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.

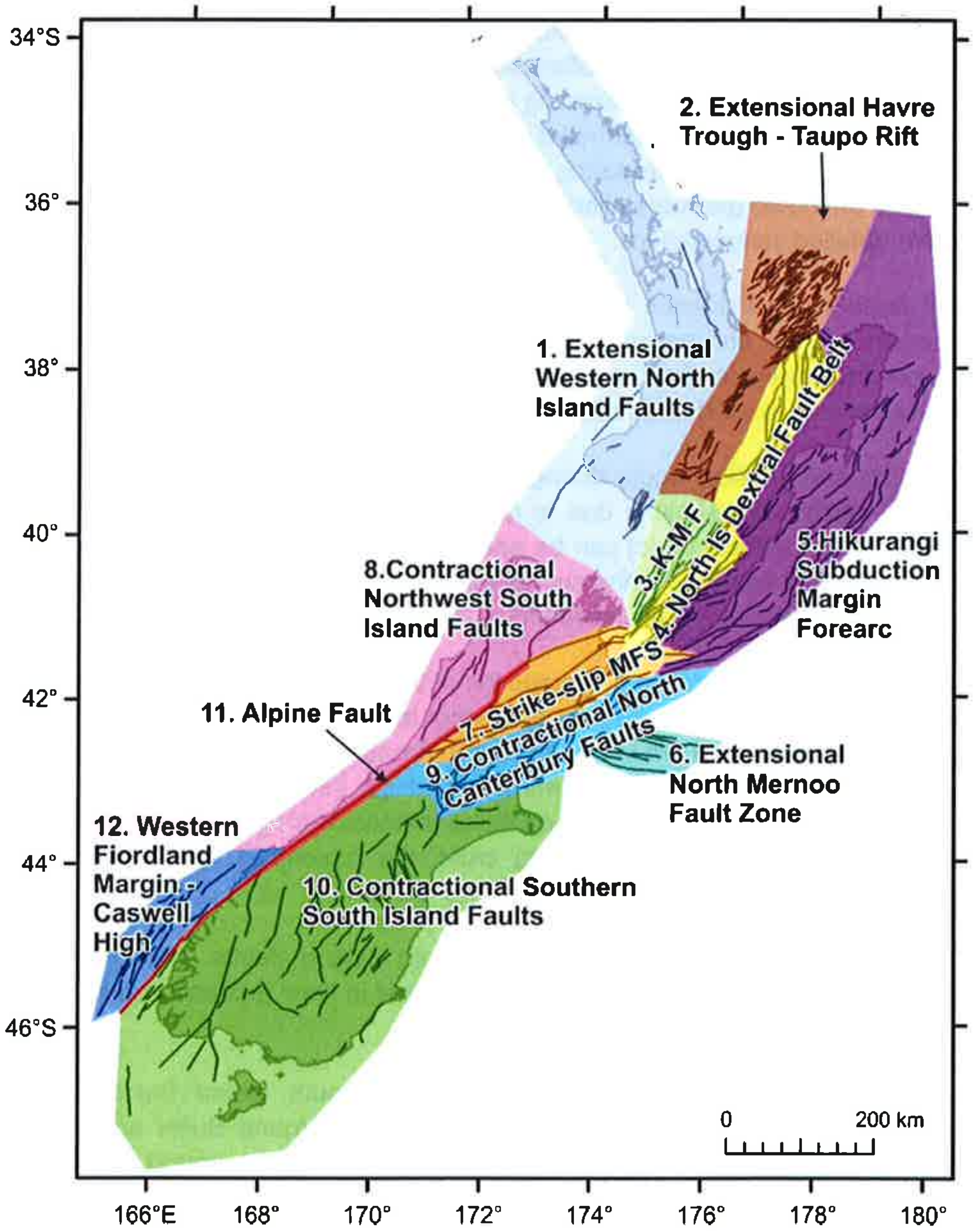

Figure 5.1 Groupings of active fault sources into domains or regions they occupy in New Zealand from Stirling *et al.*, 2011). K-M F = Kapiti-Manawatu Faults, MFS = Marlborough Fault System. Only the upper plate (non-interface) active faults are shown.

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

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[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.

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[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

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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).

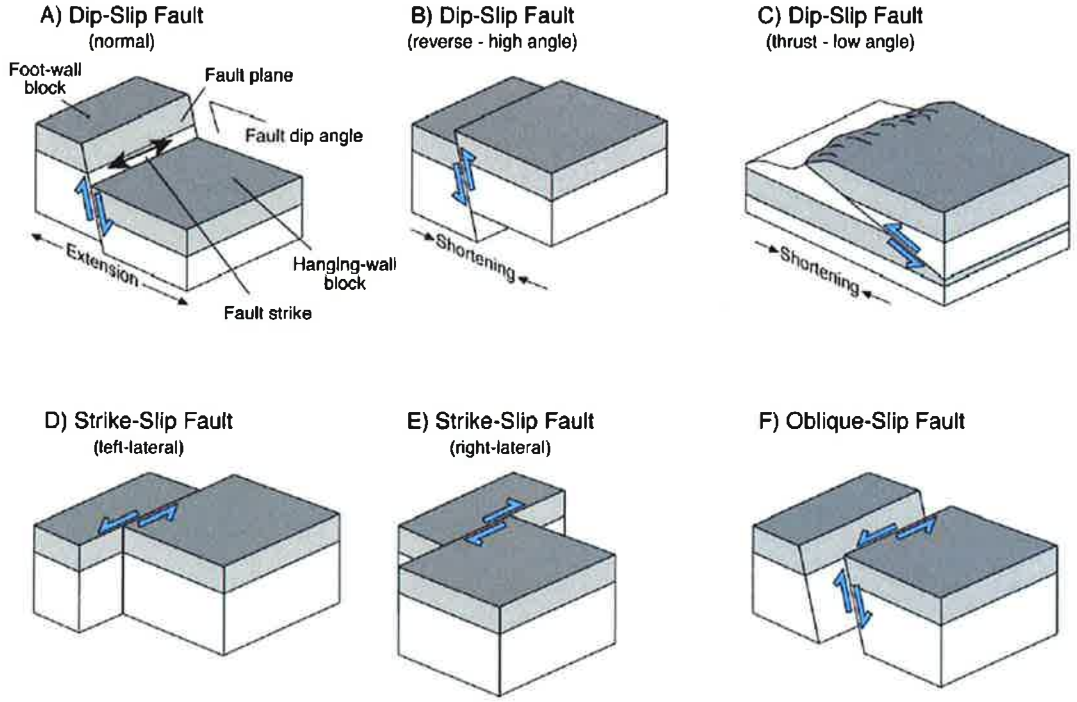

Figure A1.1 Fault classification and terminology: (A) to (C) dip-slip faulting; (D) and (E) horizontal or strike-slip faults, and (F) oblique-slip faulting. Other fault terminology is shown on block diagram (A). Figure modified from Pettinga *et al.* (2001).

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.

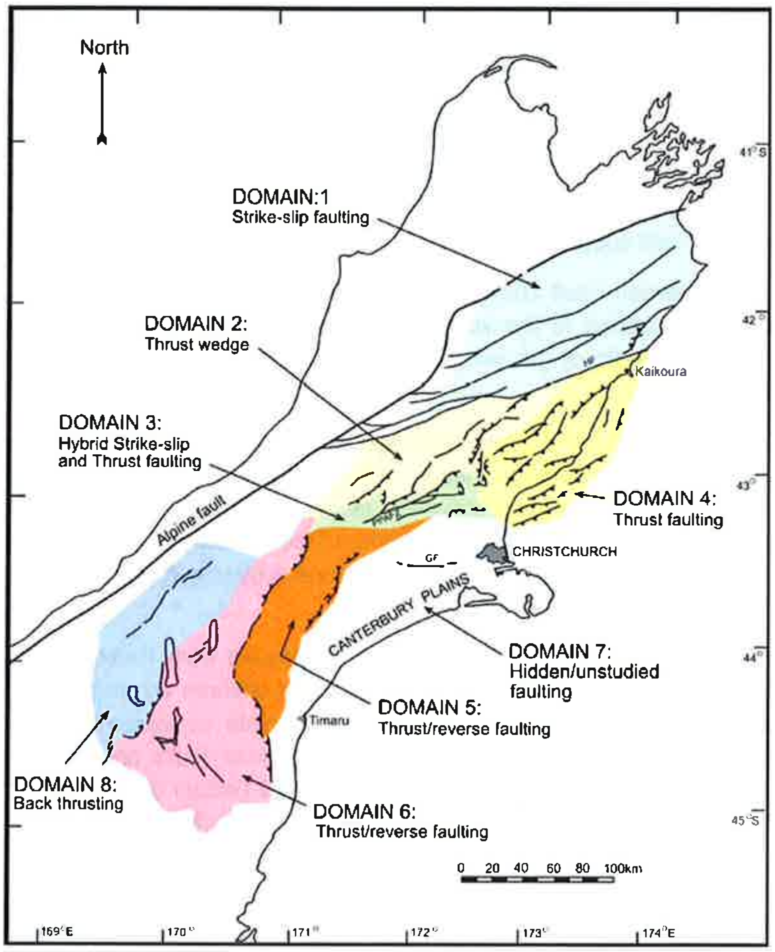

Figure A2.1 Summary map of the structural domains 1-8 for the Canterbury Region. Abbreviations: GF- Greendale fault; HF - Hope fault; PPAFZ - Porters Pass-Amberley fault zone. Figure modified from Pettinga *et al.* (1998).

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

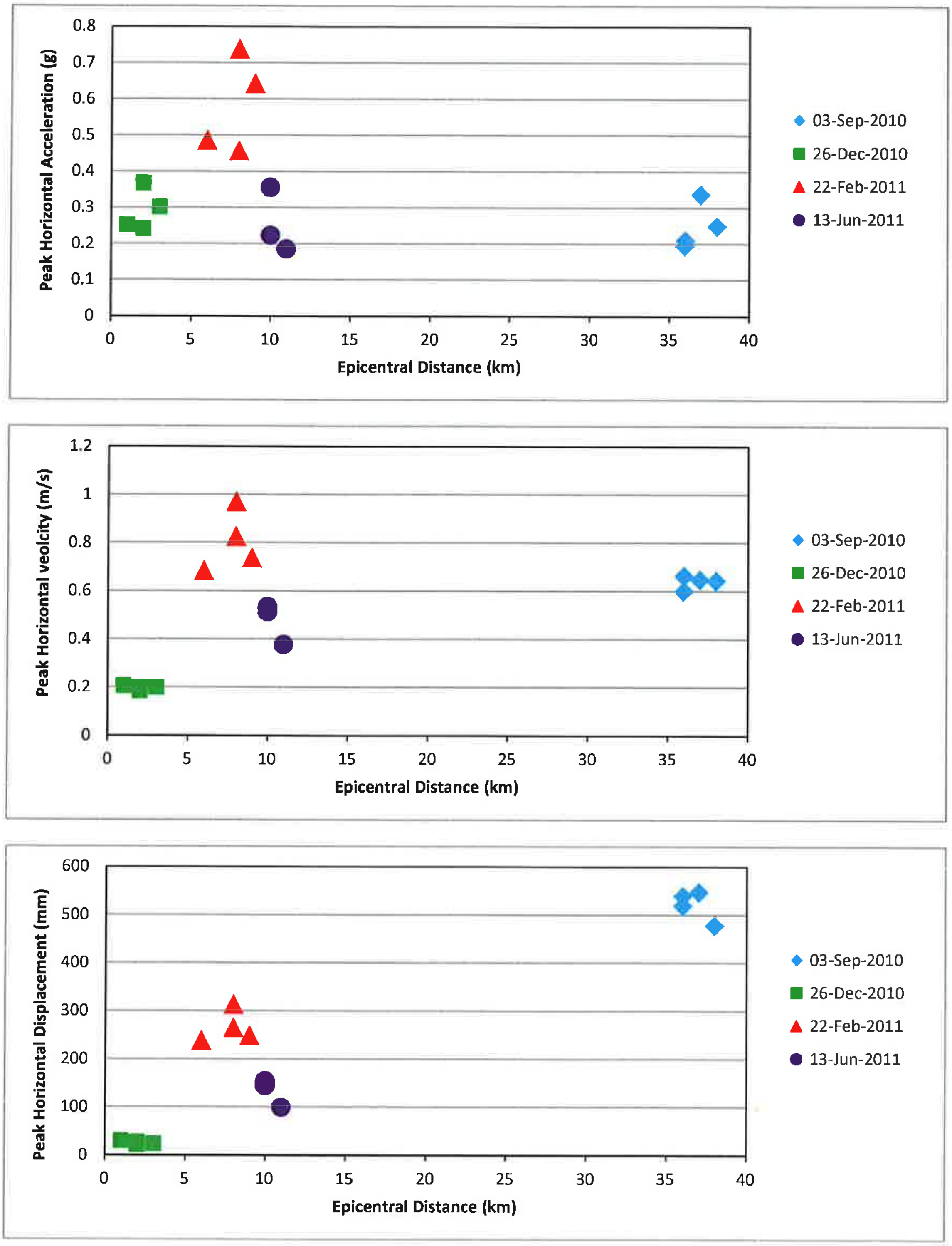

Figure A4.1 Peak horizontal accelerations (top), velocities (middle) and dynamic displacements (bottom) recorded at CBD sites in Christchurch during the four listed earthquakes. The 22 February event gave the strongest accelerations and velocities, but the 4 September 2010 Darfield Earthquake gave the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

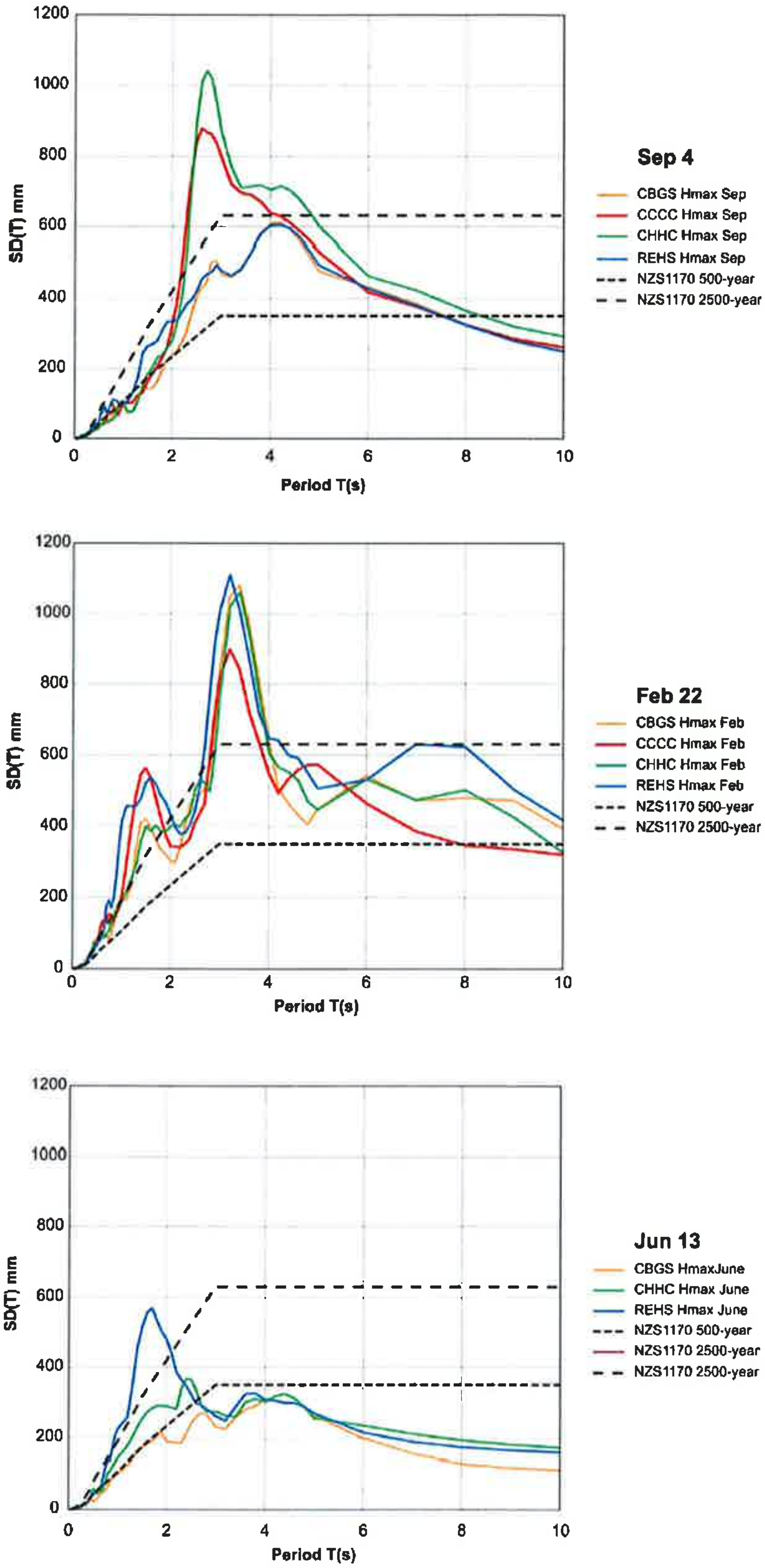

Figure A4.2 5% damped relative displacement response spectra for the larger horizontal component in the three earthquakes compared with the displacement spectra derived from the NZS1170 Z=0.22 spectra for Christchurch for return periods of 500 years (dotted) and 2500 years (dashed).

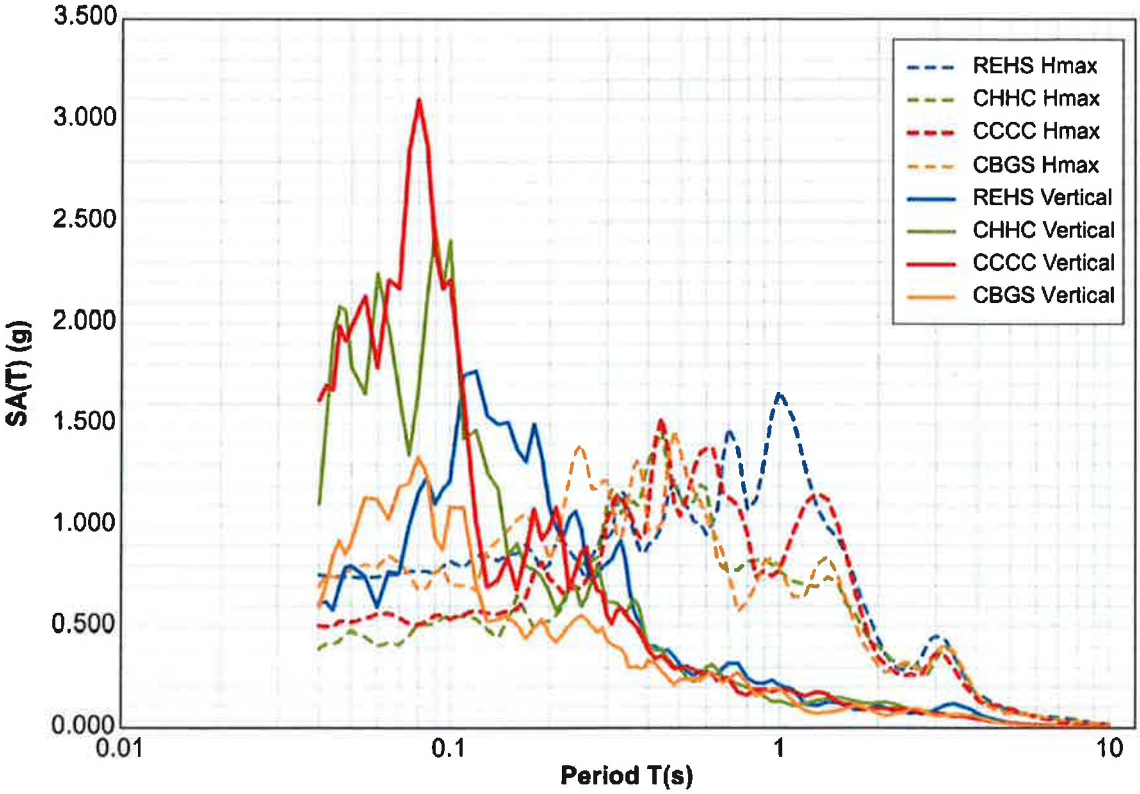

Figure A4.3 The 5% damped acceleration response spectra for the vertical (solid lines) and the larger horizontal component (dashed lines) in the 22 February 2011 earthquake. The vertical spectra exceed the horizontal spectra only for periods up to about 0.12 s to 0.25 s, before falling away sharply for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

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[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 84th 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 84th 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).

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