OVERVIEW OF STRONG-MOTION DATA FROM THE DARFIELD EARTHQUAKE

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SUMMARY

The Darfield earthquake of 3rd September 2010 UT and its aftershocks have yielded New Zealand's richest set of strong-motion data since recording began in the early 1960s. Main-shock accelerograms were returned by 130 sites, ten of which had peak horizontal accelerations in the range 0.3 to 0.82g. One near-fault record, from Greendale, had a peak vertical acceleration of 1.26g. Eighteen records showed peak ground velocities exceeding 0.5 m/s, with three of them exceeding 1 m/s. The records included some with strong long-period directivity pulses, some with other long-period components that were related to a mixture of source and site effects, and some that exhibited the effects of liquefaction at their sites. There were marked differences between records on the deep alluvium of Christchurch City and the Canterbury Plains, and those on shallow stiff soil sites. The strong-motion records provide the opportunity to assess the effects of the earthquake in terms of the ground motions and their relationship to design motions. They also provide an invaluable set of near-source motions for seismological studies. Our report presents an overview of the records and some preliminary findings derived from them.

INTRODUCTION

The Darfield earthquake provided an extensive set of ground-motion records that will allow its effects to be assessed against their causative motions, and the comparison of motions experienced against design motions. The near-source strong-motion records should also prove invaluable for seismological studies to understand the complex history of the earthquake's rupture-process [1, 2, 3].

BASIC STRONG-MOTION DATA

Accelerograms were returned by 130 of the 270 GeoNet sites operational at the time of the main-shock (Figure 1), ten of which had peak horizontal accelerations in the range 0.3 to 0.82g (Table 1). One near-fault record, from Greendale, returned a vertical acceleration of 1.26g. All of the records are available from the GeoNet website (www.geonet.org.nz).

Four levels of processing are routinely carried out on the as-recorded acceleration time histories, as follows:

1. A header containing information on the earthquake, the recording site and the recorded data is pre-pended, and the data unit is converted to mm/s/s using static sensitivity values. Data files (in ASCII format) and plots (as PDFs) are provided in folders labeled "Vol1" in the GeoNet website.
2. Full processing is carried out in the frequency domain. It includes high- and low-pass filtering, and integration to give velocities and displacements. Data files and plots are provided (Vol2 folders).
3. Absolute acceleration response spectra are calculated from the peak responses of linear single-degree-of-freedom oscillators for damping values of 1, 2, 5, 10, and 20% of critical. Relative velocity and displacement spectra are calculated in a similar manner. Data files, and linear plots of the 5% damped spectra, are provided (Vol3 folders).
4. Plots only of Fourier amplitude spectra computed from the level 2 accelerograms (Vol4 folders).

Although most of the mainshock records were available on the GeoNet website within 36 hours of the earthquake, many have now been reprocessed with broader filter passbands, and others are currently undergoing non-standard processing to retrieve permanent displacement offsets.

The standard high-pass filter initiation frequency is 0.25 Hz, which is a compromise that for most strong-motion records removes long-period noise without affecting real earthquake motions. For many of the near-source records from the main-shock of the 2010 Darfield earthquake, however, the high-pass filtering removed what appeared to be genuine long-period ground motions. Hence the main-shock records from within 100km epicentral distance have been re-filtered using a high-pass initiation frequency of 0.1 Hz. This did not greatly affect the peak accelerations, but resulted in large changes to peak velocities and displacements for many of the records (Figure 2). The data in Table 1 are from the extended-filter processing. The re-filtered records are available using the direct link

ftp://ftp.geonet.org.nz/strong/processed/Proc/2010/09_Darfield_mainshock_extended_pass_band/

There are indications that permanent displacement offsets occurred in some records at epicentral distances up to 25 km. Preliminary unreviewed versions of records processed by Zhao [4] with special techniques to retrieve permanent offsets have been loaded to the NZSEE Darfield Earthquake Clearinghouse at http://db.nzsee.org.nz:8080/en/web/lfe-darfield-2010/seismology

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Table 1: Peak horizontal ground motions recorded within 100 km epicentral distance in the Darfield earthquake of 3rd September 2010 UT. The ground subsoil categories are as defined in NZS1170.5 [5].

Epicentral Distance (km)	Fault Distance (km)	PGA (mm/s/s)	PGV (mm/s)	PGD (mm)	Site Code	Name of Recording Site	Site Subsoil Category
8	1.3	8,018	1,449	960	GDLC	Greendale	D
9	11 (6.1) (1)	4,849	402	425	DFHS	Darfield High School	D
13	8	3,005	663	724	DSLC	Dunsandel School	D
17	2	3,905	949	1,072	ROLC	Rolleston School	D
18	7	5,294	1,059	554	HORC	Hororata School	D
24	8	2,775	758	823	TPLC	Templeton School	D
25	9	4,757	1,162	737	LINC	Lincoln Crop and Food Research	D
26	18	1,987	242	213	RKAC	Rakaia School	D
29	16	2,048	478	518	CACS	Christchurch Canterbury Aero Club	D
29	24	1,716	268	309	SBRC	Southbridge School	D
31	16	2,369	629	540	RHSC	Riccarton High School	D
31	28	2,172	216	90	SPFS	Springfield Fire Station	D
35	21	2,082	825	551	PPHS	Christchurch Papanui High School	D
36	20	1,907	600	519	CBGS	Christchurch Botanic Gardens	D
36	21	2,059	663	539	CHHC	Christchurch Hospital	D
36	20	2,462	492	307	CMHS	Christchurch Cashmere High School	D
36	23	1,735	632	486	SMTC	Styx Mill Transfer Station	D – E
37	26	1,090	162	150	LRSC	Lauriston	D
37	22	3,295	647	547	REHS	Christchurch Resthaven	D
38	22	2,435	643	478	CCCC	Christchurch Cathedral College	D
39	33	866	114	117	DORC	Dorie	D
39	25	1,882	651	551	SHLC	Shirley Library	D – E
41	25	2,188	586	490	PRPC	Pages Road Pumping Station	E
43	28	1,685	574	463	HPSC	Hulverstone Drive Pumping Station	E
43	27	6,515	428	212	HVSC	Heathcote Valley Primary School	C
44	32	4,075	539	425	KPOC	Kaiapoi North School	E
44	28	3,706	296	180	LPCC	Lyttelton Port Company	B
44	29	2,009	560	475	NNBS	Christchurch North New Brighton School	E
45	38	2,042	108	70	ASHS	Ashley School	D
51	46	1,158	120	61	CSHS	Castle Hill Station	B
53	43	1,078	126	100	ADCS	Ashburton District Council	D
56	45	803	101	94	WSFC	Westerfield	D
68	56	799	90	71	MAYC	Mayfield School	D
78	73	1,578	183	98	WAKC	Waikari	C
81	79	1,006	123	138	LSRC	Lake Sumner Road	C
83	79	886	53	28	APPS	Arthur's Pass Police Station	C
85	88	324	77	88	LTZ	Lake Taylor Station	B
87	75	1,206	117	33	PEEC	Peel Forest	C
93	80	489	56	36	RPZ	Rata Peaks	B

Note 1: Distance from initial sub-event rupturing from hypocentre with reverse mechanism. Other fault distances are from a smoothed model of the Greendale Fault surface rupture as developed by Nicola Lichfield and Russ Van Dissen of GNS Science (personal communication 2010).

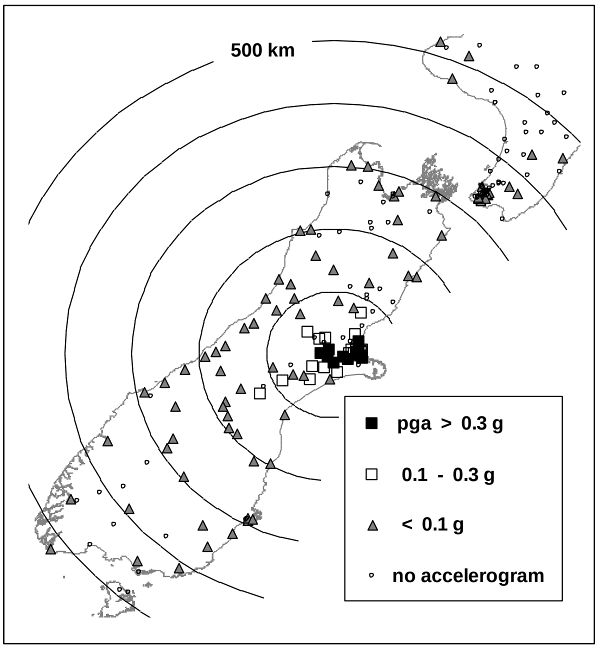

***Figure 1:** Locations of strong-motion sensors at the time of the Darfield earthquake, with peak ground acceleration levels indicated where strong-motion recordings were obtained.*

PEAK GROUND ACCELERATION ATTENUATION

Comparisons of the attenuation of the Darfield earthquake motions with models are complicated by the complexity of the source for the earthquake. Current interpretations are that the earthquake consisted of reverse-mechanism and strike-slip components [1, 2, 3], with an initial reverse-mechanism sub-event extending from the hypocentre at about 11 km depth on a steeply dipping plane to within about 2 km of the surface (named Charing Cross thrust by Beavan *et al.* [2]), striking at about 220° to intercept the strike-slip surface-rupturing Greendale Fault [3] near Greendale. The surface fault is about 4 km south of the epicentre. Table 1 shows epicentral distances, and shortest distances from a smoothed model of the surface fault rupture. The Darfield site lies only 6.1 km from the top of the Charing Cross thrust associated with the initial reverse-mechanism sub-event rupturing from the hypocentre but 11 km from the surface trace. The other near-source stations are closer to the Greendale Fault surface trace than to the epicentre. Other more distant sites north of the surface trace and epicentre will obviously be closer to the epicentre, but the difference in distance has little effect on expected motions for these locations, the closest of which is Lake Taylor at 85 km epicentral distance and 88 km from the Greendale Fault.

Figure 3 shows a comparison of the recorded peak ground accelerations on NZS1170 Class D (Deep or Soft Soil) and E sites (Very Soft Soil) with predicted median motions and plus and minus one standard deviation error bounds according to the New Zealand attenuation model of McVerry *et al.* [6] that underlies the hazard model used for development of the NZS1170 spectra [7]. The plotted values correspond to the larger horizontal component, consistent with design practice in New Zealand [5]. In Figure 3 the earthquake has been modelled with a strike-slip mechanism, corresponding to the sub-event associated with most of the moment release, and all distances except that for Darfield are those to the surface fault rupture. The plotted distance for Darfield is that to the closer Charing Cross thrust. Assuming a reverse-mechanism would increase the predicted pgas by 30%, and an oblique mechanism by 14% [6]. The Greendale pga at 1.3 km distance is considerably underestimated, as is that for Kaiapoi at 32 km. Most other records are within or close to +/- one standard deviation of the median predicted values. Only 8 of the 26 records are outside the one-sigma bounds, consistent with these bounds covering about 68% of a log-normal distribution, although there is a tendency to under-estimation of the recorded motions.

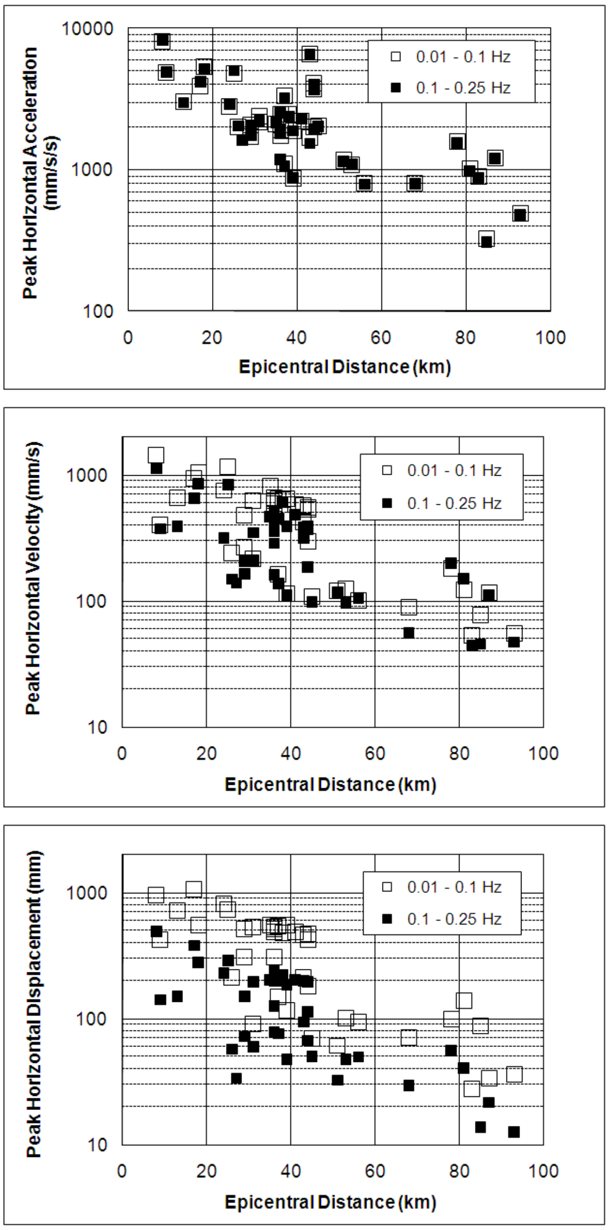

***Figure 2:** Effect of extended filter band on estimated peak horizontal ground motions.*

NEAR-SOURCE RECORDS

Many of the near-source records exhibited strong accelerations in both the horizontal and vertical components, and strong horizontal velocities. The peak horizontal ground accelerations (phgas) exceeded 0.5g at Greendale and Hororata. Vertical accelerations were over 1g at Greendale and 0.7g on four other records. Peak ground velocities reached 1.4 m/s at Greendale, over 1 m/s at Lincoln Crop and Food Research and Hororata, and over 0.5 m/s at fifteen other sites (Table 1). For some records, polarisation directions changed during the motions,

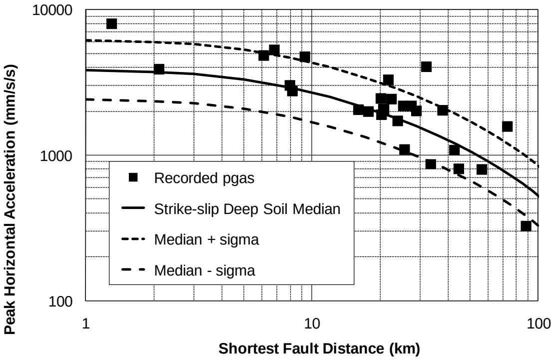

Figure 3: ***Comparison of peak ground accelerations for Class D and E sites with McVerry et al. (2006) attenuation model for New Zealand.***

consistent with rupture-directivity associated with episodes of strike-slip and reverse rupture within the mainshock.

Near-source motions reached between 2,500- and 5,000-year values at Greendale, and about 1,000- to 2,500 year levels at Hororata, compared to the NZS1170 500-year design-level (Ultimate Limit State) spectrum used for normal-importance structures (Figure 4). The NZS1170 spectra are plotted for Class D Deep Soil for a hazard factor Z= 0.3, the value listed for Darfield. The 500- and 2,500-year Return Period factor R values are 1.0 and 1.8, as in NZS1170. The approximate 5,000-year spectrum, which is not specified by NZS1170, corresponds to an additional factor of 1.3 on the 2,500-year value, as used for the increase when the return periods double between 500 and 1,000 years.

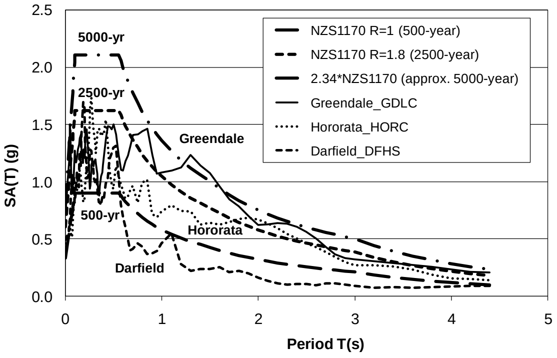

Figure 4: ***Larger horizontal component spectra from Greendale, Hororata and Darfield in the near-source region compared with NZS1170 spectra for deep soil site conditions at Darfield (Z= 0.3), for return periods of 500, 2,500 and 5,000 years (R = 1.0, 1.8, and 2.34).***

RECORDS FROM NEAR THE CHRISTCHURCH CBD

Spectra from the four stations within 1-2 km of the Christchurch Central Business District (Botanic Gardens, Cathedral College, Christchurch Hospital and Resthaven) with phgas of 0.19g to 0.34g, approximate 500 year motions of the NZS1170 structural design standard for structures with periods from 0.3 s to 1 s (about 3- to 10 storey buildings), but lie below code motions at shorter periods. Strong peaks around 2.5 s period with N-S polarisation considerably exceed code spectra. The associated large spectral displacements should have been demanding for long-period structures or structures responding beyond their yield levels, which typically correspond to considerably lower spectral accelerations than the NZS1170 elastic hazard spectra.

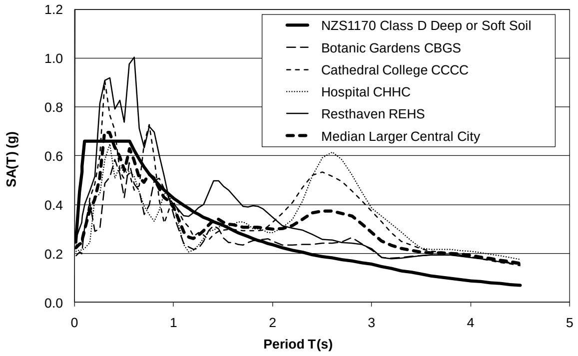

Figure 5: ***Larger horizontal component spectra from four sites within 1-2 km of the Christchurch CBD compared with NZS1170 spectra for Christchurch (Z = 0.22) for deep soil site conditions, for return periods of 500, 2,500 and 5,000 years (R = 1.0, 1.8, and 2.34).***

The large exceedance of the NZS1170 500-year spectrum at long-periods is more apparent from taking ratios of the spectra of the recorded motions to the NZS1170 R= 1.0 (500-year) spectrum, and then converting these to approximate return periods, as shown in Figure 6. The approximate return periods RP are calculated from RP (years) = 500 $R^{2.32}$, where R is the ratio to the 500-year (R=1) spectrum. This approximate formula is consistent with the NZS1170 value R= 0.5 for RP = 100 years, but under-estimates return periods longer than 500 years. This plot shows that the median pga corresponds to a return period of about 400 years, the short-period range up to 0.3 s generally lies below the 500-year values, the range from 0.3 s to 1 s corresponds to 400-500 year values, and the long-period range beyond 2 s on average lies between 1,000-year and 3,000-year motions.

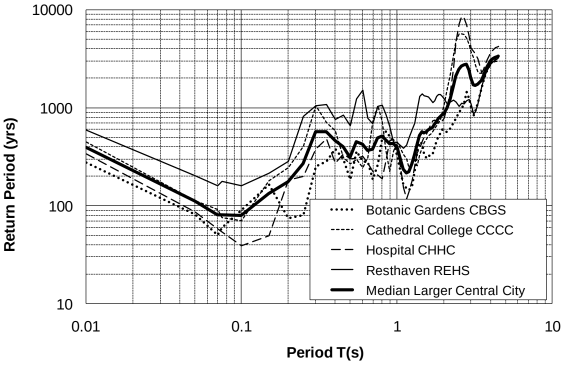

Figure 6 ***Approximate return periods as a function of spectral period for motions recorded at four sites within 1-2 km of the Christchurch CBD, and their median, estimated from ratios of the recorded spectra to the 500-year NZS1170 spectra for Christchurch (Z = 0.22) for deep soil site conditions.***

The peaks around 2.5 s presumably correspond to amplification of the motions by the several hundred metre deep gravels under Christchurch [8], but also indicate strong long-period content in the incoming waves because peaks at similar periods are not apparent in aftershock records. Figure 7 compares spectra from four earthquakes recorded at Christchurch Botanic Gardens. Two large magnitude earthquakes (Darfield mainshock M_w 7.1 and 2003 Doubtful Sound earthquake M_w 7.2) contain long-period energy that combines with the long-period site effects produced by the deep gravels under Christchurch to produce long-period spectra. The largest magnitude aftershock of the Darfield earthquake (M 5.6, 2010/09/04, 04:56 NZST [1]), and one a few days after the mainshock (M 5.1, 2010/09/08, 07:49 [1]) that produced strong motions in Christchurch city with peak accelerations of 0.15-0.25g, similar to the mainshock, lacked the long-period energy required to significantly excite the site response. There is a minor peak in the M 5.6 aftershock at a similar period to the amplifications shown in the two large magnitude events.

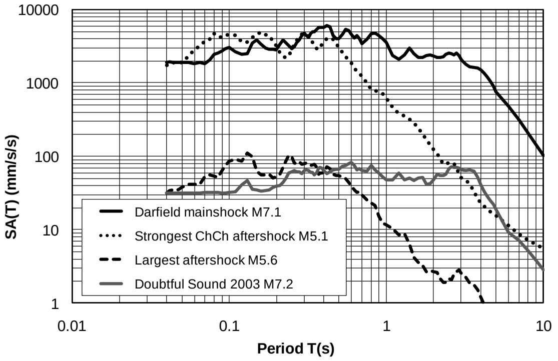

Figure 7: Four records from Christchurch Botanic Gardens demonstrating that both site and source effects contribute to long period character of some earthquake motions in Christchurch. The Darfield mainshock (M_w 7.1) and 2003 Doubtful Sound earthquake (M_w 7.2) contain long-period energy, while two moderate magnitude (M 5.6 and M 5.1) aftershocks do not.

All of the displacement records from Christchurch City showed strong polarization in a direction approximately normal to the surface trace of the Greendale Fault rupture (Figure 8). The polarization was usually distinct also in the velocity records, and sometimes in the accelerations.

RECORDS FROM THE EASTERN SUBURBS

Recorded motions from the eastern suburbs, including from within the zone of extensive liquefaction and spreading at the Hulverstone Road Pumping Station, provide important data for understanding the lateral spreading. Again, there are 2.5 s peaks well in excess of 500-year motions that may be an important feature. Phgas and 0.3 s to 1 s motions are about 80% of 500-year design motions (Figure 9), and the motions are more deficient at periods below 0.3 s.

One record stands out as being very different in character from the others in the Christchurch area (Figure 10). The strongest peak horizontal ground acceleration outside the near-source region was 0.66g recorded at Heathcote Valley School, 27 km from the fault. The peak of the 5% damped spectrum at 0.35 s exceeded 2g. However, the spectrum of this record was short period in character. Its response spectral amplitudes decreased rapidly at periods beyond its peak, and for periods of 0.85 s and longer was the weakest of the Christchurch area records. This site is at the head of Heathcote Valley, with the strong short-period response possibly caused by a shallow colluvial wedge, as shown in cross-section A-B of Brown and Weeber [9].

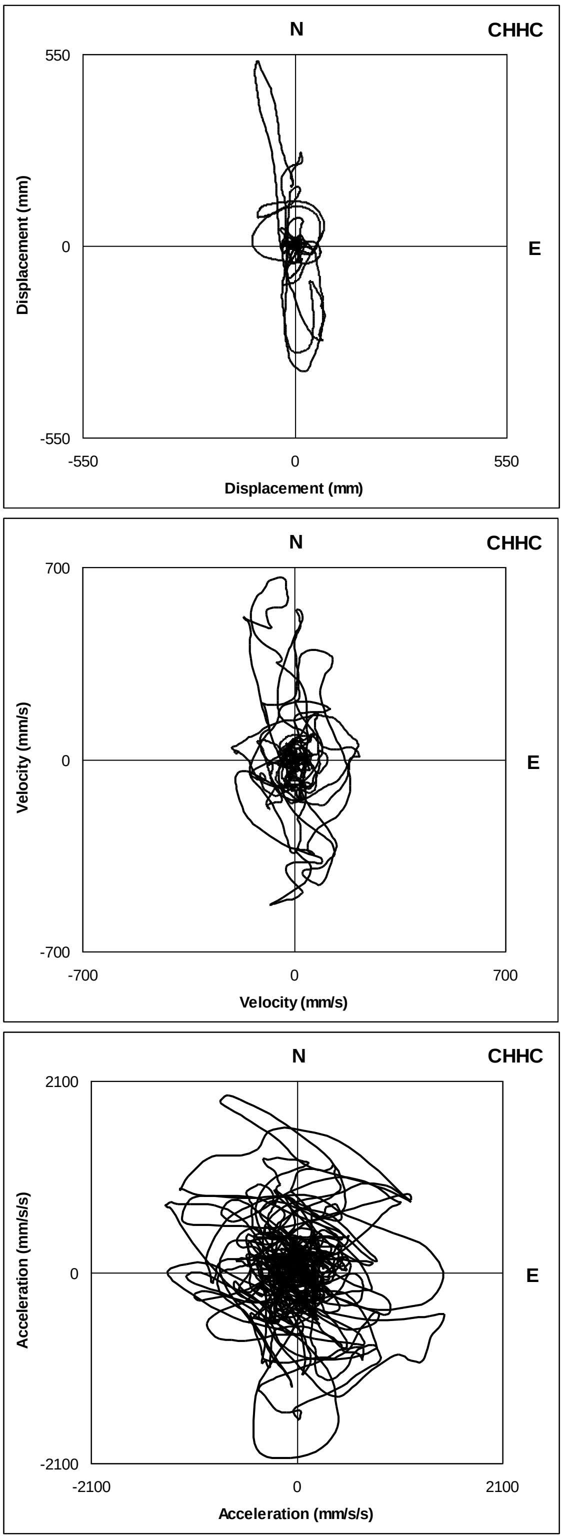

Figure 8: Typical polarisation seen in strong-motion data from within Christchurch City. The high-pass filter initiation frequency was 0.1 Hz .

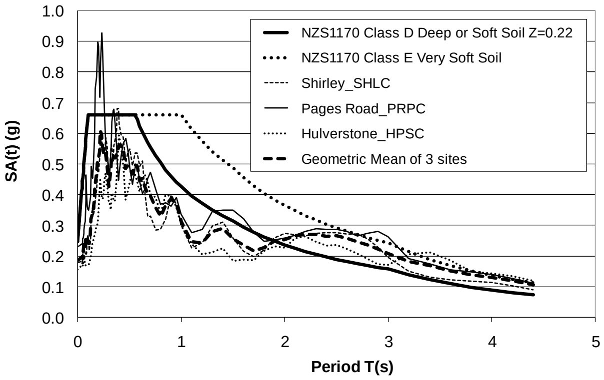

Figure 9: ***Spectra from three sites in the eastern suburbs compared with NZS1170 500-year spectra for Christchurch (Z = 0.22) for Class D Deep and Class E Very Soft site conditions.***

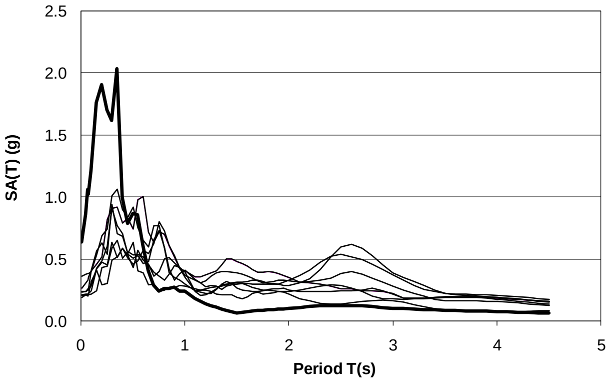

Figure 10: ***The peak ground acceleration and short-period peak of the spectrum from Heathcote Valley School stand out well above the other Christchurch records, but the spectrum falls below the other for periods beyond 0.85 s.***

DISCUSSION

This brief paper provides merely an introduction to the very rich set of strong-motion records obtained in the M_w 7.1 Darfield earthquake. These are likely to prove invaluable for many studies in the ensuing months and years to determine the nature of the damage (and in many cases, near lack of damage) in levels of earthquake motion ranging up to several times code-design levels for the region. Perhaps the most pervasive damage from the earthquake was that resulting from liquefaction and lateral spreading. This set of records should prove very helpful in developing an understanding of the ground-motion characteristics that contributed to this. Most design analyses for liquefaction are carried out in terms of magnitude-weighted peak ground accelerations, but was it the long-period characteristics of this earthquake that were a key contributor to this damage?

ACKNOWLEDGEMENTS

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