2. SEISMOLOGICAL ASPECTS

Regional seismicity and historical earthquakes

New Zealand straddles the boundary of the Australian and Pacific plates, where relative plate motion is obliquely convergent across the plate boundary at about 50 mm/yr in the north of the country, 40 mm/yr in the center, and 30 mm/yr in the south (DeMets et al. 1994). The complex faulting associated with the changing orientation of the subduction zones in the northeast and southwest, causes predominantly dextral faulting through the axial tectonic belt in the center of the country.

As a result of this complex faulting, New Zealand is a region of distributed seismicity, in that the relative movement of the Australian and Pacific plates are not accommodated by one or two faults in a narrow zone, but by many faults across a much wider zone (the axial tectonic belt). It is therefore not surprising to observe that both large historical earthquakes and recent seismicity (e.g. Figure 2-1) can occur in almost any region in New Zealand.

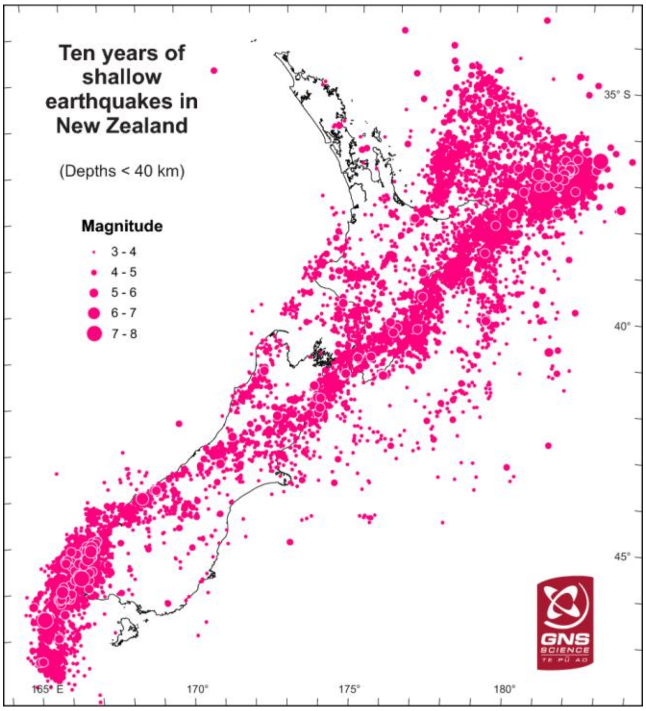


Figure 2-1. Shallow seismicity in the last ten years (as at 4 September 2010). (courtesy of GNS Science http://www.geonet.org.nz/earthquake/) .

The 22 February 2011 M_w 6.2 (M_L6.3; M_E6.7) Christchurch Earthquake

The M_w6.2 Christchurch earthquake occurred at 12:51pm local time on the 22 February 2011. The epicenter was located at -43.598°, 172.714°, at a focal depth of 4 km (J. Ristau, pers comm.), underneath Christchurch's Port Hills, approximately 8 km to the south east of the Christchurch central business district. The faulting was primarily reverse in mechanism, with a rake of 120 degrees, and does not appear to have caused a surface trace.

Figure 2-1 provides a geographical illustration of the location of the approximate fault causing the 22 February earthquake as well as the M_w7.1 earthquake which occurred on 4 September 2010 and their associated aftershocks. It can be seen that the 4 September and 22 February events have ruptured on different surfaces, which at least based on aftershock locations, does not appear to be connected by a geologic structure at depth. While it is almost undisputed that the 4 September earthquake influenced the initiation of rupture of the 22 February event, there is considerable debate as to whether the 22 February event is an 'aftershock' of the 22 September event, or whether it was 'triggered'. Such debate is a result of the spatially different locations of these two faults, as well as the assessment of whether the majority of stress on the fault at the time of the 22 February rupture was the result of primarily long term strains (i.e. a 'triggered' event), or the recent strains induced in the region since the September 4 event (i.e. an 'aftershock').

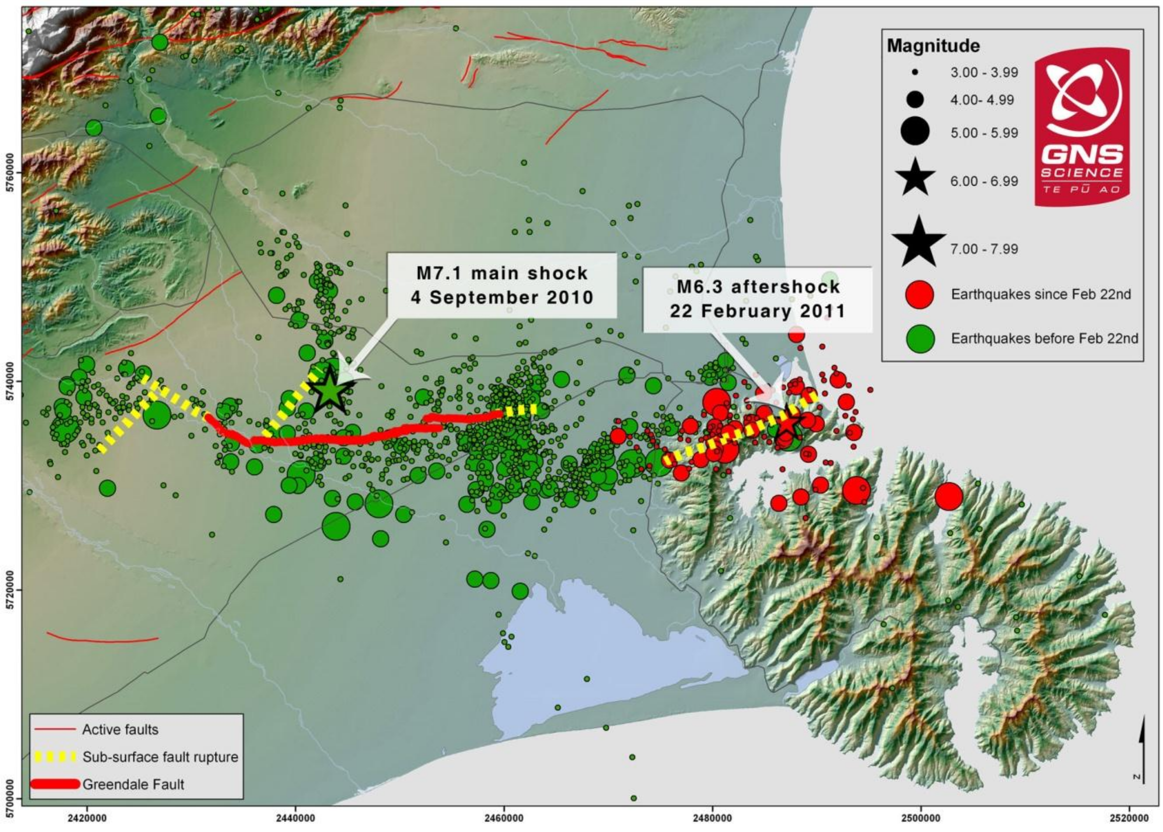


Figure 2-2. Approximate location of the surface projection of the up dip edge of the fault that caused the 22 February earthquake in comparison to the M_w7.1, 4 September earthquake and subsequent aftershocks (Figure courtesy of GNS science).

Figures 2-3 and 2-4 illustrate the space-time, and magnitude-time distributions, respectively, of earthquake events in the Canterbury region over the six months from 1 September 2010 - 1 March 2011.

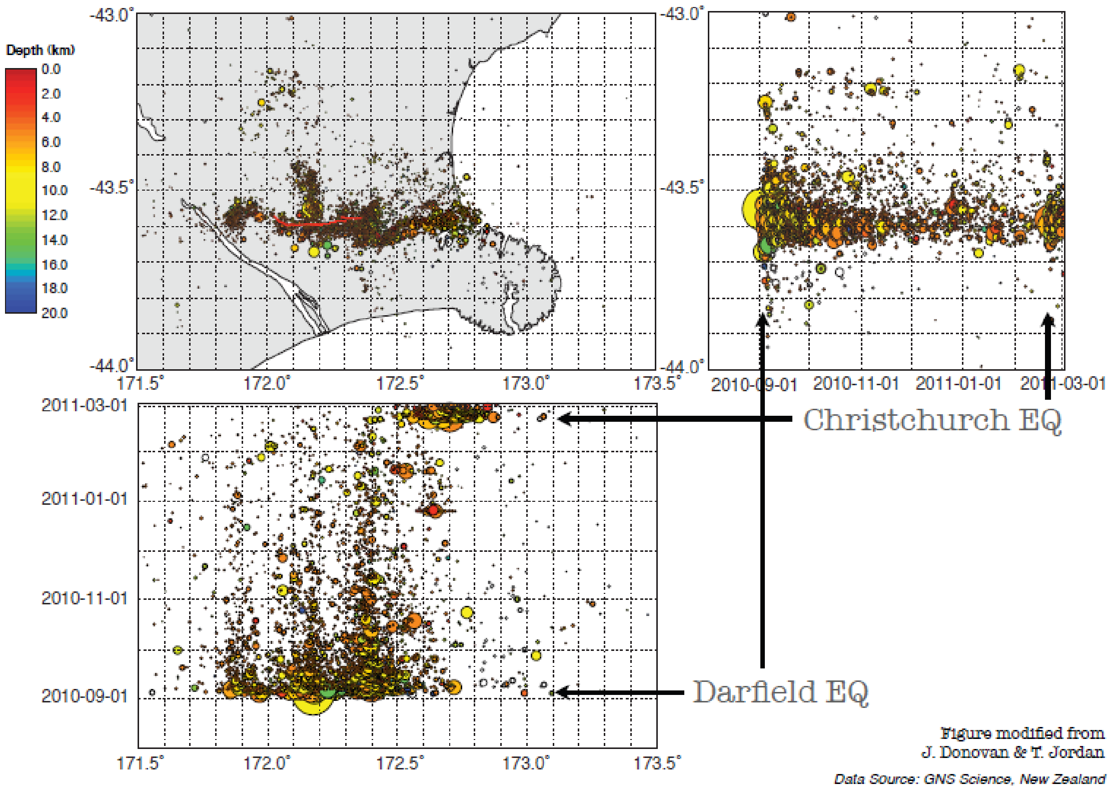


Figure 2-3. Spatial distribution of events in the Canterbury region from 1 September 2010 - 1 March 2011 (courtesy of Gavin Hayes).

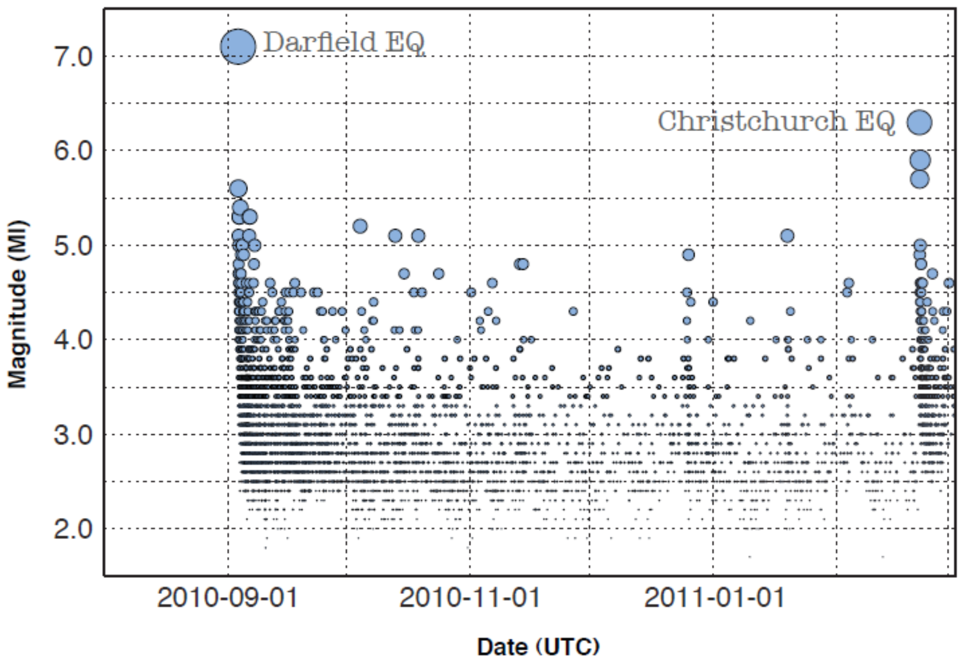


Figure 2-4. Distribution of events in magnitude and time from 1 September 2010 – 1 March 2011 (courtesy of Gavin Hayes).

Finite fault models

Because of the small magnitude of the event, finite fault models for the 22 February earthquake cannot be computed using teleseismic waveforms, the common method utilized for large magnitude events. At the time of writing, one preliminary model based on a single asperity with an elliptical tapering slip has been computed (C. Holden, pers comm.). Figure 2-5 shows the surface projection of the finite fault relative to seismometer locations in the Christchurch region. The finite fault has an along-strike length of approximately 10km and a down-dip width of 7km (which, with an average dip of 65 degrees ruptured over depths of approximately 0.5 to 7km). The finite fault dips toward the south.

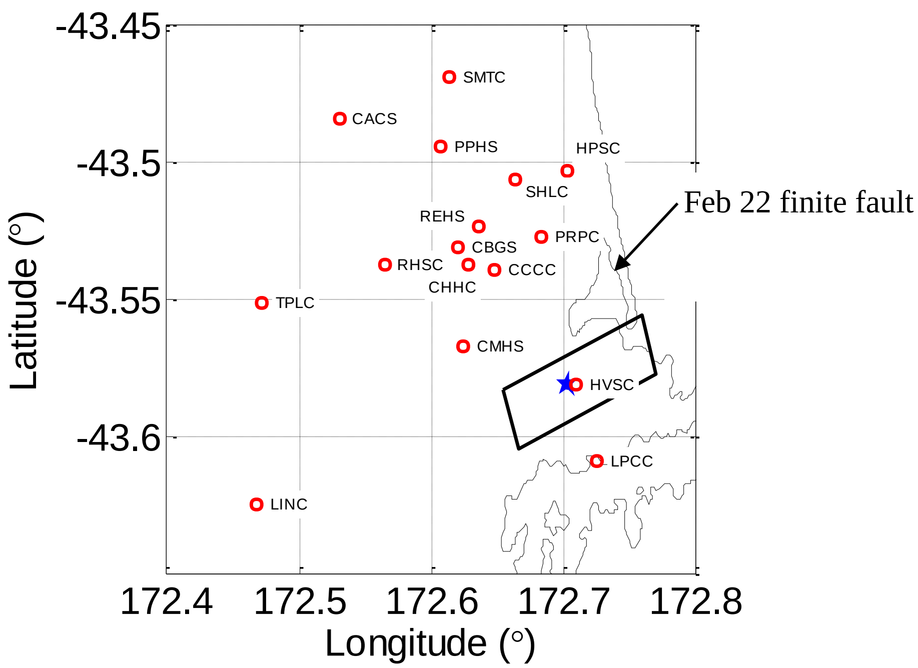


Figure 2-5. Preliminary finite fault inversion from Caroline Holden (GNS Science) relative to seismometer locations in Christchurch.

Ground motion shaking

The ground motion shaking as a result of the 22 February Christchurch earthquake was widely felt in the Canterbury region, and in New Zealand in general. Figure 2-6 shows the distribution of "felt-it" reports that were submitted online by the public. Figure 2-7 shows the USGS ShakeMap, which utilizes both predictive models of MMI, and also the publically submitted "felt-it" reports. Approximately 92,000 people were subjected to MMI IX, while 228,000 people were likely subjected to MMI VIII.

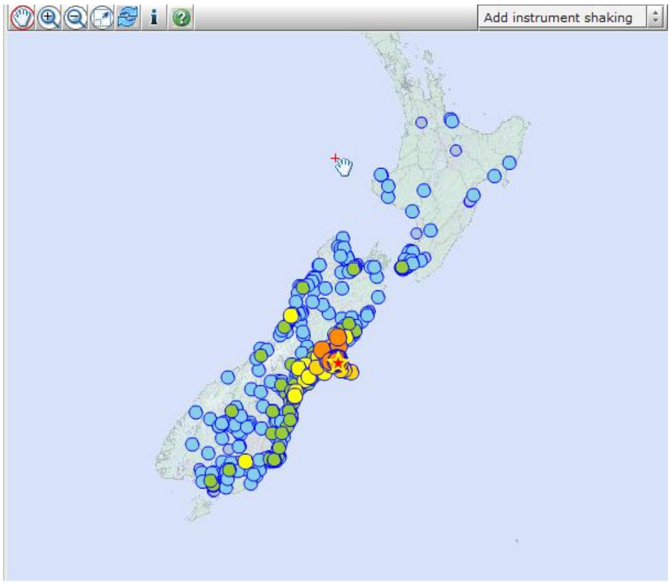


Figure 2-6. Locations of “felt-it” reports submitted online, there were 3715 reports as at 22 March 2011 (for comparison 6897 reports were posted 20 days following the 4 September, M_w7.1 event) (http://geonet.org.nz/earthquake/quakes/3468575g-shaking.html)

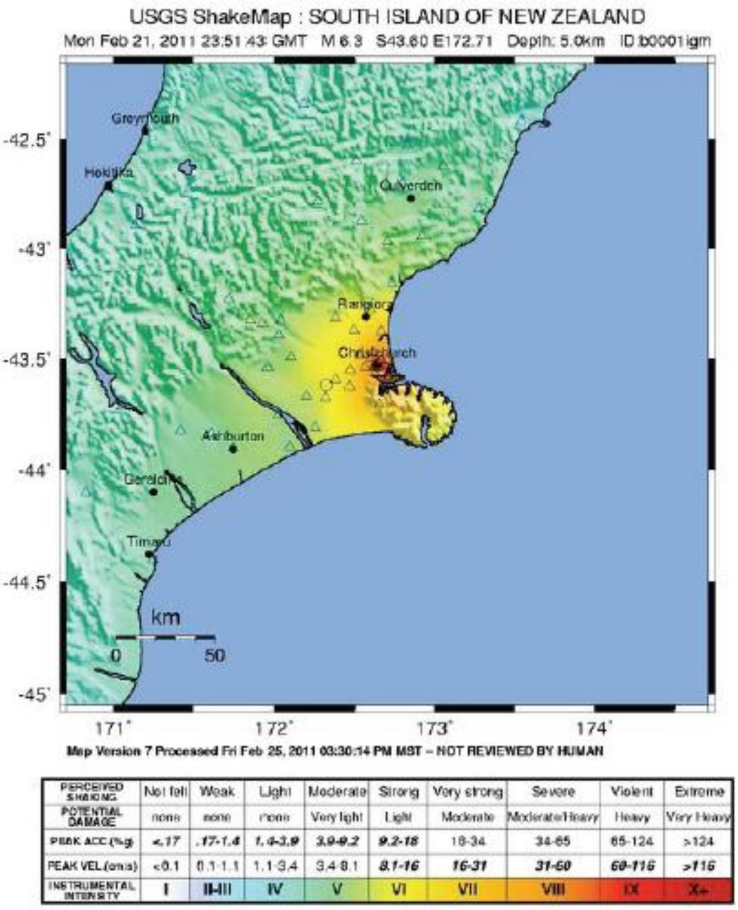
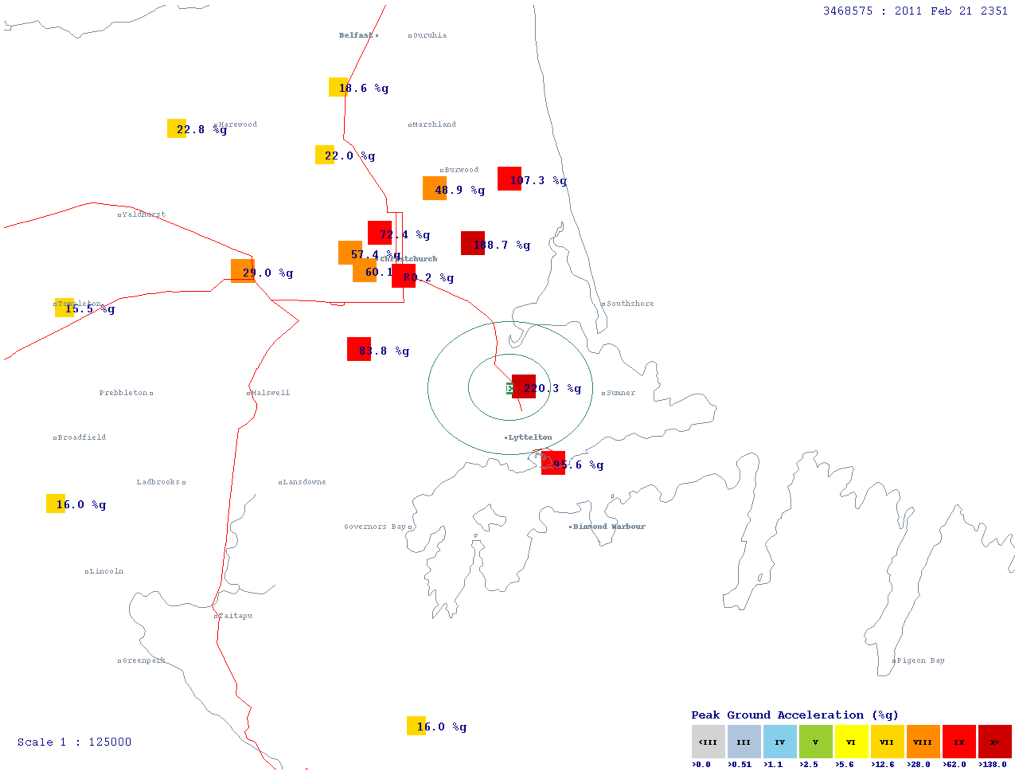


Figure 2-7. USGS ShakeMap from the M_w6.2 (M_L6.3) Canterbury earthquake (http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/b0001igm/http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/2010atbj/).

The Canterbury region is well instrumented with seismographs that recorded the strong ground motions. Figure 2-8a shows the (vector-maximum) peak ground accelerations (PGA) that were recorded throughout the region. In the near source region, which includes the Christchurch central business district, it can be seen that there are eight recordings above 0.6g. Figure 2-8b shows the vertical and horizontal PGA vectors at the recording stations. As may be observed from this figure, the vertical PGAs at many of the sites in central and eastern Christchurch are greater than or equal to the horizontal PGAs.

Figure 2-9 Figure 2-9.shows the acceleration time histories and response spectra of the ground motion recorded at Heathcote Valley School (HVSC), which was located almost directly above the epicentre. It can be seen that the ground shaking observed was extremely intense with peak accelerations exceeding 1g in both horizontal directions, vertical accelerations above 2g, and the duration of strong ground motion in the order of 5 seconds. Figure 2-9b shows that, compared to empirical predictions, the geometric mean horizontal response spectra were greater than the 84^{th} percentile prediction for vibration periods less than 0.8 seconds. Subsequent investigations have shown that the HVSC site is strongly affected by basin edge effects, which cause constructive interference between S-wave through the basin and diffracted Rayleigh waves induced at the basin edge.



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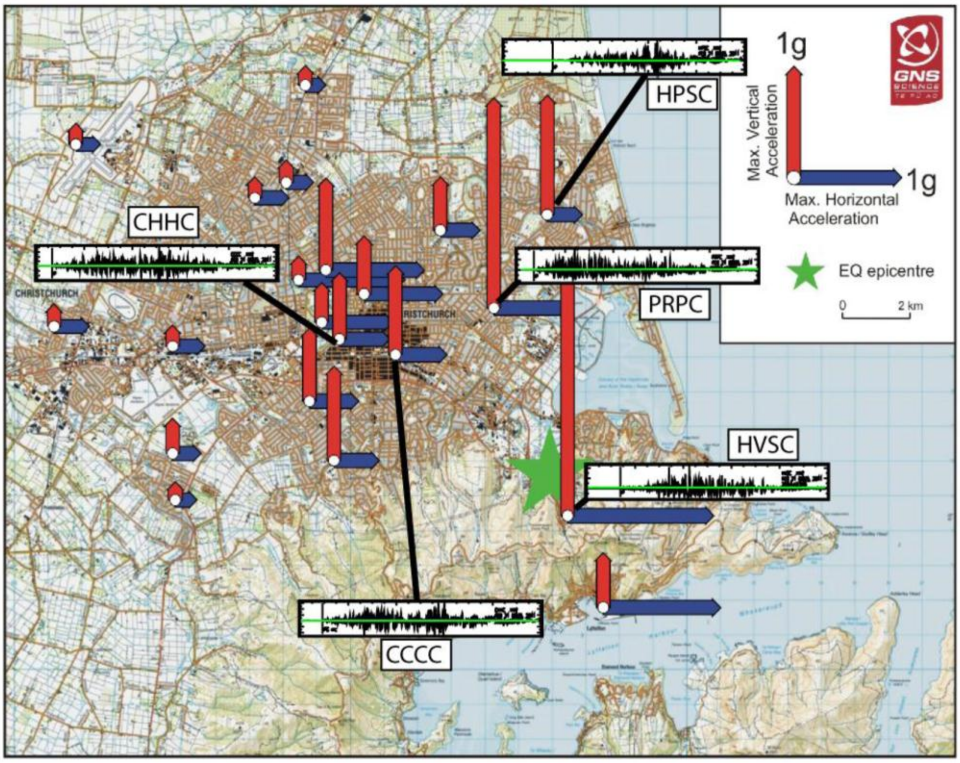

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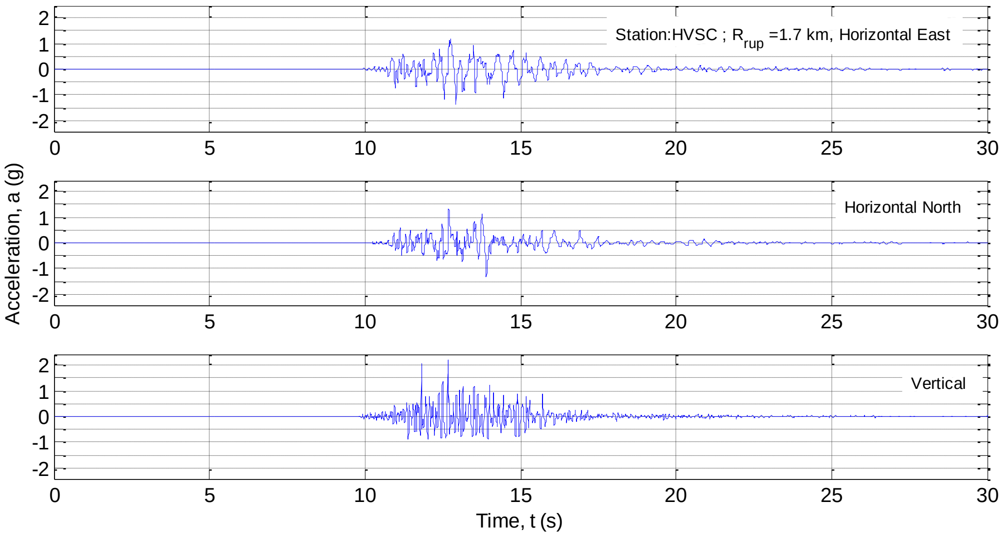
Figure 2-8. (a) Vector-maximum peak ground accelerations observed in the Canterbury region from strong motion seismographs (http://www.geonet.org.nz/news/feb-2011-christchurch-badly-damaged-by-magnitude-6-3-earthquake.html); (b) vertical and horizontal PGAs vectors (from Fry et al., 2011).



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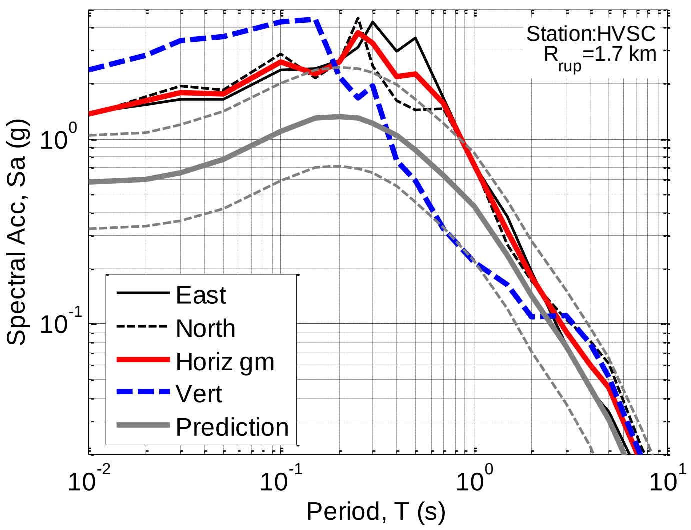
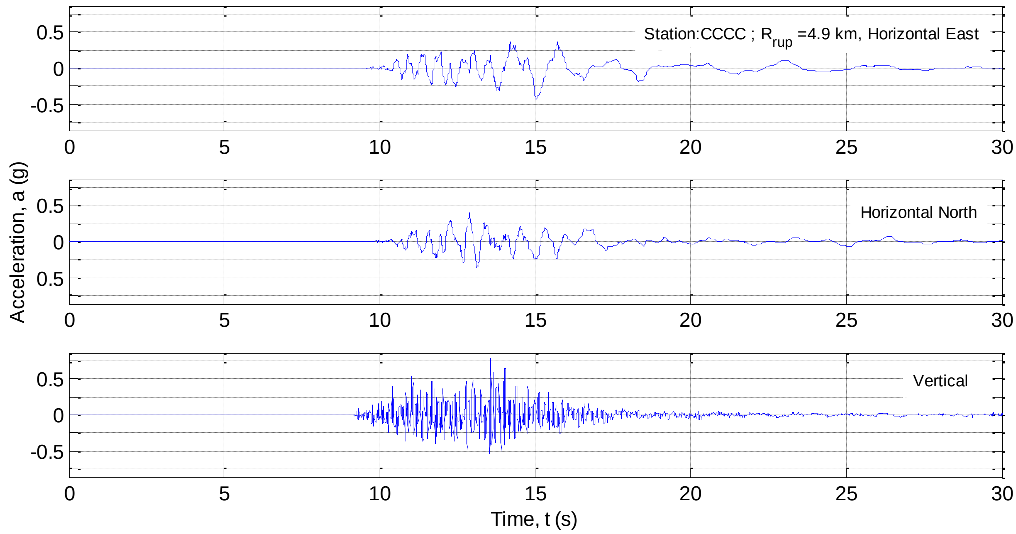


(b)

Figure 2-9. (a) Acceleration time-histories; and (b) response spectra at Heathcote Valley School (HVSC) seismograph. (Note that "Horiz gm" is the geometric mean of the two horizontal components of motion and the empirical response spectra model is that of Bradley (2010))

Figure 2-10 shows the acceleration time histories and response spectra of the ground motion observed at the Christchurch Cathedral College (CCCC) seismograph (see location in Figure 2-5). It can be seen that the peak horizontal acceleration is in the order of 0.42g, and peak vertical acceleration approximately 0.82g. In contrast to the ground motion recorded at HVSC (Figure 2-9), at CCCC it can be seen that the high frequency ground motion for vibration periods less than 0.3 seconds is approximately equal to that predicted by empirical models. On the other hand, the longer period (T>0.5s) ground motion is generally equal to or greater than the 84th percentile empirical model prediction.



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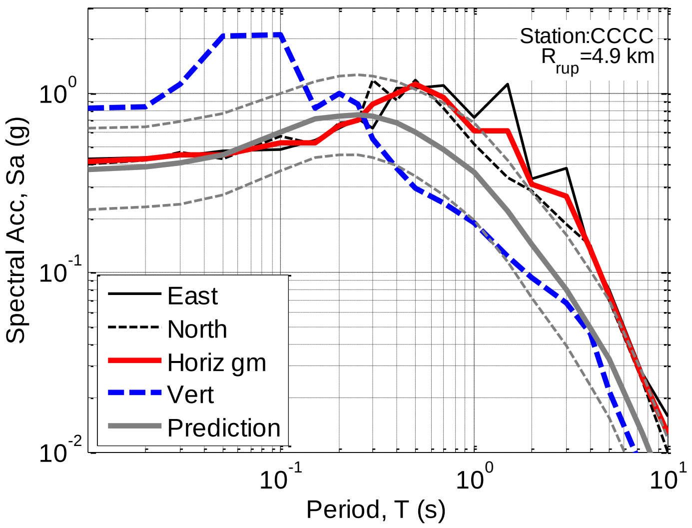

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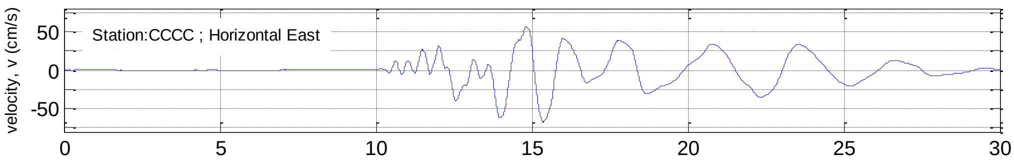
Figure 2-10. (a) Acceleration time-histories; and (b) response spectra at Christchurch Cathedral College (CCCC) seismograph. (Note that "Horiz gm" is the geometric mean of the two horizontal components of motion and the empirical response spectra model is that of Bradley (2010))

Further understanding for the differences between the ground motions recorded at HVSC and CCCC can be obtained from Figure 2-11, which shows the velocity time history of the horizontal ground motion in the east-west direction for CCCC and also the geological structure of the Christchurch region. As can be seen by comparing the acceleration and velocity time histories (i.e. Figures 2-10a and 2-11a), the majority of the direct S-waves arrive from 11-16 seconds, and then the ground motion is dominated by surface waves arrivals from approximately 16-25 seconds (the surface waves have a longer period than the S-waves, therefore having large velocity, but comparably small accelerations). Figure 2-11b provides a schematic illustration of the location of Christchurch relative to the epicentre of the 22 February earthquake. Based on Figure 2-11, the significant surface waves observed at CCCC are likely being created at the edge of the Christchurch basin. Such waves have then become 'trapped' within the basin, as a result of the large velocity contrast of the basin sediments and the underlying bedrock, leading to the observed wave train of long period ground motion above that predicted by empirical models (i.e. Figure 2-10).



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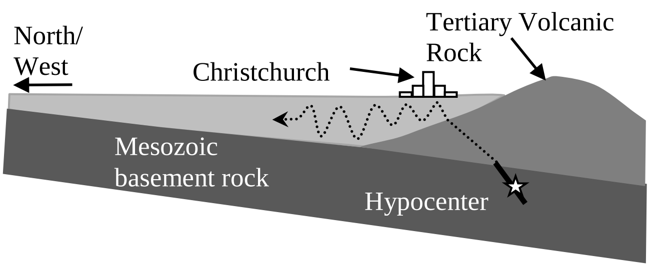

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Figure 2-11. (a) Velocity time-history in the East-West direction at Christchurch Cathedral College (CCCC), illustrating the shear wave, and surface wave arrivals; and (b) schematic illustration of the generation of surface waves and waveguide effect of the Canterbury basin.

Comparison with the 4 September 2010 earthquake

The 22 February Christchurch earthquake caused significantly more damage to Christchurch than the 4 September 2011 Darfield earthquake, primarily as a result of its close proximity to the city. Figure 2-12 shows the spatial distribution of PGA and MMI observed from the two earthquakes. It can be seen that the larger ground motion intensities in the 22 February event occur in locations with higher population density (see http://earthquake.usgs.gov/learn/topics/NewZealand2011_slides.ppt for further details).

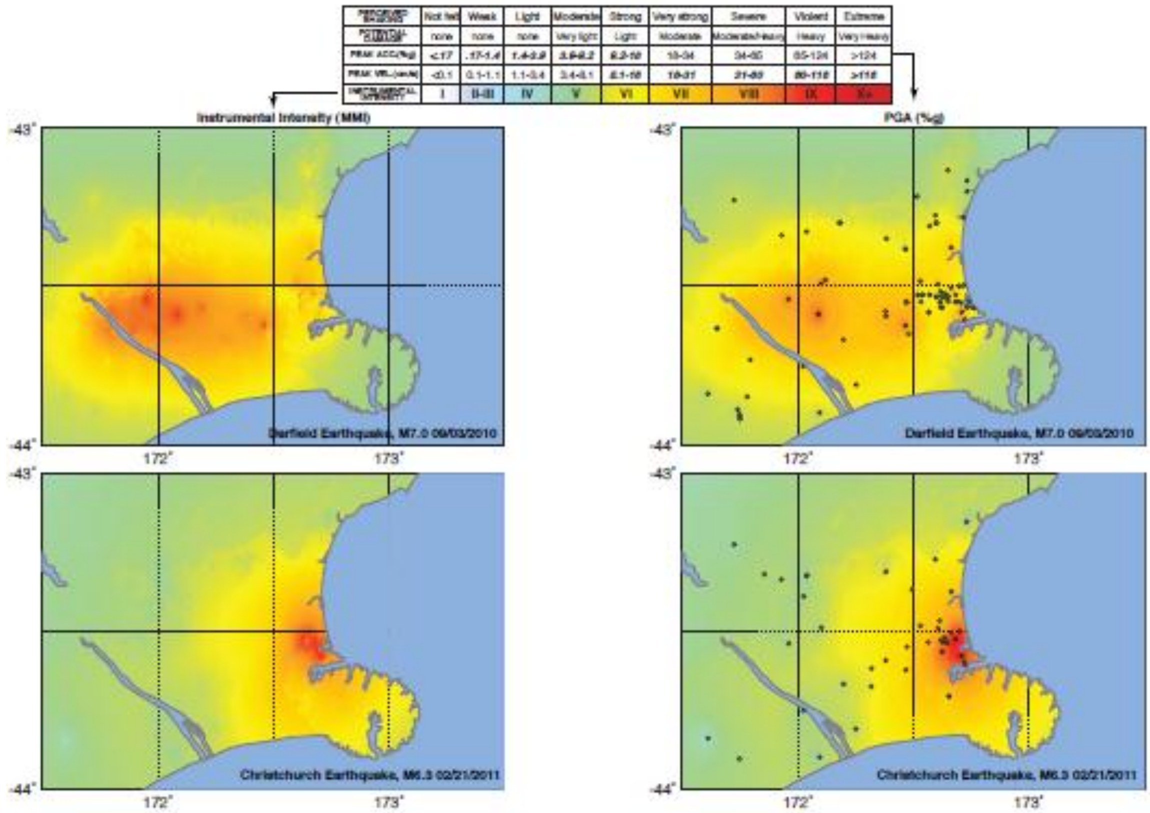
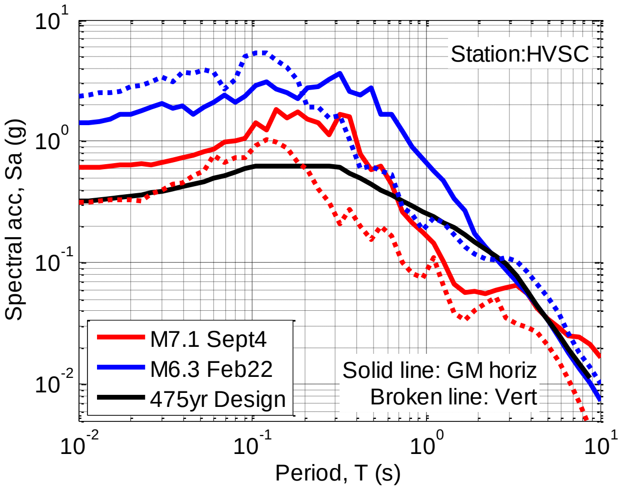


Figure 2-12. Comparison of MMI and PGA values in the Canterbury region as a result of the 4 September 2010 and 22 February 2011 earthquakes (Courtesy Gavin Hayes).

Figure 2-13 shows the pseudo-acceleration response spectra of the ground motions recorded at three locations (see Figure 2-5) for both the 4 September 2010 and 22 February 2011 earthquakes. Firstly, it can be seen that in the near-source region, which includes Christchurch's eastern suburbs and central business district (i.e. HVSC and CCCC stations), the ground motion was significantly stronger from the 22 February earthquake than the 4 September earthquake. On the other hand, as the source-to-site distance increases (e.g. PPHS) the intensity of the ground shaking due to the 22 February earthquake rapidly reduces. For this reason, as well as the differences in the sub-surface soil conditions, the damage as a result of the 22 February earthquake has been primarily limited to Christchurch's eastern suburbs and central business district. Figure 2-13 also shows the importance of local site effects, in the sense that the nature of the ground motions at many sites (e.g. PPHS) are very similar, despite being caused by two different earthquakes at different orientations to the site.



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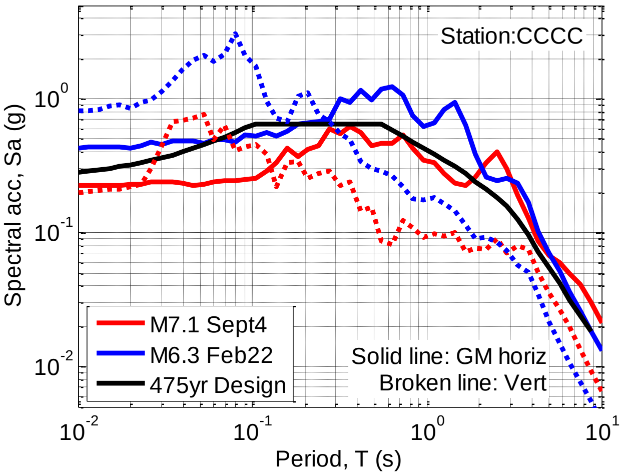

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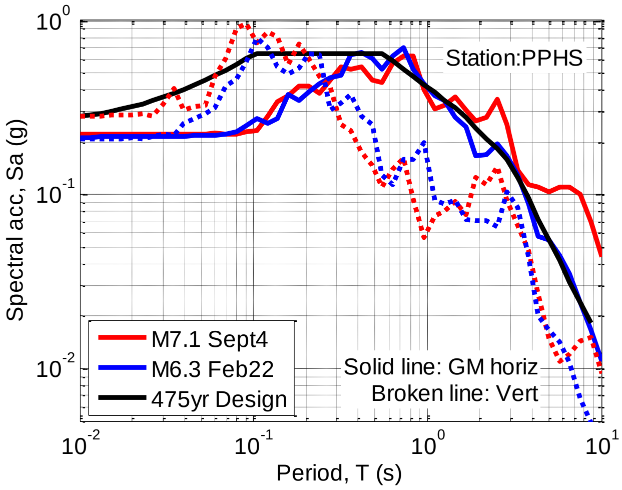

(c)

Figure 2-13. Comparison of the 4 September 2010 and 22 February 2011 ground motion response spectra: (a) Heathcote Valley School (HVSC), $R_{Darfield}$ = 24 km, R_{Chch} = 0.3 km; (b) Christchurch Cathedral College (CCCC), $R_{Darfield}$ = 19 km, R_{Chch} = 6 km; and (c) Papanui High School (PPHS), $R_{Darfield}$ = 18 km, R_{Chch} = 12 km. (R = horizontal distance from strong motion station to closest surface projection of the fault rupture.)

References

Bradley, B.A. (2010). NZ-specific pseudo-spectral acceleration ground motion prediction equations based on foreign models, Department of Civil and Natural Resources Engineering, University of Canterbury, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand. 324pp.

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S. (1994). Effect of recent revisions to the geomagnetic time scale on estimates of current plate motion, *Geophysical Research Letters*, **21**, 2191-2194.

Fry, W., Benites, R., and Kaiser, A. (2011). The Character of Accelerations in the Christchurch Mw6.3 Earthquake, Seismological Research Letters, **82**(6), 846-852.