slip source.

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).

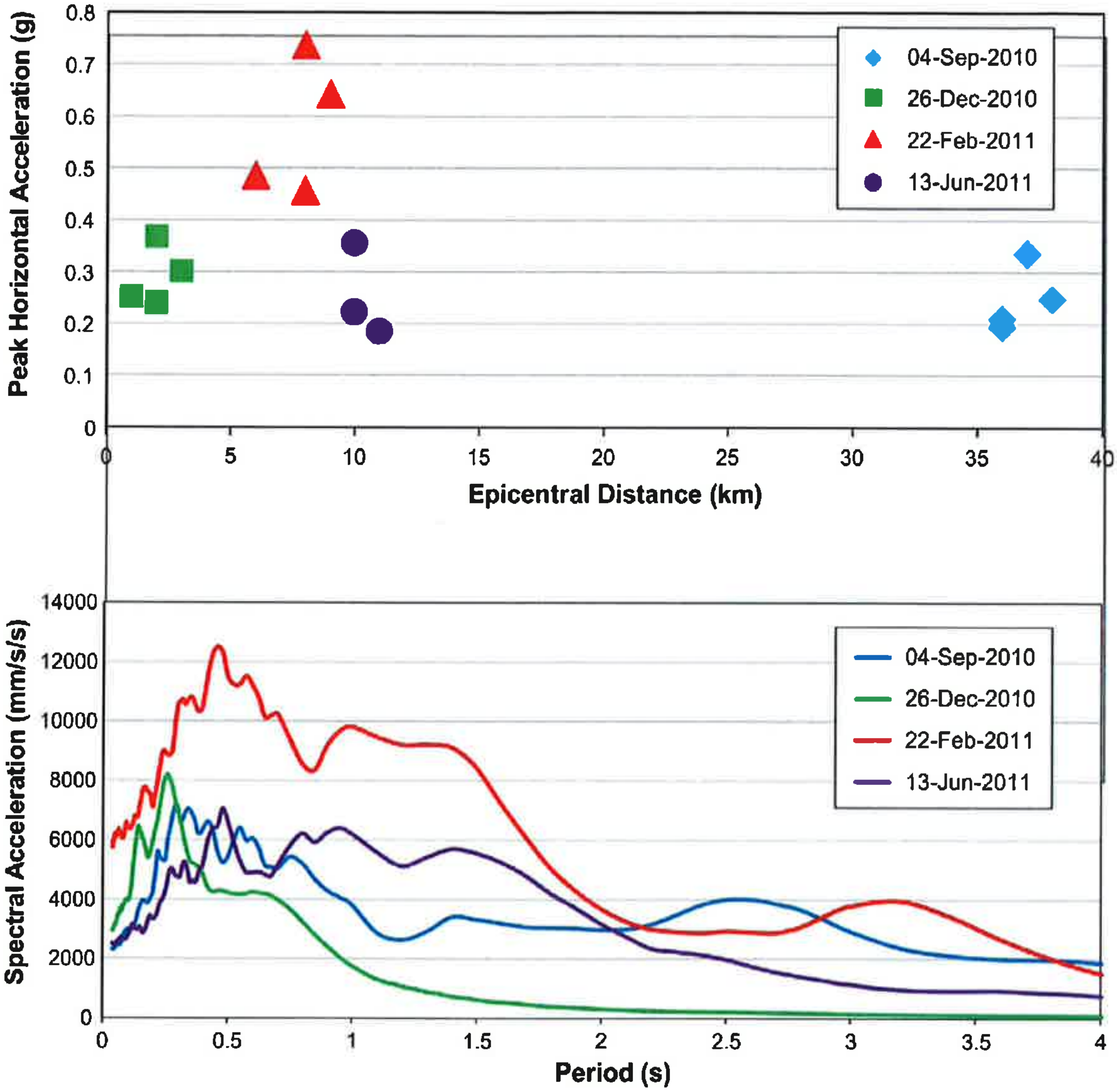

Figure 3.16 Top: Peak horizontal ground accelerations recorded at CBD stations. Recording locations include CBGS (Botanic Gardens), REHS (Resthaven), CHHC (Christchurch Hospital) and CCCC (Catholic Cathedral College). The June 13 earthquake was not recorded by the CCCC site. Bottom: Peak response-spectral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

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).

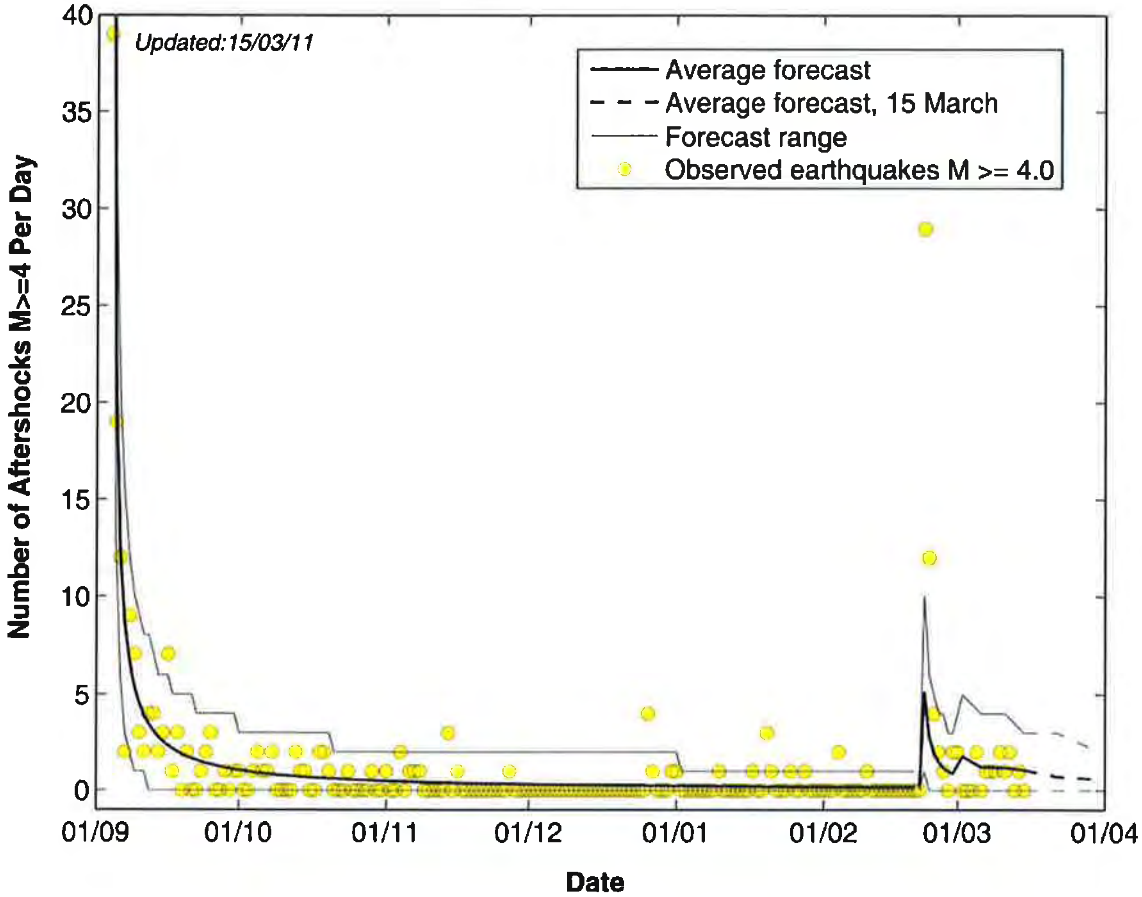

Figure 4.1 Decay of Canterbury aftershocks with time (dd/mm) since September 2010.

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.

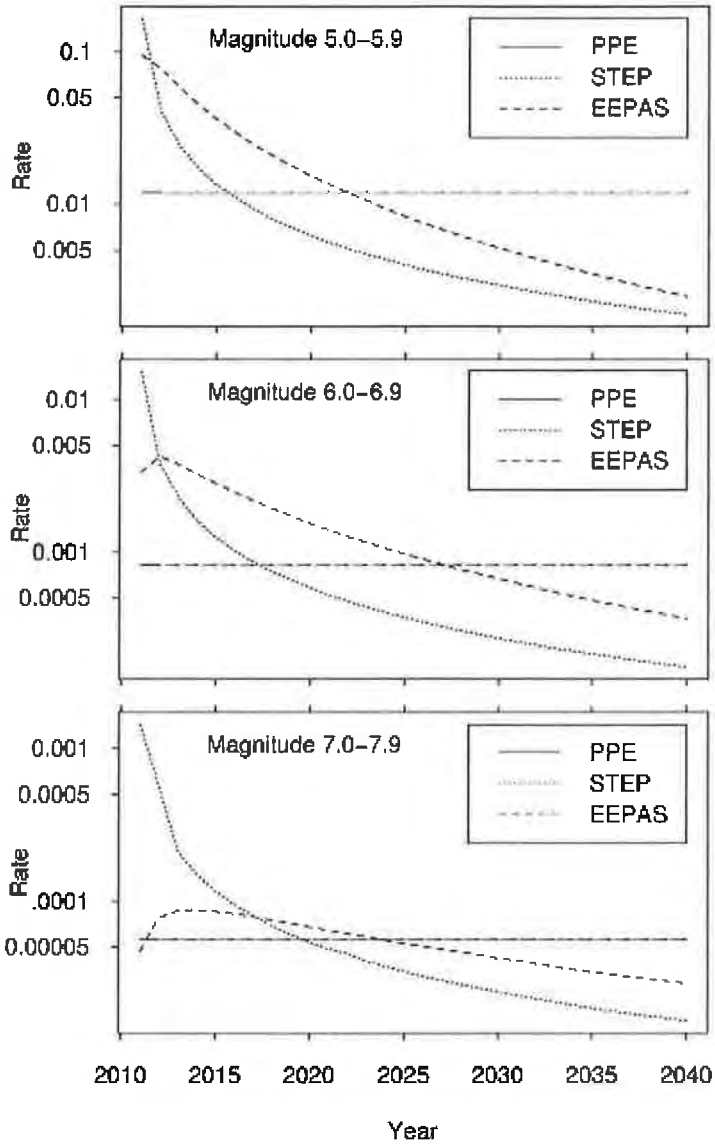

Figure 4.2 Forecast annual earthquake rates for a representative Christchurch location from the three seismicity-based models for M5.0–5.9 (top), M6.0–M6.9 (middle) and M7.0–M7.9 (bottom). The dominance of the higher rates of the STEP model initially can be seen before the EEPAS model takes over at slightly 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.

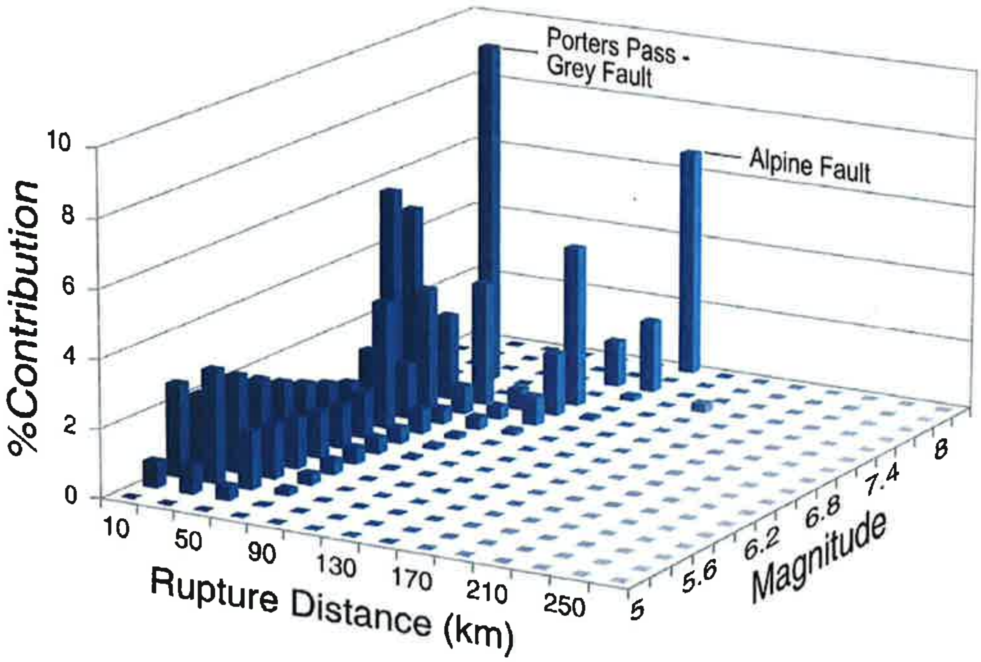

Figure 4.3a Separation of contributions of different fault sources for a representative Christchurch location for spectral accelerations of 0.5 s for 0.6 g for the original New Zealand Seismic Hazard Model. The dominant contribution is from distant fault sources such as the Alpine Fault and the Porters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

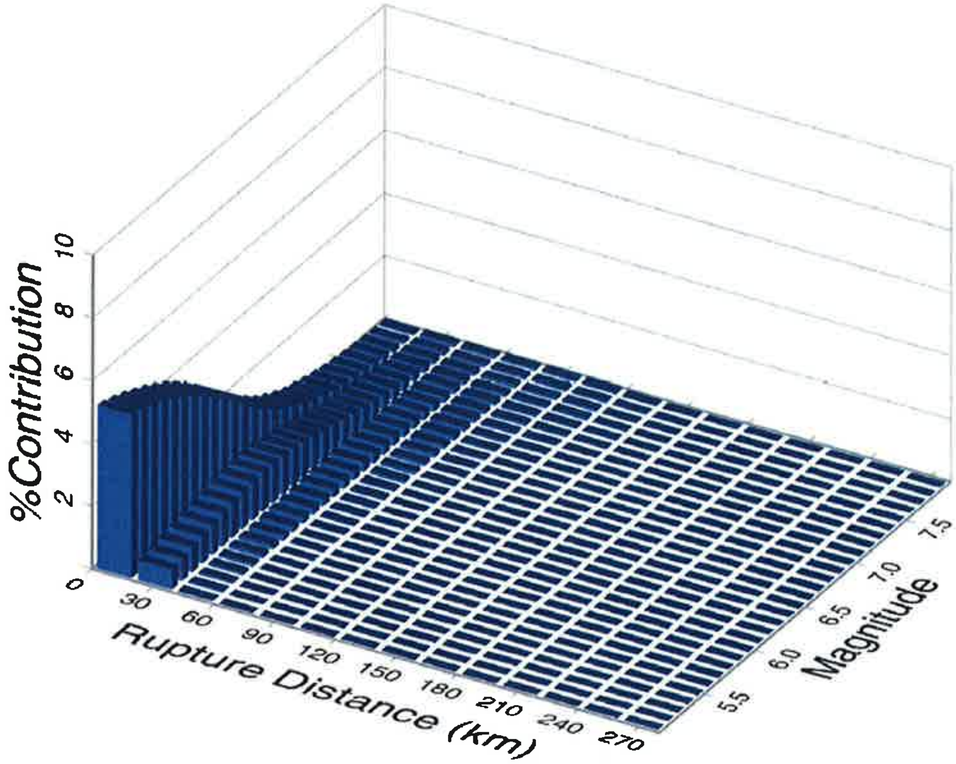

Figure 4.3b Separation of contributions of different fault sources for a representative Christchurch location for spectral accelerations of 0.5 s for 0.6 g in the new model. Note the dominant contribution of events of less than magnitude 6. For the results as presented, magnitudes less than 5.5 were 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.

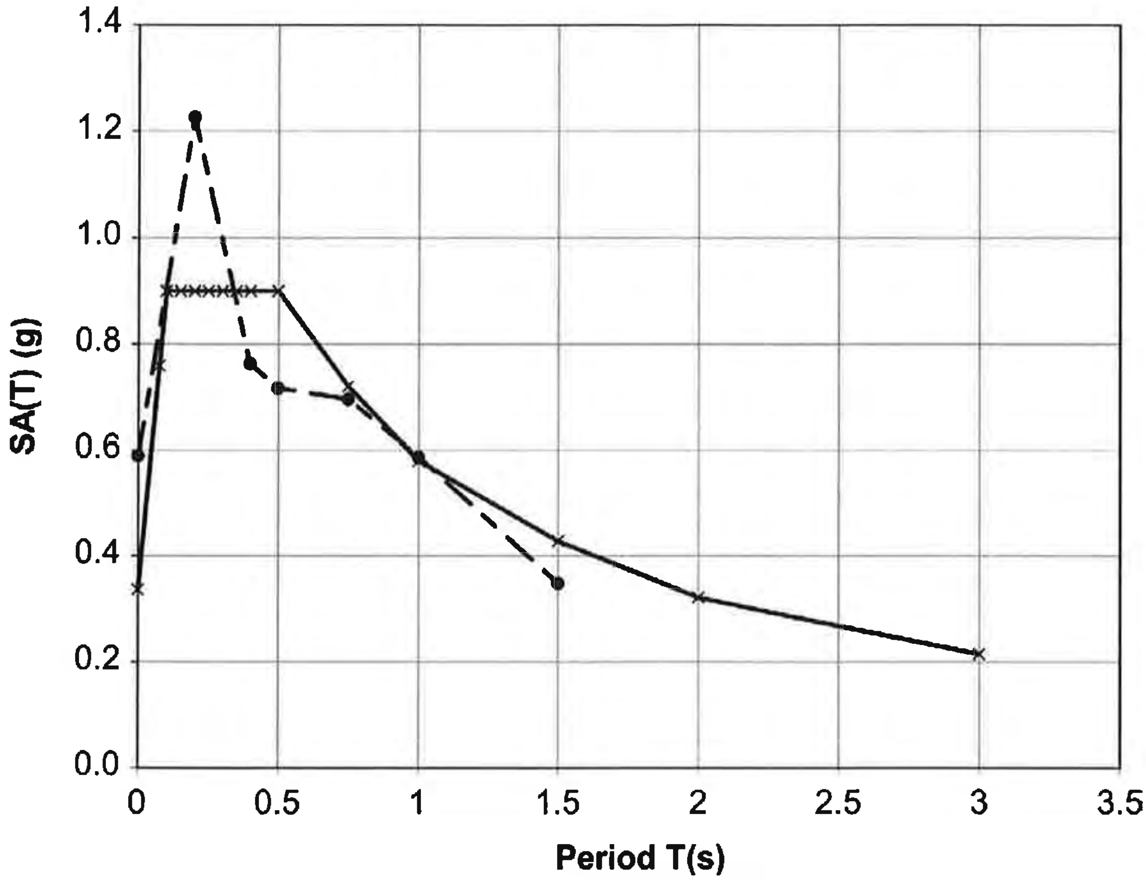

Figure 4.4 Demonstration that the Z=0.3 Class D deep soil spectrum approximately envelopes the hazard spectrum estimated with a 10% probability of being exceeded in the next 50 years, apart from truncation of the peak of the spectrum.

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.

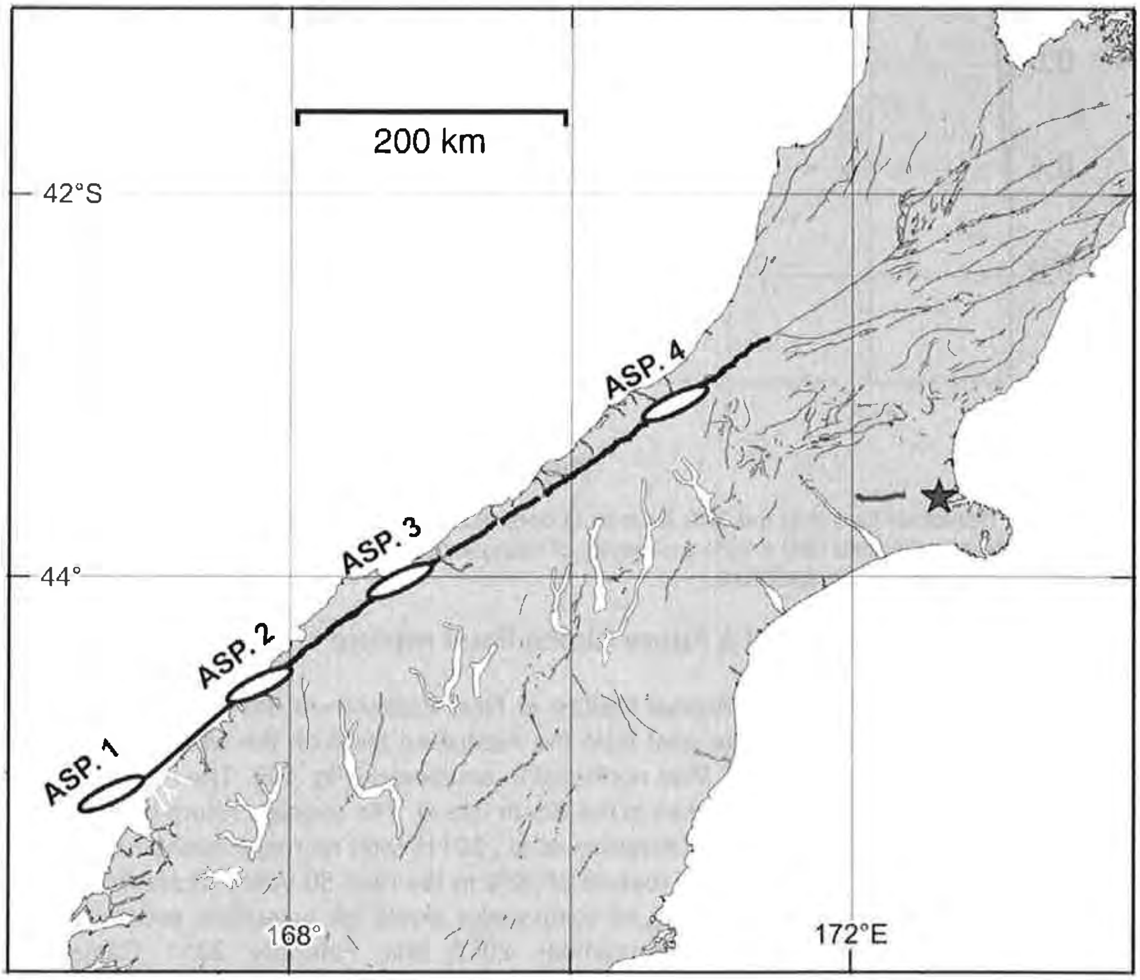

Figure 4.5 Active faults in the South Island. The bold line illustrates a likely Alpine Fault rupture; the grey line west of Christchurch is the fault trace from the Mw 7.1 Darfield earthquake; the white ellipses represent the location and size of the major potential asperities on the Alpine Fault; the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

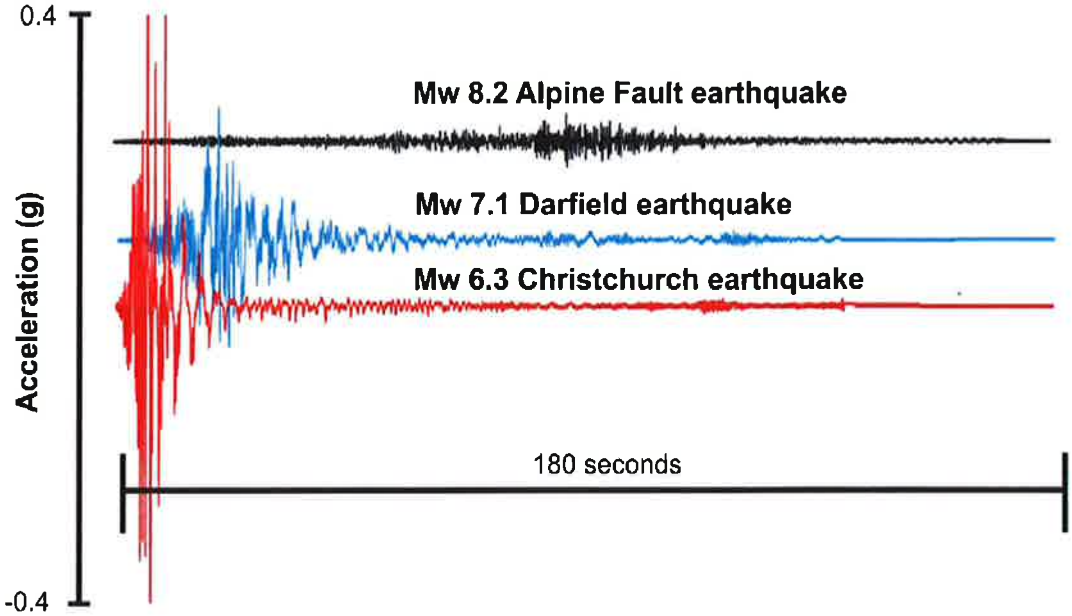

Figure 4.6 Three minutes of synthetic acceleration time histories for the larger of the two horizontal components, in terms of PGA, for a potential Alpine Fault event (black) compared with the accelerations from the M_w 7.1 Darfield earthquake (blue) and the 22 February M_w 6.3 Christchurch earthquake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

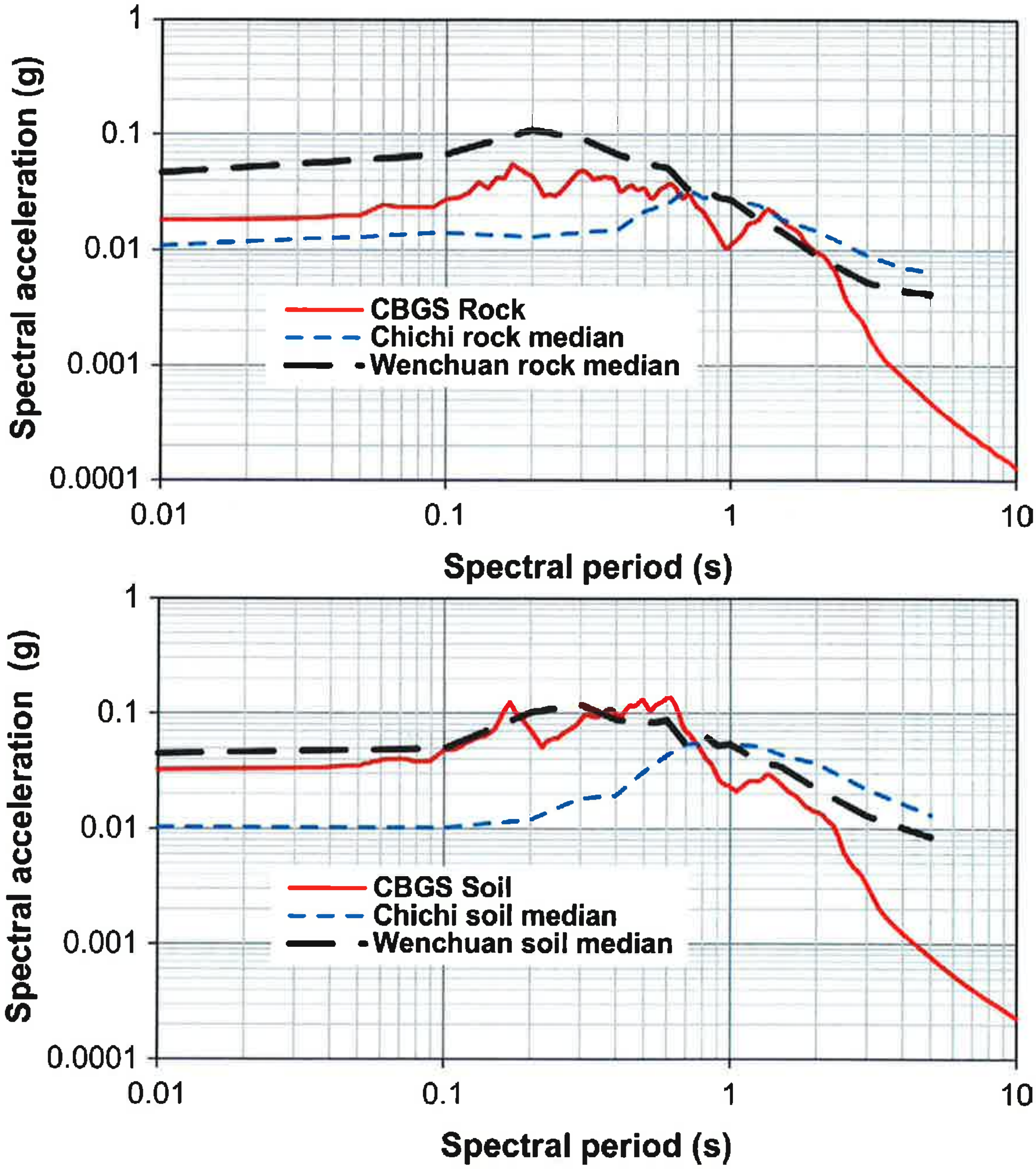

Figure 4.7 Comparison of response spectra for synthetic ground motions at Christchurch Botanical Gardens GeoNet station (CBGS) on rock (top) and on soil (bottom) with the Taiwan M_w 7.6 Chichi earthquake in 1999 and the China M_w 7.9 Wenchuan earthquake in 2008. The spectra represent the average values 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).

5.0 NATIONAL IMPLICATIONS

5.1 Where else in New Zealand could one expect earthquakes similar to the 22 February 2011 event to occur?

The principal reason why the 22 February 2011 earthquake produced much stronger shaking in Christchurch than the 4 September 2010 event was distance—the top-edge of the fault that ruptured on 22 February was located under the edge of the city, and at a shallow depth, so was within ~5 km of the CBD. In comparison, the fault rupture associated with the 4 September earthquake only came within 20 km of the CBD. Seismic waves die away rapidly with distance as they travel through the earth's crust, so only areas close to the earthquake source will be subject to really strong ground motions.

Once we take account of earthquake magnitude and distance, we see that the earthquakes of 22 February and 13 June 2011 both produced higher levels of shaking than expected compared to the average New Zealand model at distances of less than 10 km from the fault (Figures 3.10, and 3.15). As discussed in earlier sections, these earthquakes all had a high energy release (high apparent stress and high stress drop) for their magnitude (Fry and Gerstenberger, 2011; Reyners, 2011) and the expected levels of enhanced shaking can be modelled to some extent with existing mathematical relationships that take this into account (e.g. Atkinson and Boore, 2006; Fig. 3.11).

Once the stress drop effect is accounted for, shaking levels in areas closer than 10 km are still generally above the mean value. This may be the result of directivity (also discussed in earlier sections) whereby the seismic waves tend to get stacked on top of each other in the direction in which the fault rupture propagates. This is thought to be an important factor in both the 4 September and 22 February earthquakes, in which the fault orientations and rupture directions were both directed toward the Christchurch CBD.

A number of other factors may also have led to higher levels of ground shaking in Christchurch city from the 22 February earthquake.

- The earthquake occurred on a 'blind' fault (one that did not rupture all the way to the surface). International studies (e.g. Somerville, 2003) suggest that blind faults can produce higher strong ground motions than those that rupture the surface.
- The upper 30 m of the ground beneath the Christchurch CBD is of low strength. The presence of weak sediments near the surface can amplify ground shaking.
- 'Basin' effects may have been produced due to the thickness of sediments beneath Christchurch (600–1200 m to the basement rocks) and the subsurface geometry of the basin. The depth of the sediments under a city influences the seismic wave periods that will be enhanced during shaking, i.e., which period will resonate. If the seismic wave period is the same as the natural period of a building, the building can then experience anomalously strong shaking. Such effects usually affect the low frequency part of the earthquake spectrum and thus the shaking experienced by high-rise buildings.

Research is currently underway to better understand which of the above factors were the most important in generating the high levels of shaking recorded in these earthquakes. In terms of national implications, the most likely locations for future high stress drop earthquakes are probably the most poorly understood factor. High stress drop can be consequence of:

- Geometrical complexity of the fault system. The fault system that ruptured in the 4 September earthquake does not consist of a single linear fault. The 4 September earthquake involved faulting on a strike-slip fault, as well as on three reverse faulting segments on planes oriented at angles to the main strike-slip fault (Beavan *et al.*, 2010). The 22 February and 13 June events occurred on faults oriented at right angles to each other (Kaiser *et al.*, 2011). This complex geometry is characteristic of a fault system that is difficult to break, probably because it is strong and immature, and has had a small total displacement since it first formed.

- High friction on the fault plane. Faults have high friction if they have not been smoothed by many episodes of fault slip during large earthquakes or if the time between slip episodes is so long that the fault has time to heal (and strengthen). In those cases, fault rupture will release a large amount of energy (Kanamori, *et al.*, 1993). This is typical of areas with low deformation rates, such as the interior of continental plate regions (Kanamori and Anderson, 1975). The Christchurch region is an area with a low to moderate deformation rate. The rupture recurrence interval for the faults associated with the 22 February and 13 June earthquakes is unknown, but could be similar to that of the Greendale (4 September) Fault, that is, at least 8,000 years (Villamor *et al.*, 2011).

- Anomalously strong rocks in the Earth's crust (i.e. 0–30 km depth). If a fault is located in a region of strong crust, the fault will have higher strength and will consequently store more potential energy before failing. When it does rupture, it will release a higher amount of energy. Seismological studies suggest that the base of the brittle crust beneath Christchurch is deeper than normal (Reyners, 2011). While the upper brittle layer (the layer where earthquakes usually occur) of the crust beneath Canterbury is of normal strength, the upper crust has been interpreted to be tightly welded to an underlying rigid lower crust (which is believed to consist of strong oceanic rocks subducted under Christchurch millions of years ago). The welding of these layers can potentially strengthen the whole crust and lead to higher stress drops (Reyners, 2011).

- Very strong ductile (viscous) lower crust. The upper brittle crust is usually underlain by a ductile layer. After a fault has ruptured, there is an increase of stress in the contact between the two layers, and the ductile layer subsequently deforms slowly to accommodate that stress. The phenomenon of slow deep motion is reflected at the surface as post-rupture slip (creep) near the surface expression of the fault. Immediately after the 4 September 2010 earthquake, no further displacement was detected by the geodetic studies (Beavan *et al.*, 2011); this suggests that the ductile layer beneath Christchurch could be anomalously strong. While it is not clear whether this can cause high stress drop during the rupture, it could possibly be a factor in the highly active Christchurch aftershock sequence, in that strain accumulated at the bottom of the fault rupture would need to be released by earthquakes (aftershocks) rather than by creep.

Given the factors discussed above, which can all contribute to extremely high ground shaking, we now need to examine the implications for New Zealand cities. For evaluating the risk of earthquakes occurring close to cities, it is impossible to identify all active faults in a region because the relatively small faults associated with magnitude 6 earthquakes are particularly difficult to identify. For this reason, the NSHM uses background earthquake sources of up to magnitude 7.2 to supplement existing active fault information. This effectively means that, with the current state of knowledge, an earthquake of up to magnitude 7.2 (6.5 in the Taupo Volcanic Zone) could occur on an unrecognized fault nearly anywhere in New Zealand, although the likelihood of this happening in our low seismicity areas would be very small.

Any programme of research to improve our knowledge of new active faults close to cities would need to be carefully targeted because the resources needed for extensive studies would be large and the results would often be difficult to utilize. New technologies such as continuous and survey mode GPS recording of ground displacement could possibly be used to identify areas where strain is accumulating in an area where no active faults have been identified, or where there is a discrepancy between GPS and geological estimates, indicating the possibility of unknown (perhaps blind) active faults. Such information could then be used to target more detailed investigations.

Some other factors that influence seismic shaking, such as the existence of blind faults, near-surface site effects, and basin response can be effectively investigated and modelled, and such work has been undertaken in some parts of New Zealand. For example, blind thrust faults are known to exist in a number of areas, but could possibly exist in many others.

Directivity effects can possibly occur during any earthquake, but there should be no overall net increase in earthquake shaking due to directivity, simply more in some directions and less in others. This directivity effect can be anticipated for known active faults, so buildings near such faults are designed to withstand its effects. For unknown faults, directivity can be allowed for if sufficient variability is allowed for during building design.

High stress drop has been a strong characteristic of the recent Canterbury earthquakes, with some events of the 2010-2011 sequence having been some of the highest worldwide. Ruptures with high stress drop are likely to occur in areas with a low deformation rate, where faults seldom rupture (faults are strong, immature). High stress drop is even more likely if those areas also have strong crust. If we combine tectonic regions in New Zealand with low deformation (Fig. 2.2) with areas of strong crust, the regions in New Zealand that can experience high stress drop are (Fig 5.1):

- The northern half of the contractional South Island faults (the region around Christchurch). This area displays the strongest crust in New Zealand and has a low rate of deformation
- The southern half of the contractional southern South Island faults (Otago), the contractional northwest South Island faults (the region around Buller and Nelson), the southern extensional western North Island faults (the region around Wanganui), and Kapiti-Manawatu faults. These areas have low deformation rates and strong crust.

- It is also possible that areas with moderate to high deformation rates but with strong crust may also experience high stress drop, except along the major faults. For example, the North Island Dextral Fault belt, and the Hikurangi Subduction Margin forearc.

- The down-going Pacific plate (subducting slab) beneath the eastern part of the North Island also has very strong crust. High stress drop earthquakes within this plate have occurred historically in New Zealand (Mw 6.8, 1 August 1942, Wairarapa; Mw 6.2, February 1990, Weber, and Mw 5.3, 20 January 2005, Upper Hutt earthquakes; Reyners, 2011).These earthquakes can occur down to ~300 km depths, but only the shallow ones will produce high strong ground motions. Even then, distances will be such that shaking will be significantly less than Christchurch has experienced.

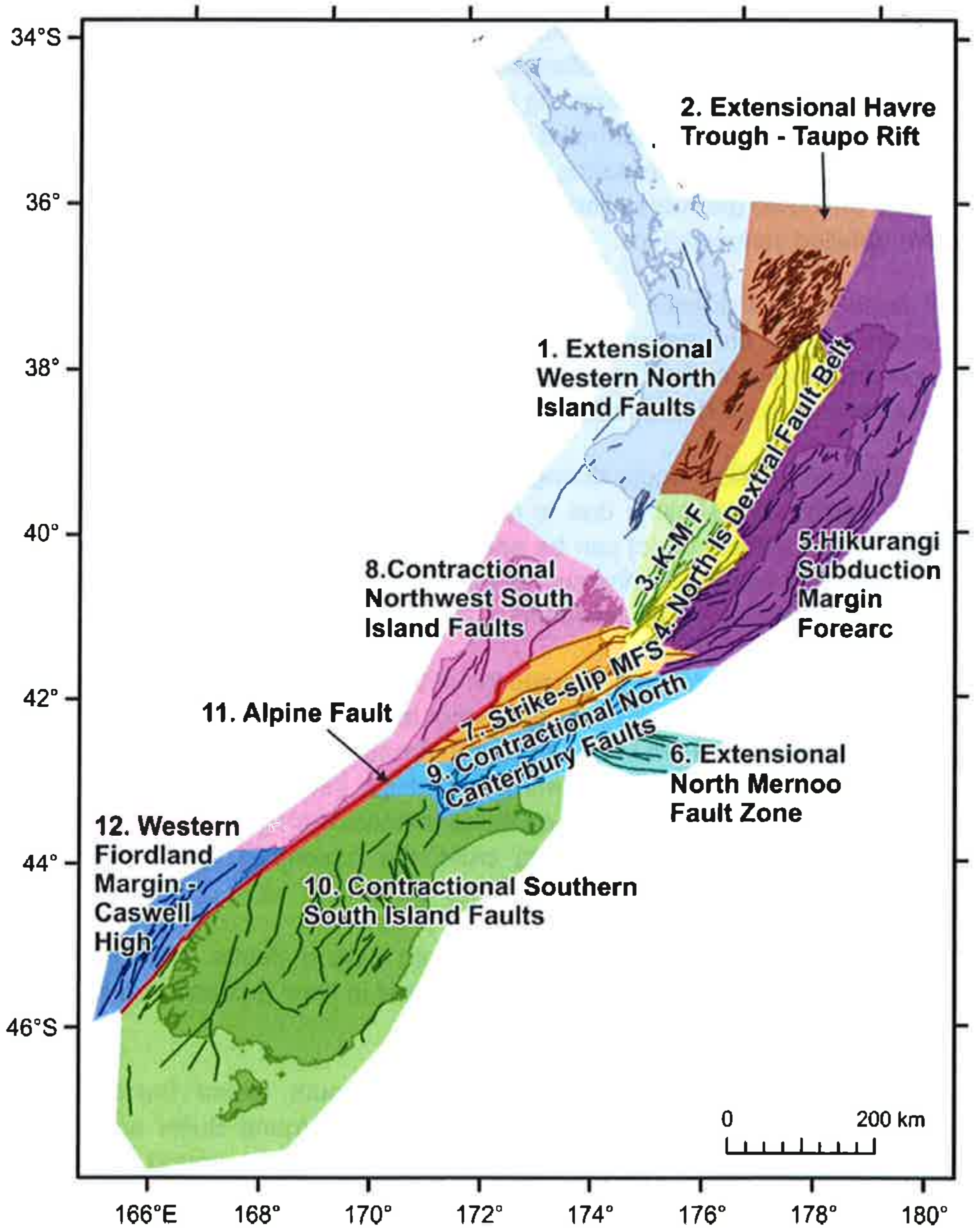

Figure 5.1 Groupings of active fault sources into domains or regions they occupy in New Zealand from Stirling *et al.*, 2011). K-M F = Kapiti-Manawatu Faults, MFS = Marlborough Fault System. Only the upper plate (non-interface) active faults are shown.

It should be noted that earthquakes with high apparent stress drops generally tend to occur on faults that seldom rupture. In the areas described above as having low deformation rates, we expect earthquakes with larger than Mw 6.5 to have recurrence time intervals of many thousands of years (Stirling *et al.*, 2011). For this reason, high stress drop earthquakes contribute little to national earthquake risk, but hazard models should take account of their likely enhanced shaking. What will contribute most to New Zealand's seismic risk are earthquakes on known active faults close to population centres. These earthquakes are well represented in the National Seismic Hazard Model (NSHM) and are incorporated in modern building design (see next section).

5.1.1 Is there a limiting magnitude for this type of earthquake?

Given the high levels of damage to Christchurch and the fact that some earthquakes in the Canterbury sequence produced higher levels of ground shaking than expected, given their magnitude, a natural concern is whether worse 'unexpected' things can happen. To address this concern we need to take into account the principal factors that led to the high levels of shaking in Christchurch (an earthquake in close proximity to a city and shaking above that expected from ground motion models) and consider the likely maximum size of earthquakes that can be involved.

In terms of shallow earthquakes in close proximity to cities, Wellington is an obvious example, given that the Wellington Fault passes through built up areas and could produce an earthquake in the range of M7.3–7.6 (Little *et al.*, 2010). Similarly, the 1931 Hawkes Bay earthquake had an estimated magnitude of 7.5 (Appendix 3). For unrecognised fault structures, however, including blind thrusts, the anticipated maximum magnitude is 7.2 (see the discussion of M_{cutoff} in Section 5.2.1).

For ground shaking above that expected from attenuation models, key factors are expected to be stress drop and directivity effects. As mentioned above, earthquakes with high apparent stress generally tend to occur on faults that seldom rupture. Of the low slip-rate faults in the NSHM, the maximum expected magnitude is 7.6. While severe shaking would be expected from such an earthquake, it is expected to be a very rare event. For a number of large known active faults, directivity effects are already accounted for in the NSHM (Section 5.5.2), the largest likely earthquake being an Alpine Fault rupture with a magnitude of 8.1 (Section 4.2). However, a relevant issue related to directivity arising from the Christchurch experience is the need to incorporate directivity effects from smaller earthquakes (Section 5.2.4.2) either explicitly in models or through an allowance for greater variability.

5.2 The New Zealand National Seismic Hazard Model

Seismic hazard models aim to predict likely long-term rates of ground shaking for use in engineering design. The National Probabilistic Seismic Hazard Model (NSHM) for New Zealand has been developed steadily since the early 1980's (e.g. Smith and Berryman, 1986; Stirling *et al.*, 2002) and has recently been updated to incorporate new information from on-going research (Stirling *et al.*, 2011). The 2002 model served as the basis for the design spectra of the New Zealand Standard NZS1170.5:2004 (Standards New Zealand, 2004) covering earthquake design actions in New Zealand.

In this section we discuss the key components of seismic hazard models, namely the earthquake source model (where earthquakes are likely to happen) and the prediction of ground motions that those earthquakes are likely to produce. We also describe the nature of subsequent updates to the model and anticipated future changes, especially in light of the Christchurch experience. Finally, we describe how the model is used in the design of buildings.

5.2.1 The earthquake source model

The 2002 NSHM estimates future earthquake activity for New Zealand using the locations, estimated magnitudes, recurrence intervals and types of 'characteristic' earthquakes for about 306 fault sources that have been recognised from detailed geological and geophysical studies.

Scientists cannot identify all active faults in a region because smaller faults (e.g., associated with earthquakes of $M_w<7$) often lack any surface expression and so are particularly difficult to identify. For this reason a model of background seismicity consisting of earthquakes located at points (instead of on faults) is used. The background sources allow us to compensate for the lack of fault data. The background source model uses a Gutenberg-Richter type[2] seismicity distribution developed from the New Zealand earthquake catalogue (available from GeoNet) for the period 1840–1997 to represent the majority of New Zealand's earthquakes — those that have not been associated with the known faults.

The above two source models are combined by using a regional maximum magnitude, M_{cutoff}, below which the background seismicity model is used, with some contribution from the fault model, and above which only the fault source model is used. The implication of this is that an earthquake above M_{cutoff} is considered implausible if not identified by an active fault. In the 2010 update to the NSHM (Stirling *et al.*, 2011), the M_{cutoff} was revised upward to M=7.2 for all regions except the Taupo Volcanic Zone, which was assigned $M_{cutoff}=6.5$. The 2002 version of the model used $M_{cutoff}=7.0$ for Canterbury. The choice of M_{cutoff} is subjective, but ultimately comes down to understanding how complete the knowledge is of the number of active faults capable of producing earthquakes above a given magnitude. In low seismicity areas, or areas with few active faults, the choice of M_{cutoff} can have significant implications for the estimated hazard.

5.2.2 Prediction of ground motions

The second key part of the NSHM is a ground motion attenuation relationship (or mathematical model) that predicts how strong ground shaking from future earthquakes will be depending on magnitude and distance away. It also takes into account the effect on ground-shaking of different near-surface site conditions (based on the NZS1170.5 site classes Strong Rock, Rock, Shallow Soil and Deep or Soft Soil) and different types of earthquakes.

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[2] A Gutenberg-Richter type model (Gutenberg and Richter, 1944) defines the average occurrence rate (N(M>m) of earthquakes exceeding magnitude m by the relation $N(M>m)=a\ (10^{-bm} - 10^{-bM_{max}})$, where, a and b are constants for a particular location derived from the earthquake catalogue, and M_{max} is a region-dependent maximum magnitude for the earthquakes represented in the distributed seismicity model. Typically, b is close to 1, so the rate of earthquakes falls off by approximately a factor of 10 for a unit increase in magnitude.

The attenuation relationship used in the NSHM (McVerry *et al.*, 2006) was based on international models, with modifications to better match New Zealand records of earthquake ground shaking. Various constraints were used to preserve features of the international models for near-source motions from larger magnitude earthquakes, for which there was a lack of New Zealand data. The New Zealand model has different expressions for crustal earthquakes and subduction zone earthquakes, with different international models (Abrahamson and Silva, 1997 and Youngs *et al.*, 1997, respectively) as the starting point for the New Zealand model. Initial development of the New Zealand attenuation relationship (McVerry *et al.*, 2006) began around 1998, and was completed by 2000. It is the New Zealand equivalent to the Next Generation Attenuation (NGA) models that have been developed in recent years in the U.S.A.

Near-fault factors in the NSHM take account of directivity effects that may occur near to fault ruptures. These factors enhance the estimated shaking beyond 1.5 s periods for locations located within 20 km of any of twelve major faults in the NSHM. The enhancement is for shaking in the direction perpendicular to the fault. This factor was developed from the Somerville *et al.* (1997) broad-band model, in which the motions are enhanced by a factor that increases with spectral period and magnitude.

Basin effects are, to some extent, accounted for in the broad building site classifications for deep or soft soils associated with the NSHM. However, these classifications are often a first approximation where details of the basin structure are unknown. Basins will tend to amplify waves at particular frequencies depending on the depth to bedrock (deeper basins tend to amplify longer period waves), the shear-wave velocity within the basin and the basin shape.

The seismicity model and attenuation relationship are combined to obtain probabilistic estimates of ground motions around the country. The probabilistic seismic hazard (PSH) model gives the estimated occurrence rates (or likelihood) for various strengths of earthquake shaking. The methodology was largely based on that of Frankel (1995) and Stirling *et al.* (1998).

5.2.3 Updates of the National Seismic Hazard Model since 2002

Since publication of the 2002 NSHM, two major updates of the model have taken place, the first being a regional update focussed on Canterbury (Stirling *et al.*, 2008), followed by a national-scale update in 2010 (Stirling *et al.*, 2011). The 2010 update pre-dated the Mw 6.3 Christchurch earthquake on 22 February 2011, but post-dated the Mw 7.1 Darfield earthquake on 4 September 2010.

The regional update of Canterbury in the NSHM was undertaken to provide Environment Canterbury with an up-to-date probabilistic seismic hazard model for their Earthquake Hazard and Risk Assessment project (Kingsbury *et al.*, 2001). The Canterbury model was a regional update of the 2002 NSHM in terms of earthquake sources, whereas the McVerry *et al.* (2006) attenuation relationship continued to be used for ground motion estimates. Newly identified fault sources were included in the update, mainly offshore from north Canterbury, Kaikoura and northeastern Marlborough, and all fault sources in the Canterbury region were assigned 'characteristic' earthquake magnitudes estimated from new New Zealand and international scaling relationships (i.e. magnitude derived from the length and estimated width of each fault source). The distributed seismicity model was updated for the entire country with earthquake data from 1998 to mid-2006 for the Canterbury model, and a new modelling method was also applied to the distributed seismicity model (Stock and Smith, 2002).

The 2010 update of the NSHM included over 200 new fault sources (mainly offshore), bringing the total number to about 530, and the New Zealand and international scaling equations used in the Canterbury model were applied to all faults. The Greendale Fault, source of the 4 September 2010, Mw 7.1, Darfield earthquake, was included in the fault source model at a late stage, albeit with a very long estimated recurrence interval (>10,000 years). This means that it has very little effect on the estimated long-term seismic hazard for Christchurch. The distributed seismicity model was also updated with earthquake data from 2006 to mid-2009, and the associated modelling methodology changed after rigorous evaluation of the various methods available (Stirling *et al.*, 2011). A new seismic regionalisation was also applied to the distributed seismicity model (Fig. 5.1).

No attempt was made to include other post-September 2010 seismicity in the NSHM update — short-term (time varying) hazard estimates for Canterbury are being addressed separately (Section 4.1). The new NSHM thus generally uses the same time-invariant methods embodied in the earlier NSHM, in that hazard is based on the long-term average rate of occurrence of earthquakes on the active faults. The only time-varying input to the new NSHM (i.e. hazard increasing with the time elapsed since the last earthquake) is on the major faults of the Wellington region (Rhoades *et al.*, 2010; Van Dissen *et al.*, 2010).

Probabilistic seismic hazard maps produced from the new NSHM show a similar pattern of hazard to the 2002 model at the national scale, with some significant reductions and increases in hazard in certain regions. The most significant differences seen on hazard maps and in uniform hazard spectra are:

- Reductions in Auckland and Northland, which are due to the new distributed seismicity model (e.g. Auckland's PGAs show a reduction from just over 0.1 g to 0.08 g for the c. 500 year return period);
- Increases in the south-eastern North Island due to the new Hikurangi subduction zone modelling (uniform hazard spectra increase at periods of 0.4 seconds and greater in Wellington);
- Slight increases in Christchurch for periods less than about 0.6 seconds due to the new distributed seismicity model; and
- Slight increases for Dunedin, again due to the new distributed seismicity model.

5.2.4 Future Changes to the National Seismic Hazard Model (NSHM)

The reasons for the exceptional damage caused by the Canterbury earthquake sequence have been discussed above in Sections 3 and 5.1. Here we discuss the implications for future changes to the NSHM. To understand these implications, two components of the model must be considered, namely the earthquake source model and the methods for calculating ground motion attenuation (the diminishing of shaking intensity with distance from the fault rupture). In re-evaluating the model, it must be stressed that the NSHM represents an average model of seismicity and hazard for the country. While we have obtained a large volume of new data from the Canterbury earthquakes, this represents data from only a relatively small number of earthquakes from one region, compared to the rest of the historical earthquake record for New Zealand, so care must be taken not to over-interpret these data.

5.2.4.1 *Future changes to the earthquake source model*

With a few exceptions for major faults, in the NSHM earthquakes are considered to be Poissonian (occurring randomly)—in other words, the probability of the future occurrence of any given earthquake is not influenced by the occurrence of any earthquakes before it. Recent research results from the Alpine, Hope, and Porters Pass Faults will enable us to move beyond simple Poissonian probabilities of earthquake occurrence. By using conditional probabilities, or probabilities of earthquake occurrence on faults based on known times of previous ruptures, better estimates of hazard can be calculated. For example, a hypothetical fault may have a chance of rupture of 1-in-300 years. If we have data indicating that this fault has not ruptured in, for example, 250 years, we can refine the probability to reflect that information, resulting in a higher predicted probability of rupture at present. Such modelling is highly dependent on good data on multiple past ruptures on a fault. As mentioned above, conditional probabilities have been used for Wellington faults in the latest update to the NSHM and for the Alpine, Hope and Porters Pass faults in the new seismic hazard model for Canterbury (Section 4.1). The next update to the NSHM will also need to include the largest events from the Canterbury earthquake sequence, but as their recurrence intervals are so long they will not greatly alter the long-term seismic hazard for Christchurch.

The background seismicity model in the NSHM is created by using all earthquakes we have recorded since about 1840. From this earthquake catalogue, we remove all aftershocks. The reason for removing them is that an aftershock sequence that was active 100 years ago will likely represent a higher rate of earthquakes than is considered likely for the current time period and will therefore result in an over-estimate of the hazard for a region. However, as has been demonstrated in Christchurch, the contribution of aftershocks to the overall hazard after a main shock has occurred can be very significant. Two aspects of the contribution of aftershocks to hazard that must be considered in refining the NSHM are: 1) leaving aftershocks in the catalogue for estimating the background seismicity rate, without predicting unjustified localised high rates of seismicity; and 2) allowing for an increase in expected seismic activity rates following an earthquake. For the latter, we currently do this after the fact (e.g. in the new seismic hazard model for Canterbury). In other words, we can estimate the increase in hazard after the occurrence of a large event, but we cannot allow for all possible main shock-aftershock sequences in the probabilistic seismic hazard (PSH) model. More research into how we can allow for this by using conditional probabilities is required.

Alternative ideas for smoothing seismicity, including aftershocks, are required and can build upon current research on this problem. Our recent aftershock modelling has been based on the STEP model (Gerstenberger *et al.*, 2004, 2005). There are other alternative models, such as the ETAS model (Ogata and Zhuang, 2006; Rhoades, 2009) and their use should be investigated. A global project to test earthquake forecast models (Schorlemmer and Gerstenberger, 2007), including aftershock models, against observed earthquakes, can also provide input to this process.

In addition to aftershock activity, it is known that there is a small chance that large earthquakes can trigger (or bring forward in time) other large earthquakes over distances of tens of kilometres and time frames from months to decades (see discussion in Section 4.1). Research is currently underway to understand how best to optimise the combination of

EEPAS with the fault-based model of the NSHM, including the spatial distributions used, in order to obtain a better estimate of the seismic hazard in Canterbury for the next few decades. Future development of the NSHM could incorporate such a composite source model.

As mentioned earlier, the active fault and background earthquake source models are combined by using a regional maximum magnitude, M_{cutoff} , of 7.2 for most parts of the country. In areas with low seismic activity, or areas with few active faults, the choice of M_{cutoff} can have significant implications for the estimated hazard. In consideration of the large number of damaging events that have occurred recently on previously unmapped faults, both globally and in New Zealand (including all Canterbury events), a thorough re-evaluation of M_{cutoff} is warranted, with a full consideration of uncertainties.

5.2.4.2 Future changes to how ground motions are predicted

Future improvements to the ground motion attenuation models for New Zealand need to incorporate new strong motion data from the Canterbury earthquake sequence, as well as much larger international ground-motion datasets than were available in 1996 when the international models that serve as the bases for the McVerry *et al.* (2006) model were developed. In addition, specific factors arising from the Christchurch experience need to be addressed, especially relating to earthquake stress drop and directivity. Other factors, such as basin response and the effect of near surface soils, will also be refined as a result of on-going research.

Theoretical relationships exist for modelling high stress drop events in attenuation relationships (Atkinson & Boore, 2006); however, to utilise these relationships in the NSHM requires better knowledge of the regional variability in earthquake stress drops and also analysis of the stress drops of the earthquakes used to develop the McVerry *et al.* (2006) relationship. One efficient way to estimate stress drop and to understand its regional variation is through the calculation of energy magnitudes, M_e, for all significant New Zealand earthquakes. Doing so requires an improved velocity model, but on-going work may allow for calculation of M_e in the near future.

The NSHM takes account of the expected directivity effects for earthquakes on 12 specific faults in the model. These near-fault directivity factors do not come into play for Christchurch or the Canterbury Plains, as the nearest fault to Christchurch for which this factor is required is the Kakapo Fault, at a distance of 100 km. Similarly, at its nearest point, the Alpine Fault is about 125 km from Christchurch.

According to the modelling that underlies the NSHM, the magnitude of the Christchurch earthquake should have been insufficient to cause strong directivity effects. However, it appears that forward-directivity may have contributed to the unusually strong motions in this earthquake for areas within 10 km of the earthquake rupture plane (see Section 3), in a manner consistent with a more recently developed narrow-band directivity model. As mentioned above, the NSHM near-fault directivity factors were developed from the Somerville *et al.* (1997) broad-band model. In more recent studies (Somerville, 2003), these effects are instead modelled over a narrow range of frequencies, with the centre frequency increasing with magnitude. If directivity is shown to have been a major factor in enhancing the shaking produced by the 22 February 2011 earthquake, consideration will need to be given to including narrow-band directivity in the updated NSHM.

Including a directivity factor for background (non-fault) sources is more problematical because there is no way to predict the direction of rupture. In this case, directivity may be accounted for by an appropriate increase in variability of expected ground motions. Such an increase would cause a small increase in predicted hazard across the country.

Basin effects are, to some extent, accounted for in the broad building site classifications for deep or soft soils used with the NSHM. However, these classifications are often a first approximation where details of the basin structure are unknown. Basins will tend to amplify waves at particular frequencies depending on the depth to bedrock (deeper basins tend to amplify longer period waves), the shear-wave velocity within the basin and the basin shape. Better determination of these properties will enable calculation of basin response (and the resonant frequencies of the basin) in a particular area. More detailed understanding of basin effects for various earthquake scenarios (and source locations) can be achieved by numerical wave modelling using a 3D model of the subsurface, where we have reasonably detailed knowledge of the basin structure (e.g. Benites & Olsen, 2005).

Improved information on site effects relies on a detailed knowledge of the particular site for which a probabilistic seismic hazard value is being calculated. This is currently done, in order of increasing detail, via regional maps of site conditions based on soil types, via detailed engineering geology analysis of the particular site, or using results from detailed micro-zonation studies, the latter allowing for the best understanding of the local variability of site conditions. Few micro-zonation studies have been carried out in the country, but through additional studies we will be able to improve the probabilistic seismic hazard estimates for more of New Zealand.

5.2.5 Use of the National Seismic Hazard Model in earthquake design

The NSHM provides the probabilistic hazard estimates used as the basis for the specification of design motions both in the New Zealand Standard NZS1170 and in specific hazard analyses carried out for major projects. In addition, there are deterministic lower and upper bounds based on motions estimated for specific earthquake scenarios: the lower bound is for motions at a distance of 20 km from a magnitude 6.5 earthquake and the upper bound for motions alongside the fault in a magnitude 8.1 Alpine Fault earthquake. Detailed discussion of the development of the NZS1170 section on site hazard spectra is provided in McVerry (2003), as well as in the commentary clauses of the standard. The main features are discussed in detail in Appendix 5.

As mentioned in Section 4.1, NZS1170 approximates the hazard estimates from the NSHM by specifying the hazard spectrum for horizontal loading as the product of four factors:

- 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 coefficients 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.

Consistent with long-time New Zealand practice, the defined elastic site hazard spectrum is for the larger of two orthogonal horizontal acceleration response spectrum components of random orientation.

The spectral shape factor is defined for four site classes: Strong Rock/Rock, Shallow Soil Sites, Deep or Soft Soil Sites and Very Soft Soil Sites. The rock classes are defined principally in terms of compressive strength, with any surface layer of material of less than 1 MPa compressive strength (i.e. soil rather than rock) required to be less than 3 m in thickness. The soil class definitions take into account both soil type and depth, with the Shallow and Deep or Soft Soil Site classes nominally separated by a site period of 0.6 s. In practice, the definitions are generally descriptive in nature, rather than requiring measurement of shear-wave velocities. A table supplies depths of various soil types that may be taken as corresponding to the 0.6 s boundary when shear-wave distributions with depth are unknown. The site-period approach recognises that the long-period site response of deep deposits of stiff or dense soils or gravels differ markedly from those shown by deposits of only a few tens of metres of the same material. Class E Very Soft Soil requires about 10 metres depth or more of materials that are likely to have shear-wave velocities of 150 m/s or less. The first three site classes are covered by the New Zealand attenuation model, and their spectral shape factors were obtained by fitting hazard results. The Class E spectra were derived by extending the plateau of the spectral shape for Class D Deep or Soft Soil to 1 s period, recognising the possibility of strong long-period amplification for Class E sites. Spectral shape factors are discussed in more detail in Appendix 5.

The hazard factor Z is a mapped quantity derived directly from the NSHM, corresponding to half the 0.5 s value of the magnitude-weighted[3] shallow soil spectrum for a return period of 500 years. The period of 0.5 s was selected for normalising the spectra to achieve reasonable matches of the shapes of the 500-year spectra throughout New Zealand when using a single normalisation period in place of two, as used in United States codes.

There is a minimum allowable value of Z=0.13, which comes into play in regions with low seismic activity such as Northland, Auckland and Dunedin; for those locations it corresponds to stronger earthquake motions than those with a return period of 500 years. The minimum Z factor is based on the 84th percentile motions from a magnitude 6.5 earthquake at 20 km distance. There is also an upper bound associated with 84th percentile motions estimated for

[3] See textbox 'Magnitude Weighting' in Appendix 5

a site alongside the fault in a magnitude 8.1 Alpine Fault earthquake. NZS1170 tabulates Z for many New Zealand towns, and also shows it in map form. Z values range from 0.13 for Auckland and Dunedin to 0.60 at Otira and Arthur's Pass, with a value of 0.4 for Wellington. The value of 0.22 for Christchurch increases to 0.30 at Darfield and 0.33 at Rangiora. Z factors will continue to be updated in future versions of the NSHM and, as mentioned in Section 4.1, will change with time for the new Canterbury seismic hazard model.

Structural designers are required to ensure that structures satisfy various performance conditions, referred to as limit states[4]. Currently, it is not practical to design for a collapse limit state, because structural performance at such an extreme level of loading is difficult to assess. Instead, design is for a lower level of earthquake motion, for a level of structural performance that can be more reliably predicted, known as the Ultimate Limit State (ULS). Target levels for the probability of collapse are of the order of 10^{-4} to 10^{-6} per year, to achieve an annual fatality risk of about 10^{-6} per year, as stated in Commentary Section C2.1 of NZS1170.5.

Seismic design for normal structures (NZS1170 Importance Level 2, IL2) for the Ultimate Limit State is based on motions with an estimated a return period of 500 years. Longer return periods of 1,000 years and 2,500 years are required for IL3 and IL4 structures, respectively. IL3 structures are those 'that as a whole may contain people in crowds or contents of high value to the community or pose risks to people in crowds'. IL4 structures are those 'with special post-disaster functions'. Table 3.2 of AS/NZS1170.0:2002 provides examples of structures that fall into the various Importance Levels.

The Return Period Factor, R, provides the conversion to return periods other than 500 years, as required for the Serviceability Limit State (SLS), or for the Ultimate Limit State for some types of structures, depending on their Importance Level. It is based on a representative variation of spectral acceleration of 0.5 s with return period for locations in New Zealand. The directly calculated 2,500-year R-factor for Christchurch is 1.55. As mentioned in Section 4.1, R has been adjusted for the new seismic hazard model for Christchurch, and would be adjusted appropriately for any new NSHM.

Usually, it is horizontal earthquake motions that are of importance for structural design. NZSZ1170.5 has a simplistic approach for vertical motions, taking the vertical spectra to be 0.7 times the horizontal spectra at the same location. Commentary clause C3.2 in the New Zealand Standard discusses vertical spectra, and provides several references on this topic (Niazi and Bozorgnia, 1992; Bozorgnia and Niazi, 1993; Ambraseys and Simpson, 1996). It points out that vertical spectra usually decrease more rapidly than horizontal spectra with increasing spectral period. It also points out that in regions close to the fault source the high-frequency content of vertical motions is often very strong, and may exceed the horizontal values. It concludes with the comment that 'At locations where the seismic hazard is dominated by a fault at a distance of less than 10 km, it may be more appropriate to assume that the vertical spectrum equals the horizontal spectrum for periods of 0.3 s and less'. These observations have been borne out by the nature of some of the vertical spectra in Christchurch (Section 3), although prior to the February earthquake there was no suggestion that the seismic hazard for Christchurch was dominated by nearby faults. In the light of the extreme vertical accelerations that were generated by the 22 February 2011 earthquake, the approach to designing for vertical motions in NZSZ1170.5 needs to be urgently re-evaluated.

[4] See textbox 'Limit states' in Appendix 5

6.0 CONCLUSIONS

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 has been a principal factor in determining how much shaking has been experienced. All of the three largest events have released high levels of energy for their size. It is thought that this is because the faults involved slip very occasionally and so are very strong.

Focussing of the seismic shaking, arising from the direction of rupture along the fault (known as directivity), is thought to have increased the severity of ground motions experienced in central Christchurch during the September and February earthquakes, but did not play a strong role in the Boxing Day or June earthquakes for the CBD area.

Overall there is a close match between the amounts of damage caused by the earthquakes and the horizontal ground shaking. Recordings of particular note were those from sites close to the CBD where the peak horizontal accelerations during the 22 February event were approximately twice as strong as during the other three earthquakes. Also notable were the strong vertical accelerations that exceeded the horizontal motions at some locations.

Although the 4 September 2010 earthquake was significantly larger than the other events, its epicentre was over 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 (displacements are another important ground motion measure, especially in the case of tall buildings).

At certain recording sites in the Christchurch CBD, shaking from the three largest earthquakes exceeded both the 500-year and more stringent 2,500-year design levels in the New Zealand Loadings Standard for certain frequencies of shaking.

The level of seismic hazard in Canterbury is currently higher than normal because of the numerous aftershocks that are occurring. In addition, there is a slight possibility that an earthquake of a size comparable to the main shock might be triggered. This elevated level of hazard needs to be considered when reassessing the safety of existing structures and when designing new buildings and infrastructure. In order to provide appropriate seismic design coefficients, a new seismic hazard model has been developed for Canterbury that reflects this increased level of hazard, taking into account likely rates of aftershocks, the small likelihood of larger earthquakes and the normal background seismicity and fault sources. The enhanced ground shaking observed from the February and June 2011 earthquakes has also been incorporated. The new model (which is still being developed) raises the Z factor (or regional design level) from 0.22 to 0.3 for Christchurch (Wellington's value is 0.4).

The Alpine Fault is a major geological feature in New Zealand, being 650 km long and crossing the South Island from northeast to southwest. The average return period of the fault is in the range 260–400 years, with no major event occurring in the last 294 years. It is a potential source of earthquakes up to magnitude 8.2. An Alpine Fault earthquake, however, would be at its closest 125 km from Christchurch. Some preliminary work to estimate the ground motions in Christchurch from such an event is presented here. These motions were calculated for very soft ground conditions, as are found in the Christchurch CBD and indicate that the maximum horizontal acceleration would be less than 0.04 g (compared to 0.4–0.8 g in February), but the duration of shaking could be at least 3 minutes.

The National Seismic Hazard Model for New Zealand is used to predict likely long-term rates of ground shaking to inform the Loadings Standard used in engineering design. Key components of this model are the earthquake sources (where earthquakes are likely to happen) and the ground motions that those earthquakes are likely to produce. In light of the lessons from Christchurch, the next update to this model will need to assess the importance of such factors as unknown faults close to major cities, enhanced ground shaking from a given earthquake and directivity in the ground shaking produced.

For evaluating the risk of earthquakes occurring close to cities, it is impossible to identify all active faults in a region because the relatively small faults associated with magnitude 6 earthquakes often have no surface expression so are particularly difficult to find. For this reason, the national model uses additional background earthquake sources of up to magnitude 7.2 to supplement existing active fault information. This assumes that an earthquake of up to magnitude 7.2 could occur on an unrecognized fault nearly anywhere in New Zealand, although the likelihood of this happening in low seismicity areas of the country is very small. Given this uncertainty, we need to be sure that the shaking from such earthquakes is correctly accounted for.

The unusually strong shaking observed from some of the larger Canterbury earthquakes can be allowed for in hazard models, providing we can anticipate where such events will occur. Current thinking is that they are likely to occur in areas with a low deformation rate, where faults seldom rupture and, as a result, are strong.

Fault directivity effects are already incorporated in the national hazard model (and building designs) for some of our major active faults. However, if directivity is shown to have been a major factor in enhancing the shaking produced by the 22 February 2011 earthquake, consideration will need to be given to including directivity for smaller earthquakes. Directivity effects can also be included in building design if sufficient variability in shaking is allowed for. In the light of the extreme vertical accelerations that were generated by the 22 February 2011 earthquake, the approach to designing for vertical motions in the Loadings Standard also needs to be re-evaluated.

Other factors that influence seismic shaking, such as the existence of blind faults, near-surface site effects and basin response can be assessed and some work has been undertaken in parts of New Zealand, but is far from complete.

7.0 ACKNOWLEDGEMENTS

This report draws on much work undertaken by other earth scientists in New Zealand and overseas, so where appropriate, such work has been referenced. We would like thank Professor Rick Sibson for useful discussions. We would also like to acknowledge the vision of the Earthquake Commission in supporting the GeoNet project from its inception in 2001 and, in addition, over many years helping to support New Zealand's national capability in earthquake science and engineering. Thanks are also due to Penny Murray, Carolyn Hume and Philip Carthew for assistance with report production.

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APPENDIX 1 DEFINITION AND CLASSIFICATION OF FAULTS

Faults are rock fractures across which there has been significant movement of the block on one side relative to the other. Faults represent the response of the rock formations to compression, tension or shearing forces. They can be classified on the basis of their orientation and the relative movement or slip across the *fault plane* (Fig. A1.1).

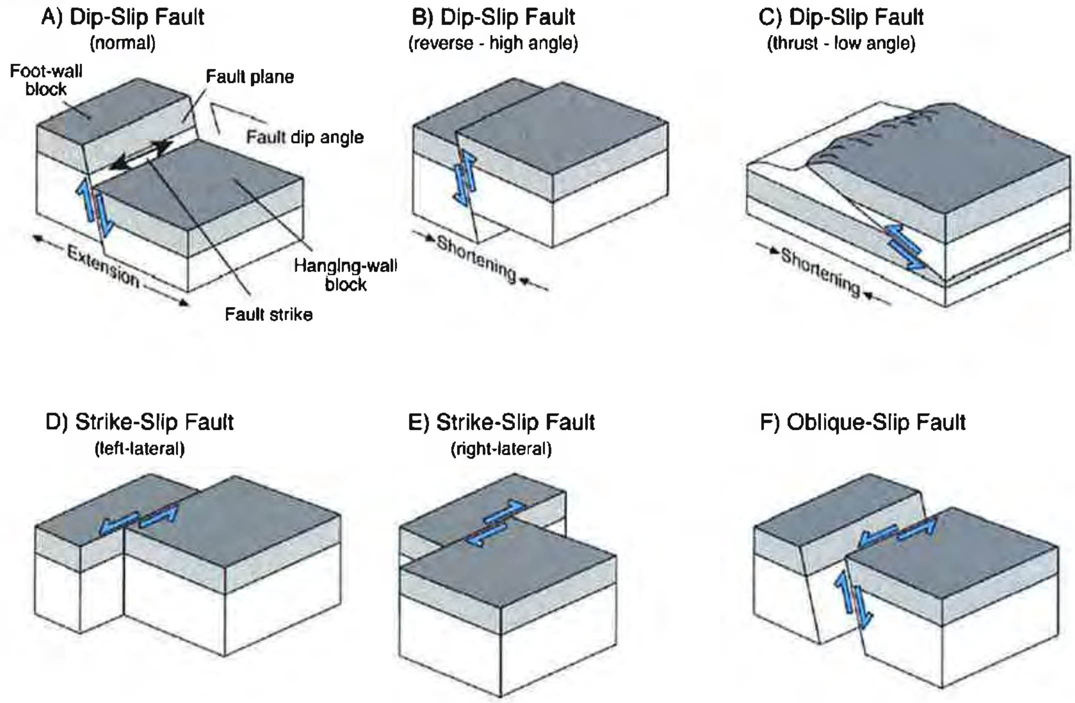

Figure A1.1 Fault classification and terminology: (A) to (C) dip-slip faulting; (D) and (E) horizontal or strike-slip faults, and (F) oblique-slip faulting. Other fault terminology is shown on block diagram (A). Figure modified from Pettinga *et al.* (2001).

Dip-slip faults are those in which the relative movement of one side to the other is parallel to the direction of inclination (the dip) of the fault (Fig. A1.1). If the upper block (hanging wall) above the fault plane has moved down the fault plane then the fault is called a *normal fault*, and if the upper block has moved up the fault plane it is called a *reverse fault*. When a fault plane has a shallow angle of dip (less than 45°) and the upper block has moved up the fault plane, it is called a *thrust fault*. Normal faults form in areas where the crust is being pulled apart, while reverse and thrust faults form in areas that are being compressed.

Strike-slip or lateral faults are defined by horizontal movement parallel to the line of the fault plane (Fig. A1.1). Strike-slip faults are often vertical, and movement is described as right-lateral or left lateral, based on the relative direction of movement of the ground on one side of the fault to the other. *Oblique-slip faults* occur where relative movement across the fault includes both horizontal and vertical slip (see Fig. A1.1).

A *fault trace* is the line where a fault intersects the ground surface and may be recognized by a displacement of the ground surface. If one side of a fault rises above the level of the other side, it may form a step-like linear *fault scarp*. Visible fault traces and fault scarps indicate that movement along the fault has been geologically recent.

A *fault strand* is an individual fault of a set of closely spaced, sub-parallel faults, while a *fault splay* is a subsidiary fault that diverges from a more prominent fault. Fault splays are common near the ends of major faults.

The term *slip rate* is used to refer to the average rate of displacement at a point along a fault. The slip rate is determined from offset geologic features whose age can be estimated. It is measured parallel to the dominant slip direction or estimated from the surveyed vertical or horizontal separation of geologic markers in the field.

APPENDIX 2 TECTONIC STRUCTURE OF THE CANTERBURY REGION

Much of the Canterbury region is located within the wide zone of active earth deformation associated with the oblique collision between the Australian and Pacific tectonic plates east of the Alpine Fault (see Fig. 2.3). The present day tectonic tempo of active earth deformation is greatest along the narrow zone adjacent to the Alpine Fault, and where the plate boundary zone transfers across South Island, through the Marlborough and north Canterbury areas to link with the offshore trench and subduction zone from near Kaikoura northward. In the north Canterbury region, the southward transition from subduction to continental collision is associated with tectonic shortening, crustal thickening and uplift. Landforms reflect the ongoing nature of this active earth deformation, and also show that the Australia-Pacific plate boundary zone deformation has progressively widened here, and continues to do so, during the Quaternary (~ last 1-2 myrs). East of the main divide of the Southern Alps, in central and south Canterbury, the tempo of tectonic deformation progressively diminishes to the east and southeast.

The upper crustal geological structure of the north Canterbury region is dominated by northeast trending active faults and folds which accommodate the transfer of relative plate motion between the Hikurangi Trough and the Alpine Fault and the Southern Alps to the southwest. For the central and south Canterbury region, structures are generally more northerly in trend, and are forming in response to the continent-continent collision zone of the eastern side of the deformation wedge to the Southern Alps.

A2.1 Major fault systems affecting the Canterbury region

The regions in and around Canterbury can be divided into eight distinct *structural domains* (Fig. A2.1) in which individual active faults are fundamentally related both in terms of their tectonic setting, style, geometry and rates of deformation with respect to the plate boundary zone. The eight domains are:

- *Domain 1 - Marlborough Fault Zone:* A major system of NE-trending strike-slip faults including the Hope, Clarence, Awatere and Wairau faults, which near their SW and NE terminations splay and form into oblique thrust faults. Along the Kaikoura coast, both north and south of the Hope fault, thrust faults, dipping mainly due west, serve to dissipate motion on this fault and accommodate crustal shortening associated with subduction of oceanic crust of the Pacific plate.

- *Domain 2 - West Culverden Fault Zone:* A west dipping system of thrusts and/or reverse faults and fault-related folds are mapped to the west of Culverden Basin. This range-front system of faults represent the eastern margin of the wedge-shaped Southern Alps foothills forming this structural domain in north Canterbury.

- *Domain 3 - Porters Pass-Amberley Fault Zone:* The Southern Alps foothills, and range front along the northwest margin of the Canterbury Plains, are evolving in response to a hybrid system of interconnected east-northeast trending strike-slip faults, and linking oblique thrusts and/or reverse faults with associated fault-related folds. The Porters Pass-Amberley Fault Zone is a juvenile fault system reflecting the latest phase of plate boundary zone widening in the late Pleistocene (0.5 to ~1 million years).

- *Domain 4 - North Canterbury Fold and Fault Belt:* Southwest from Kaikoura, thrust faults extend through the NE part of the onshore Canterbury region, and offshore across the continental shelf and slope. The thrusts are evolving in response to oblique plate convergence and the transition to continent-continent collision west of the Chatham Rise. Thrust faults are typically associated with strongly asymmetric folds involving greywacke basement and Tertiary cover rocks, and are expressed as topographic ridges separated by fault-related synclinal valleys floored by Quaternary alluvium and Tertiary formations. These NE-striking thrusts extend to within 5 km of the Hope Fault, implying that major right-lateral shear associated with the transfer of plate motion across northern South Island is mainly restricted to the Hope Fault and other faults of the Marlborough fault system. Further south the east-dipping thrusts extend west to the foot of the main ranges, along the north margin of the Canterbury Plains and southwest end of Culverden basin.

- *Domain 5 - Mt Hutt-Mt Peel Fault Zone:* The active earth deformation forming the Southern Alps and eastern foothills is essentially driven by the continent-continent plate collision across central South

Island. The eastern range front is characterised by active thrust faulting forming a complex segmented array of faults, folds and associated ground warping along the west margin of the Canterbury Plains from near Mt Hutt to south of Mt Peel.

- *Domain 6 - South Canterbury Zone:* Further south, the margin of the Southern Alps is again defined by a number of thrust faults east of the MacKenzie Basin and south of the Rangitata River. Major fault zones are mapped along the eastern range front of the Hunter Hills, and the Fox Peak Fault Zone defines the boundary between Domains 5 and 6.

  Domain 7 - Canterbury Plains Zone: Active earth deformation, mostly obscured beneath the Quaternary alluvium of the Canterbury Plains is indicated by earthquake activity. The 4 September 2010 right lateral-slip Greendale fault surface rupture associated with the M7.1 Darfield Earthquake is one such structure. This was further re-enforced by the subsurface ruptures associated with the 22 February and 13 June 2011 earthquakes, both on previously unrecognised buried faults in the subsurface beneath Christchurch and surrounds. The Canterbury Plains region thus needs to be a target for future research to locate and document other hidden faults capable of generating moderate to large earthquakes in the region.

- *Domain 8 - Southern Alps Zone:* Major active faults located in the area east of the main divide in central South Island include the Ostler thrust fault zone and the Main Divide fault zone. Deformation is accommodated on numerous oblique reverse/thrust faults, and is reflected by the crustal uplift within the Southern Alps.

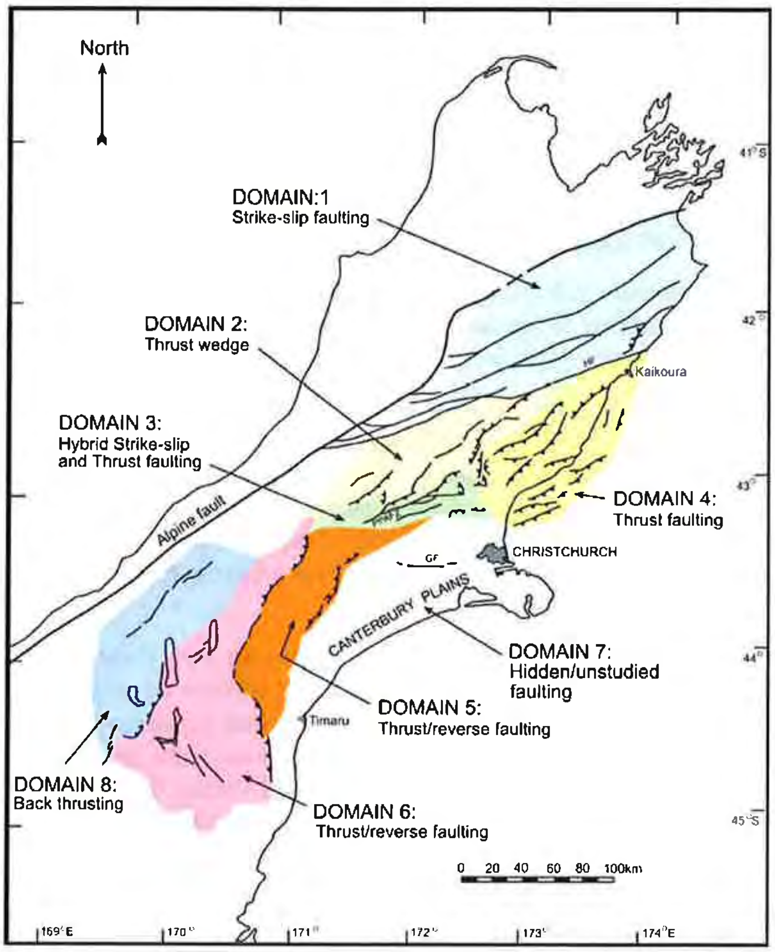

Figure A2.1 Summary map of the structural domains 1-8 for the Canterbury Region. Abbreviations: GF- Greendale fault; HF - Hope fault; PPAFZ - Porters Pass-Amberley fault zone. Figure modified from Pettinga *et al.* (1998).

APPENDIX 3 PREVIOUS MAJOR EARTHQUAKES IN NEW ZEALAND HISTORY

A3.1 Earthquakes in Māori oral history

Māori oral history includes accounts of earthquakes, including large earthquakes in Taupo, Rotorua, and the Whanganui River areas. According to Māori tradition, Wellington's harbour originally had two entrances and Miramar was an island. A great earthquake known as 'Hao-whenua' (land swallower or destroyer) raised the area and the channel between Miramar and the mainland silted up, converting Miramar to a peninsula.

A3.2 A shaky early history - 1840 to 1904

Settlers in the Wellington area felt their first earthquake on 26 May 1840, barely four months after arriving in New Zealand.

8 July 1843 – Western Hawke's Bay (Wanganui) earthquake

On 8 July 1843, an earthquake of estimated magnitude 7.6 shook the North Island, with building damage in Wanganui. Two people were killed by a landslide triggered by the quake—the earliest written report of an earthquake causing deaths in New Zealand.

16 October 1848 – Marlborough (Awatere) earthquake

On 16 October 1848, at 1:40 AM, settlers in the upper South Island and lower North Island experienced a strong earthquake, of magnitude 7.4-7.7. A major fault along the Awatere Valley ruptured over a length of 105 kilometres, with up to 8 metres of horizontal movement. Damage in Wellington was severe, with nearly 80 buildings seriously damaged. Wooden buildings survived well, but many brick buildings collapsed—a man and his two children were killed by a falling brick building during an aftershock.

23 January 1855 - Wairarapa earthquake

New Zealand's largest historical earthquake, a powerful magnitude 8.2-8.3 shock, occurred on 23 January 1855 and was centred near the Wairarapa and Wellington. The southern end of the Rimutaka Range rose by over 6 metres, and land shifted as much as 13–18 metres horizontally along the western edge of the Wairarapa. Despite damage to buildings in Wellington, the number of fatalities was very low—one in Wellington, with perhaps eight others in the Wairarapa and Manawatu. The earthquake also created a tsunami in Cook Strait and Wellington harbour.

19 October 1868 - Cape Farewell earthquake

On 19 October 1868, a powerful earthquake with an estimated magnitude of 7.2-7.6 occurred just north of Farewell Spit. The earthquake damaged houses in the Collingwood, Pakawau and Farewell Spit area, and also the Taranaki region.

1 September 1888 – North Canterbury (Amuri) earthquake

On 1 September 1888, at 4:12 AM, a magnitude 7.0-7.3 earthquake centred near Amuri damaged settlements in the Hope Valley and Hanmer region. Caused by rupture along the Hope Fault in north Canterbury, it was one of the first documented examples worldwide of a large earthquake with horizontal ground movement along a fault. The quake brought down the top 7.8 metres of the spire of Christchurch Cathedral.

16 November 1901 – Cheviot earthquake

On 16 November 1901, at 7:47 AM, a magnitude 6.8 earthquake centred near the township of Cheviot shook the north Canterbury region. Cheviot was badly damaged and a baby was killed in the collapse of a sod hut. Christchurch had some minor damage, and Christchurch Cathedral lost the top 1.5 metres of its spire.

A3.3 A quiet period - 1905 to 1928

Few damaging earthquakes of magnitude 7 or greater occurred between 1905 and 1928. Every year from 1913 to 1926 the New Zealand Official Yearbook noted that 'earthquakes in New Zealand are rather a matter of scientific interest than a subject for alarm'.[1]

A3.4 A cluster of major earthquakes - 1929 to 1947

9 March 1929 – Arthur's Pass earthquake

On 9 March 1929, the Arthur's Pass National Park area was struck by a magnitude 7.0 earthquake. There were no deaths, but the quake caused many landslides and closed the main highway to the West Coast for several months.

17 June 1929 – Buller (Murchison) earthquake

On 17 June 1929, at 10:20 AM, the northern South Island was shaken by a massive magnitude 7.3 earthquake centred near Murchison. The quake triggered at least 50 large landslides. Of the 17 people who died in the quake, 14 were killed by landslides. Slides blocked the Buller and Maruia rivers, and Seddonville was damaged by floods when a landslide dam burst. Many roads were heavily damaged and could not re-open for months.

3 February 1931 - Hawke's Bay (Napier) earthquake and 13 February aftershock

New Zealand's deadliest earthquake occurred at 10:48 AM on 3 February 1931. In the magnitude 7.4-7.6 Hawke's Bay earthquake, 256 people died—161 in Napier, 93 in Hastings and 2 in Wairoa. Most people were killed by the collapse of buildings and by falling debris (Fig. A3.1). In Napier fires burned uncontrolled for two days, gutting four hectares of the business district. The fault that caused the earthquake did not reach the surface, but the land was warped upward, with parts of Napier raised by nearly 3 metres.

The largest aftershock, a powerful magnitude 7.3-7.5 earthquake, occurred ten days after the main earthquake—its epicentre was about 50 kilometres from that of the main quake.

Photo: Alexander Turnbull Library, 1/2-002952-F

Figure A3.1 Completed just one year before the quake, the Nurses' Home in Napier collapsed in the 1931 Hawke's Bay earthquake, killing 11 people and injuring six. The earthquake and ensuing fires caused extensive damage in both Napier and Hastings.

15 September 1932 - Wairoa earthquake

At 1:27 AM on 15 September 1932, a magnitude 6.9 earthquake shook Wairoa and Gisborne and caused large slips. Wairoa had many damaged buildings, including its hospital. A bridge over the Wairoa River being built to replace one destroyed a year earlier in the Napier earthquake collapsed. Gisborne also had some damaged buildings.

5 March 1934 – Horoeka (Pahiatua) earthquake

At 11:50 PM on 5 March 1934, the Hawkes Bay and Wairarapa area experienced a magnitude 7.2-7.4 quake. Centred near Horoeka, east of Pahiatua, the earthquake caused extensive damage there and in Eketahuna, Woodville, Dannevirke, Masterton, Palmerston North, Foxton and Levin. There was one death, the victim of a heart attack.

24 June and 2 August 1942 – Masterton earthquakes

Two major earthquakes centred near Masterton struck the Wairarapa and Wellington area on 24 June and 2 August 1942—the first was magnitude 6.9-7.2, the second magnitude 6.8. One man was killed in the June earthquake by gas leaking from a fractured pipe. Damage to buildings in Wellington and towns in the Wairarapa was extensive, due to the cumulative effect of the two earthquakes. Two blocks of Manners Street were closed for several months after the August quake because of the dangerous state of the buildings. The cost of repairs from these quakes was so great that the government set up an Earthquake and War Damage Commission for earthquake insurance in 1944.

27 June 1946 - Lake Coleridge earthquake

This magnitude 6.5 earthquake caused minor structural damage to homesteads in the Upper Rakaia basin and the Lake Coleridge hydro-electric power station. There were also numerous landslides and changes to watercourses. It was followed by numerous aftershocks that persisted until the end of 1949.

A3.5 Another extended quiet period - 1949 to 2000

The latter half of the twentieth century in New Zealand, from 1949 to 2000, was a relatively quiet period for earthquake activity. Just a few large magnitude earthquakes occurred, with most of them too far offshore to cause much damage. However, the 1968 Inangahua earthquake and smaller magnitude 6.5 Edgecumbe earthquake caused extensive damage.

24 May 1968 – Inangahua earthquake

On 24 May 1968, the northern South Island was rocked by a magnitude 7.1 earthquake centred near the town of Inangahua Junction, near Murchison. The shaking triggered numerous landslides that killed two people and blocked roads through the region for months. A large landslide temporarily blocked the Buller River, and hundreds of people were evacuated by helicopter from the valley downstream of the landslide.

2 March 1987 – Edgecumbe earthquake

On 2 March 1987, at 1:42 PM, a magnitude 6.5 earthquake hit the Bay of Plenty region. Luckily, a minor foreshock occurred seven minutes before the main quake, so some factories and schools had already been evacuated. No one was killed, but about 25 people were injured. A fault rupture, about 7 kilometres long and up to 4 metres high, opened up across the countryside. Property damage was widespread in Edgecumbe and Kawerau.

A3.6 New Zealand earthquakes in the twenty-first century

The twenty-first century has seen an increase in the number of large earthquakes. Before the Canterbury and Christchurch earthquakes of 2010 and 2011, however, the most powerful earthquakes were 'subduction earthquakes' centred in or near Fiordland.

21 August 2003 – Fiordland earthquake

Just after midnight on 21 August 2003, the Fiordland area was shaken by a magnitude 7.2 earthquake, centred at Secretary Island. The quake triggered more than 400 landslides and generated a 20 cm high tsunami.

20 December 2007 – Gisborne earthquake

On 20 December 2007 at 8.55 pm, a magnitude 6.6 earthquake, centred 50 kilometres off the east coast of the North Island, caused substantial damage in Gisborne's central business district, with three buildings collapsing. An elderly woman died from a heart attack, and 11 people were injured.

15 July 2009 – Fiordland earthquake

A magnitude 7.8 earthquake centred in Fiordland National Park near Dusky Sound struck on 15 July 2009. No injuries or fatalities were reported, and it caused only minor damage and some landslides. Land near the epicentre rose about one metre and Puysegur Point moved 30 cm closer to Australia.

APPENDIX 4 STRONG MOTION DATA

More than 100 accelerograms were returned by the GeoNet earthquake recorder network during each of the largest events in the Canterbury earthquake sequence, starting with the Darfield Earthquake of September 2010. For many reasons, this dataset is the most significant recorded in New Zealand since strong-motion recording began here in the early 1960s. Since then, there have been 61 New Zealand records with PGA greater than 0.3 g. Sixty-nine percent of these were from the Christchurch earthquake and aftershock sequence, 23 % from the Darfield Earthquake and aftershocks, and just 8 % from other earthquakes. In addition, two building response records exceeding 0.3 g were recorded in the February event (0.84 and 0.46 g) in the Christchurch Police Station. Of particular importance are the seventeen ground and structural records from the sequence within 10 km of the fault plane. The strong motion data set will be invaluable in seismological studies. When combined with construction and ground data it will provide a unique opportunity to explain and then help prevent similar levels of damage in future large earthquakes.

Table A4.1 lists the most significant records from the Canterbury earthquakes, with the most significant points highlighted (distance < 10 km, PGA > 1 g, important locations). None of the records from the magnitude 4.9 earthquake of 26th December 2010 were strong enough to be included.

Accelerations were clearly strongest in the February 22 Christchurch earthquake. However, displacements were greatest during the 4 September Darfield earthquake, in keeping with expected from the larger magnitude event (Fig. A4.1). Large earthquakes such as the September 4 Darfield event tend to generate stronger low-frequency motions, thus the sizes of the peak displacements were largest for this event, somewhat smaller for the February and June events, and very small for the magnitude 4.7 Boxing Day earthquake.

Table A4.1 Earthquake records with peak ground accelerations (PGA) of 0.5 g and above. 'Dist' is the distance from surface projection of the fault plane(s) to the recording site, except for the June event where epicentral distances are listed (and the fault plane is yet to be accurately determined). 'CBD' indicates a site in the Central Business District of Christchurch.

Earthquake	Dist. (km)	PGA (g)		Type of Site	Name of Recording Site
		Vertical	Horizontal		
4 Sept. 2010 Mw 7.1	**1.3**	**1.3**	0.8	Rural	Greendale
	9	0.9	0.5	Rural	Lincoln Crop and Food Research
	8	0.9	0.3	Rural	Templeton School
	7	0.8	0.5	Rural	Hororata School
	2	0.7	0.4	Rural	Rolleston School
	6	0.4	0.5	Rural	Darfield High School
	27	0.3	0.6	Valley	Heathcote Valley Primary School
22 Feb. 2011 Mw 6.2	**2.8**	0.8	0.5	**CBD**	Catholic Cathedral College
	3.9	0.6	0.4	**CBD**	Christchurch Hospital
	4.7	0.5	0.7	**CBD**	Christchurch Resthaven
	4.7	0.4	0.6	**CBD**	Christchurch Botanic Gardens
	3.8	0.8	0.5	**High-rise**	Christchurch Police Stn (13th Flr)
	7.1	0.5	**1.0**	Port	Lyttelton Port Company
	2.3	**1.9**	0.7	Soft soil	Pages Road Pumping Station
	3.8	**1.1**	0.3	Soft soil	Hulverstone Drive Pumping Station
	1.1	0.9	0.4	Soft soil	Christchurch Cashmere High Sch.
	3.7	0.8	0.8	Soft soil	North New Brighton School
	3.9	**2.2**	**1.7**	Valley	Heathcote Valley Primary School
13 June 2011 Mw 6.0	**6**	0.5	0.3	Port	Lyttelton Port Oil Wharf
	5	0.3	0.6	Port	Lyttelton Port Company
	3	**1.1**	**2.0**	Ridge Crest	Godley Drive
	1	0.7	0.8	Ridge Crest	Panorama Road
	3	0.6	0.6	Ridge Crest	Summit Road
	6	0.8	0.5	Soft soil	Pages Road Pumping Station
	3	0.7	**1.1**	Valley	Heathcote Valley Primary School

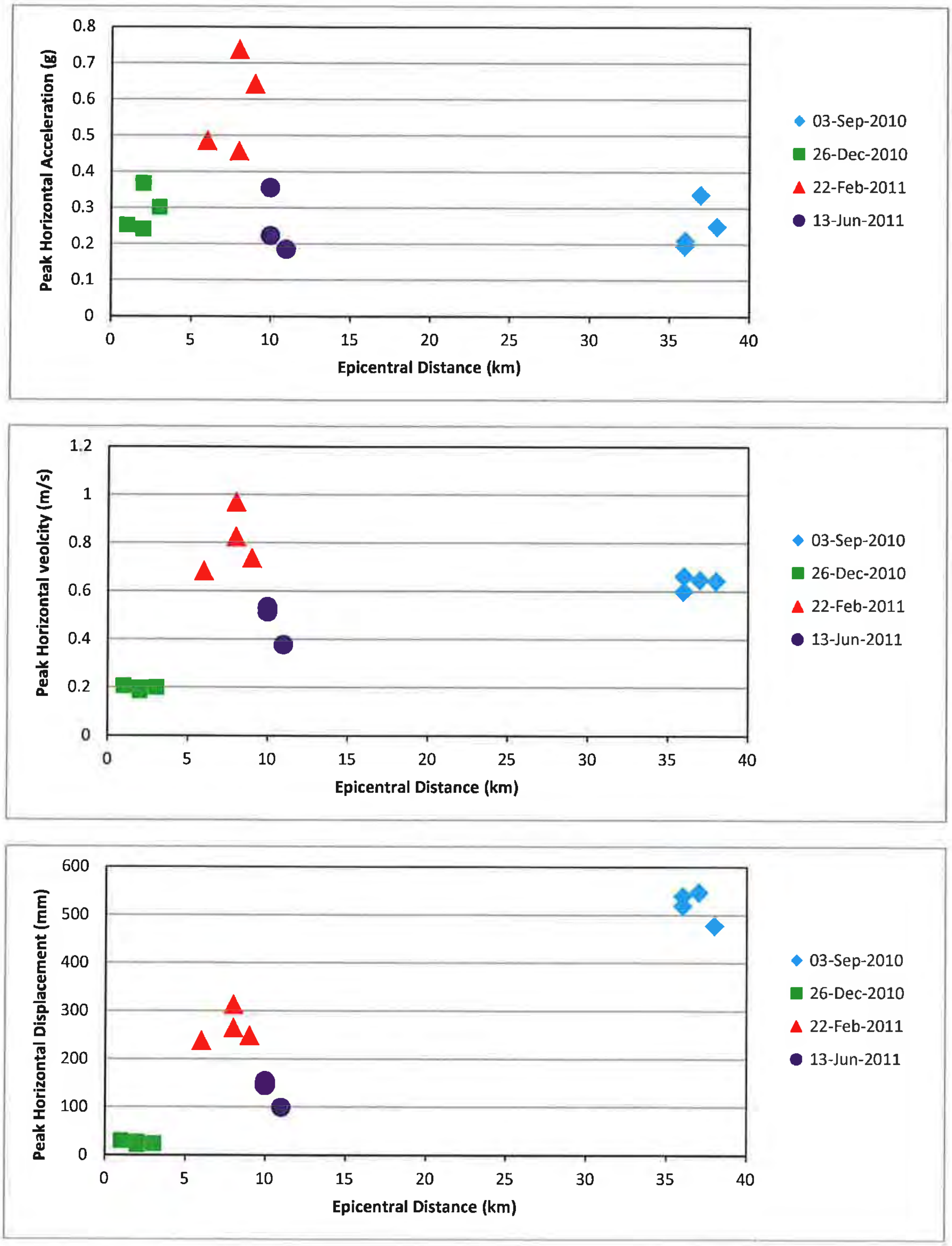

Figure A4.1 Peak horizontal accelerations (top), velocities (middle) and dynamic displacements (bottom) recorded at CBD sites in Christchurch during the four listed earthquakes. The 22 February event gave the strongest accelerations and velocities, but the 4 September 2010 Darfield Earthquake gave the largest dynamic displacements.

A4.1 Displacement spectra and vertical spectra

Figure A4.2 shows the 5% damped relative displacement response spectra for the motions recorded in the 4 September 2010, 22 February 2011 and 13 June 2011 earthquakes at the REHS, CHHC, CCCC, and CBGS sites surrounding the Christchurch CBD. The plots are for the larger of the as-recorded orthogonal horizontal components, consistent with NZS1170 design motions. They are compared with the NZS1170 Class D deep or soft soil spectra derived using $SD(T)=C(T)(T/2\pi)^2$ for Christchurch's hazard factor $Z=0.22$ and return period factors of $R=1.0$ (500 year return period) and $R=1.8$ (2,500 year return period).

The September spectra range from close to the NZS1170 500-year spectrum for periods less than 2 s to exceeding the 2,500 year spectrum for two of the sites for periods from about 2.2 s to 4 s. The February spectra are close to or exceed the 2,500 year spectra for all four sites for periods up to about 4 s, and lie between the 500 and 2,500 year spectra for periods from 4 s to 10 s. The June spectra exceed the 500 year spectrum, and the 2,500 year spectrum at some periods for the REHS SITE, before falling below the 500 year spectrum for periods longer than about 2–2.5 s.

The maximum 5% damped relative displacement demands reached to over one metre for one of the sites in September and three of the sites in February.

A feature of the February earthquake was strong peak vertical ground accelerations that exceeded the peak horizontal ground accelerations at some locations (Fig. 3.8). The vertical spectra are strong only at short periods. Figure A4.3 shows that for the four sites surrounding the CBD, the vertical spectra (solid lines) exceed the horizontal spectra (dashed lines) only for periods up to about 0.12 s to 0.25 s, before falling away sharply for periods longer than about 0.35 s.

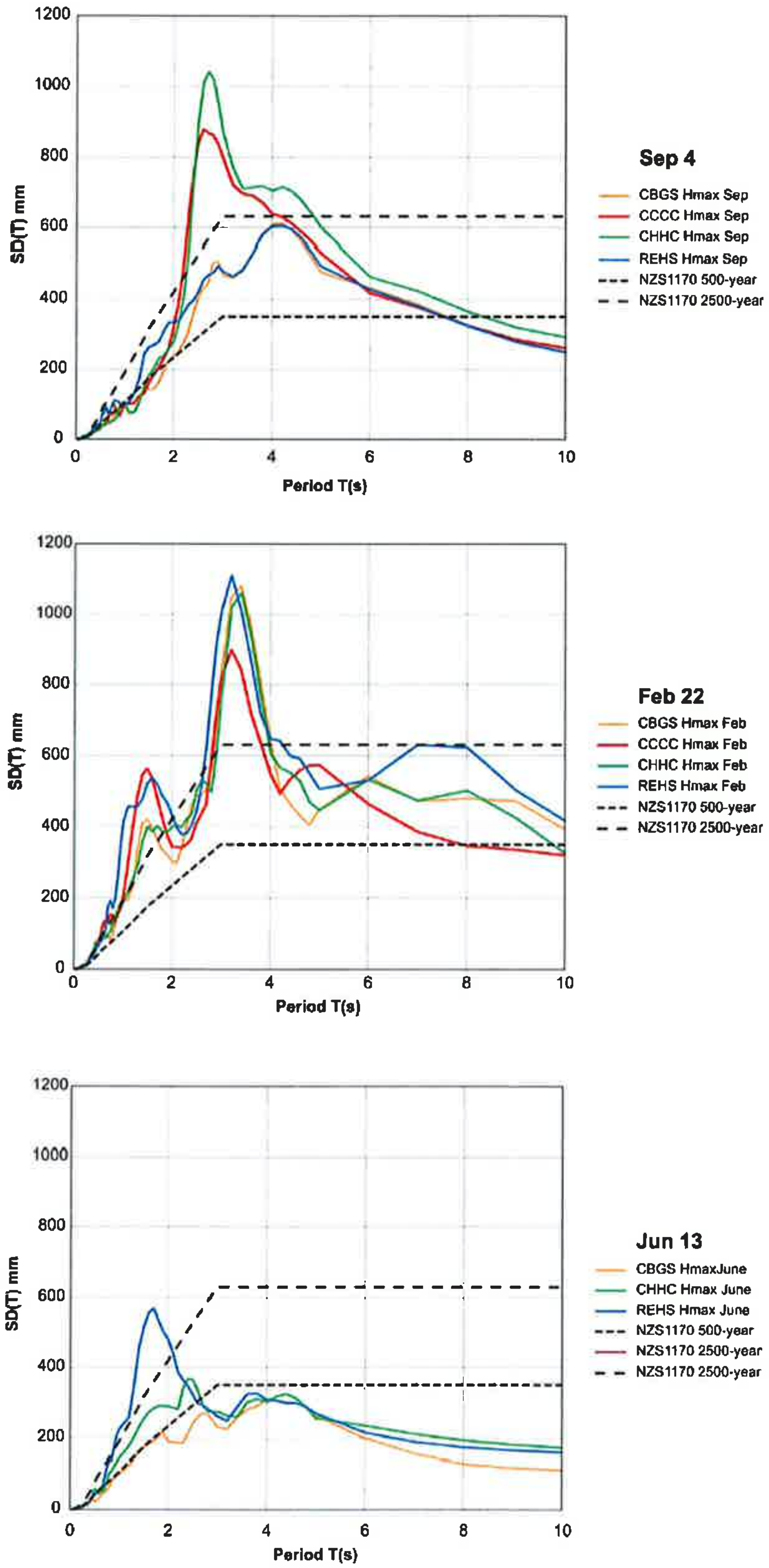

Figure A4.2 5% damped relative displacement response spectra for the larger horizontal component in the three earthquakes compared with the displacement spectra derived from the NZS1170 Z=0.22 spectra for Christchurch for return periods of 500 years (dotted) and 2500 years (dashed).

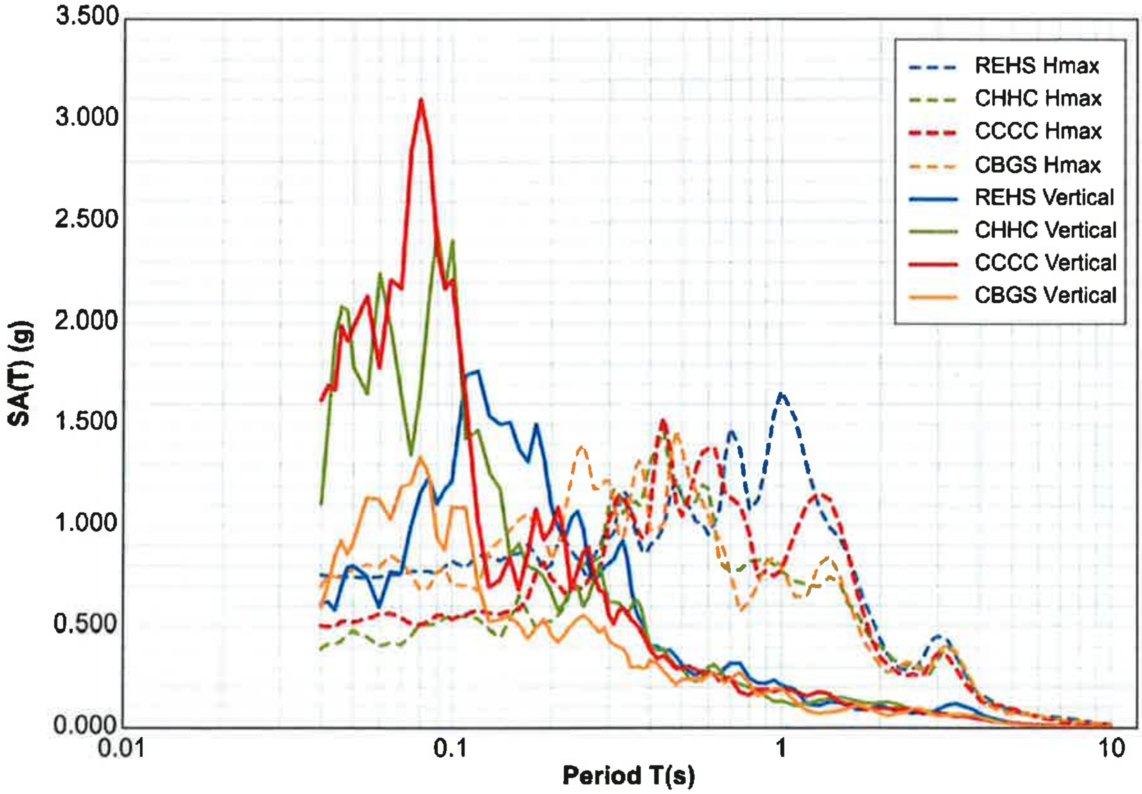

Figure A4.3 The 5% damped acceleration response spectra for the vertical (solid lines) and the larger horizontal component (dashed lines) in the 22 February 2011 earthquake. The vertical spectra exceed the horizontal spectra only for periods up to about 0.12 s to 0.25 s, before falling away sharply for periods longer than about 0.35 s.

APPENDIX 5 USE OF THE NATIONAL SEISMIC HAZARD MODEL IN EARTHQUAKE DESIGN

The NSHM is used in earthquake engineering design through forming the basis for the specification of design motions both in the New Zealand Standard NZS1170 and in specific hazard analyses performed for major projects.

The seismic design motions specified in NZS1170.5:2004 are based on probabilistic hazard estimates from the NSHM. There are deterministic lower and upper bounds corresponding to motions estimated for specific earthquake scenarios, namely associated with the motions at 20 km distance from a magnitude 6.5 earthquake and those alongside the fault in a magnitude 8.1 Alpine Fault earthquake. Detailed discussion of the development of the NZS1170 section on site hazard spectra is provided in McVerry (2003), as well as in the commentary clauses of the standard. The main features are discussed below.

NZS1170 approximates the hazard estimates from the NSHM by specifying the elastic site hazard spectrum for horizontal loading, C(T), as the product of four factors

$$C(T) \quad = \quad C_h(T)\ Z\ R\ N(T,D)$$

Consistent with long-time New Zealand practice, the defined elastic site hazard spectrum C(T) is for the larger of two orthogonal horizontal acceleration response spectrum components of random orientation.

The spectral shape factor $C_h(T)$ is defined for four site classes : Strong Rock/Rock, Shallow Soil Sites, Deep or Soft Soil Sites and Very Soft Soil Sites. The rock classes are defined principally in terms of compressive strength, with any surface layer of material of less than 1 MPa compressive strength (i.e. soil rather than rock) required to be less than 3 m in thickness. Soil class definitions take into account both soil type and depth, with the Shallow and Deep or Soft Soil Site classes nominally separated by a site period of 0.6 s. In practice, the definitions are generally descriptive in nature, rather than requiring measurement of shear-wave velocities. A table supplies depths of various soil types that may be taken as corresponding to the 0.6 s boundary when shear-wave distributions with depth are unknown. The site-period approach recognises that deep deposits of stiff or dense soils or gravels exhibit long-period site response characteristics markedly different from those shown by deposits of only a few tens of metres of the same material. Class E Very Soft Soil requires about 10 metres depth or more of materials that are likely to have shear-wave velocities of 150 m/s or less. The first three site classes are covered by the New Zealand attenuation model and their spectral shape factors were obtained by fitting hazard results. The Class E spectra were derived by extending the plateau of the spectral shape for Class D Deep or Soft Soil to 1 s period, recognising the possibility of strong long-period amplification for Class E sites. Spectral shape factors are discussed in more detail later in this section.

The hazard factor Z is a mapped quantity derived directly from the NSHM, corresponding to half the 0.5 s value of the magnitude-weighted[5] shallow soil spectrum for a return period of 500 years. The period of 0.5 s was selected for the normalisation of the spectra to achieve reasonable matches of the shapes of the 500-year spectra throughout New Zealand when

[5] See textbox 'Magnitude Weighting'

using a single normalisation period in place of two, as used in U.S. codes. The factor of a half was to achieve a numerical value of the Z-factor that corresponds to the value in *g* of the peak ground acceleration for the rock site class, a requirement to conform with ISO standards. The rock peak ground acceleration is not used directly for scaling the spectra because it is a notoriously poor spectral scaling parameter. There is a minimum allowable value of Z=0.13, which comes into play in low seismicity regions such as Northland, Auckland and Dunedin, corresponding to stronger earthquake motions than those with a return period of 500 years for those locations. The minimum Z factor is based on the 84^{th} percentile motions from a magnitude 6.5 earthquake at 20 km distance. There is also an upper bound RZ=0.7 (the Return Period Factor, R, is discussed below), associated with 84^{th} percentile motions estimated for a site alongside the fault in a magnitude 8.1 Alpine Fault earthquake. NZS1170 tabulates Z for many New Zealand towns, and also shows it in mapped form. Z values range from 0.13 for Auckland and Dunedin to 0.60 at Otira and Arthur's Pass, with a value of 0.4 for Wellington. The value of 0.22 for Christchurch increases to 0.30 at Darfield and 0.33 at Rangiora.

Magnitude Weighting

A feature of the hazard estimates performed in deriving the NZS1170 spectra is that the spectra incorporate magnitude weighting for periods up to 0.5 s, addressing a criticism of uniform-hazard spectra that they tend to be dominated by contributions from moderate-magnitude earthquakes, and do not reflect the effect of duration in causing structural damage. The magnitude weighting method scales the expected spectra for any event according to earthquake magnitude, to reflect duration effects which affect the damage potential of motions for a given peak response.

The magnitude weighting procedure used in formulating the earthquake loadings given in NZS1170.5 is the same as that used in modifying peak ground accelerations in the long-established Seed and Idriss methodology (Seed and Idriss 1982; Idriss, 1985) for assessing liquefaction potential. A study by Kennedy *et al.* (1984) for the US Nuclear Regulatory Commission which was discussed in Idriss (1985) showed that the magnitude weighting factors developed for liquefaction studies are also relevant to the response of ductile structures.

In Idriss's method, response spectrum values for magnitude M are scaled by a factor $(M/7.5)^{1.285}$ for periods between 0.0 s and 0.5 s. This factor is intended to produce estimates that are equivalent to magnitude 7.5 values in terms of damage potential. As a result, at short spectral periods magnitude-weighted spectral accelerations are usually less than those from uniform hazard analysis. For example, the magnitude weighting factor for magnitude 6 is 0.75. For spectral periods longer than 0.5 s, small-to-moderate magnitude earthquakes produce significantly weaker motions than larger magnitude events, so scaling is not necessary.

Currently, it is not practical to design for a collapse limit state, because structural performance at such an extreme level of loading is difficult to assess. Instead, design is for a lower level of earthquake motion, for a level of structural performance that can be more reliably predicted, known as the Ultimate Limit State (ULS). Target levels for the probability of collapse are of the order of 10^{-4} to 10^{-6} per year, to achieve an annual fatality risk of about 10^{-6} per year, as stated in Commentary Section C2.1 of NZS1170.5.

Seismic design for normal structures (NZS1170 Importance Level 2, IL2) for the ULS is based on motions with an estimated a return period of 500 years. Longer return periods of 1,000 years and 2,500 years are required for IL3 and IL4 structures, respectively. IL3 structures are those 'that as a whole may contain people in crowds or contents of high value to the community or pose risks to people in crowds'. IL4 structures are those 'with special post-disaster functions'. Table 3.2 of AS/NZS1170.0:2002 provides examples of structures that fall into the various Importance Levels.

Limit States

Structural designers are required to ensure that structures satisfy various performance conditions, referred to as limit states. The performance requirements are to meet objectives that 'frequently occurring earthquake shaking can be resisted with a low probability of damage sufficient to prevent the building from being used as originally intended', and that 'the fatality risk is at an acceptable level' (NZS1170.5, Clause C 2.1). Normal use structures are required to satisfy two limit states, Serviceability Limit State 1 (SLS1) and the Ultimate Limit State (ULS). Structures designated as having special post-disaster functions are required also to satisfy a more severe Serviceability Limit State 2 (SLS2).

SLS1 requires a structure to continue to be used as originally intended without repair. For earthquakes, this requirement is to be met in motions with a return period of 25 years.

SLS2 requires that the structure must remain operational in more severe motions, usually those with a return period of 500 years.

The ULS requirements are that the structure must not endanger people within or adjacent to the structure; displacements of the structure are such as to avoid unintended contact between parts of the structure or separate structures on the same site if that contact would cause damage sufficient to endanger people or detrimentally affect the response of the structure, or reduce the strength of structural elements below their required strength; the structure does not deflect beyond a site boundary adjacent to which other structures can be built; and there is no loss of integrity of the structure or its parts. The return periods associated with the ULS depend on the Importance Level of the structure, and its design life. Usually they are 500 years for normal use structures, 1,000 years for major structures, and 2,500 years for post-disaster structures.

The Return Period Factor, R, provides the conversion to return periods other than 500 years, as required for the SLS, or for the ULS for some types of structures, depending on their Importance Level. It is based on a representative variation of SA(0.5 s) with return period for locations in New Zealand. The R-factors for return periods of 1,000 and 2,500 years are 1.3 and 1.8, respectively. Figure C3.3c of NZS1170.5:2004 compares the NZS1170 R-factor curve with the actual hazard curves for Auckland, Wellington, Christchurch, Dunedin and Otira calculated from the NSHM. Christchurch has a less rapid increase of R with return period than most parts of New Zealand. The directly calculated 2,500-year R-factor for Christchurch is 1.55, considerably less than the NZS1170 requirement of 1.8, i.e. the specified 2,500-year design motions for Christchurch are enhanced by a factor of 1.8/1.55 over the hazard estimates.

The main reason for differences between site-specific and NZS1170.5 spectra is that in NZS1170.5 a given site-class is assigned the same spectral shape for all locations in New Zealand for all return periods. The shapes of the hazard spectra on which $C_h(T)$ are based vary with location and return period, reflecting different combinations of magnitudes and distances of the earthquakes that contribute most to the hazard for a specific location and return period. The spectral shapes assigned in NZS1170 are required to be conservative, and are close to upper-bound envelopes across New Zealand of the spectral shapes actually obtained from hazard analyses, apart from truncation of the peaks of the spectra. For some locations in New Zealand, the NZS1170 spectra may over-estimate the site-specific spectra estimated using the same seismic hazard model, often substantially for longer periods, exceeding about 1 s.

Another constraint in developing the NZS1170 spectra is that the ratios between the descending branches of spectra for different site classes are taken as constant rather than varying with spectral period. This requirement makes it impossible to obtain good matches between the NZS1170.5 spectra and site-specific spectra across all site classes at any location.

In addition, the peaks of the NZS1170.5 spectra are truncated for both the Modal Response Spectrum (MRS) and Equivalent Static methods of analysis, at 0.3 s for rock and shallow soil sites and at 0.55 s for deep soil sites for MRS analysis, while estimated spectra generally peak at higher values at about 0.2 s period.

Usually, it is horizontal earthquake motions that are of importance for structural design. NZSZ1170.5 has a simplistic approach for vertical motions, taking the vertical spectra to be 0.7 times the horizontal spectra at the same location. Commentary clause C3.2 discusses vertical spectra, including providing several references on this topic (Niazi and Bozorgnia, 1992; Bozorgnia and Niazi, 1993; Ambraseys and Simpson, 1996). It points out that vertical spectra usually decrease more rapidly than horizontal spectra with increasing spectral period. It also points out that in the near-source region the high-frequency content of vertical motions is often very strong, and may exceed the horizontal values. It concludes with the comment that 'At locations where the seismic hazard is dominated by a fault at a distance of less than 10 km, it may be more appropriate to assume that the vertical spectrum equals the horizontal spectrum for periods of 0.3 s and less'. These observations have been borne out by the nature of some of the vertical spectra in Christchurch (Section 3), although prior to the February earthquake there was no suggestion that the seismic hazard for Christchurch was dominated by nearby faults.

A.5.1 Uniform Hazard Spectra, and Deterministic Design Spectra

PSH results are usually presented in terms of uniform hazard PGAs and 5% damped acceleration response spectra (see Earthquake Response Spectra textbox in Section 3) for a selection of return periods, ranging from 10 years to 10,000 years. This range spans the return periods required for serviceability limit states (see Limit States textbox above) to maximum design motions required for dams. Uniform hazard spectra do not represent the motions expected in any particular earthquake scenario, so the dominant contributions may come from different earthquake sources for different spectral periods and return periods.

In uniform hazard spectra, the exceedance rate of a given spectral acceleration at a site of interest is estimated by summing the contributions of all modelled earthquake sources. The spectral acceleration-exceedance rate pairs can then be interpolated to obtain the uniform hazard spectra for selected return periods. The complexity of understanding which events are contributing to a uniform hazard spectrum often leads to the consideration of deterministic or scenario spectra. Scenario spectra correspond to the motions expected with a given probability if the particular earthquake occurs. Scenario spectra also provide the ability to ground-truth the uniform hazard spectra by comparing them with motions expected from particular earthquakes. The probability levels most frequently used are the 50th or 84th percentile levels. These probability levels correspond to the median and one standard deviation above the median estimates of the motions. When the hazard at a particular location is governed by a particular earthquake source, equivalent deterministic and uniform hazard spectra can be calculated. However, it is rare for the overall hazard to be contributed by a single earthquake, in which case comparisons are difficult because the contributions to the uniform hazards spectra from other potential earthquake sources is unknown.

The design spectra in NZS1170 are based mainly on uniform hazard spectra, with deterministic upper and lower bounds to the level of motions required to be considered. Other engineering design documents, especially for structures such as dams (NZSOLD, 2000) that require consideration of lower probability motions, allow the use of both scenario and uniform hazard spectra, with considerable judgement required in selecting the appropriate design spectra from the various scenario and uniform hazard candidates. Examples of the use of joint probabilistic-deterministic approaches in the New Zealand environment are provided by McVerry (2007).

GNS SCIENCE
TE PŪ AO

www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657