SUPPLEMENTARY STATEMENT OF EVIDENCE OF BRENDON ARCHIE BRADLEY

Comparison of the 4th September 2010 ground motions in the Christchurch CBD and "design ground motions"

16th July 2012.

1. Ground motion severity on a structure is a function of its: (i) amplitude; (ii) frequency content; and (iii) duration.

2. Page 46 of my evidence given in **WIT.BRADLEY.0003.1**: Figure 8, appended here, illustrates the ground motion response spectra of the four ground motions which were in close proximity to the CTV site (and which my evidence conclusively demonstrates are representative of the ground motion at the CTV site).

    a. Firstly, it should be noted that such elastic response spectra represent ground motion severity primarily in terms of its amplitude and frequency content, and only partially in terms of duration.

    b. It can be seen that at a vibration period of 1 second the design spectral acceleration is 0.375g. The observed ground motion spectral accelerations are 0.27, 0.35, 0.35, and 0.40, which correspond to 72%, 92%, 92% and 107% of the design spectrum. That is, the range of the four records is 72% to 107% of the design ground motion spectral amplitude with an average of 91%. Hence, the amplitude and frequency content related aspects of ground motion severity are approximately equal to the design spectrum.

3. Ground motion duration is at least partly considered in response spectra because a response spectrum illustrates the peak displacement of a single degree of freedom structure; and large displacements will not occur if the ground motion duration is so short that a state of resonance, which often leads to such large displacements, cannot be achieved.

4. However, a response spectrum only illustrates the single peak displacement, and therefore a separate, and explicit, measure of duration is insightful. There is no question that a larger ground motion duration (for the same ground motion amplitude and frequency content) is more severe on a structure.

5. Ground motion duration is principally a function of earthquake magnitude, since earthquake magnitude is indicative of the time it takes for the earthquake rupture to actually occur.

6. In order to understand the appropriate duration of a 'design ground motion' for Christchurch it is necessary to examine the contribution of various earthquake sources to the seismic hazard in Christchurch. This is conventionally referred to as a seismic hazard deaggregation. The results for a spectral acceleration of 1 second for site class D in central Christchurch is a mean magnitude of M_w7.4. Hence the duration of ground motion from this mean magnitude of M_w7.4

is not significantly different than the duration of a magnitude M_w7.1 ground motion. The assumption that a 'typical design ground motion' will have an extremely long duration is not consistent with earthquake sources which dominate the seismic hazard for Christchurch, upon which the design response spectrum is based.

7. The magnitude M_w7.1 ground motions in Sept 4 were actually larger than the mean durations expected as a result of several physical phenomena [complex bi-lateral rupture, basin-generated surface waves]. Hence the ground motion duration in the CBD from the Darfield earthquake is very similar to what would be expected from an expected magnitude M_w7.4 earthquake which as I have just explained represents the mean magnitude of earthquake sources dominating the seismic hazard in Christchurch.

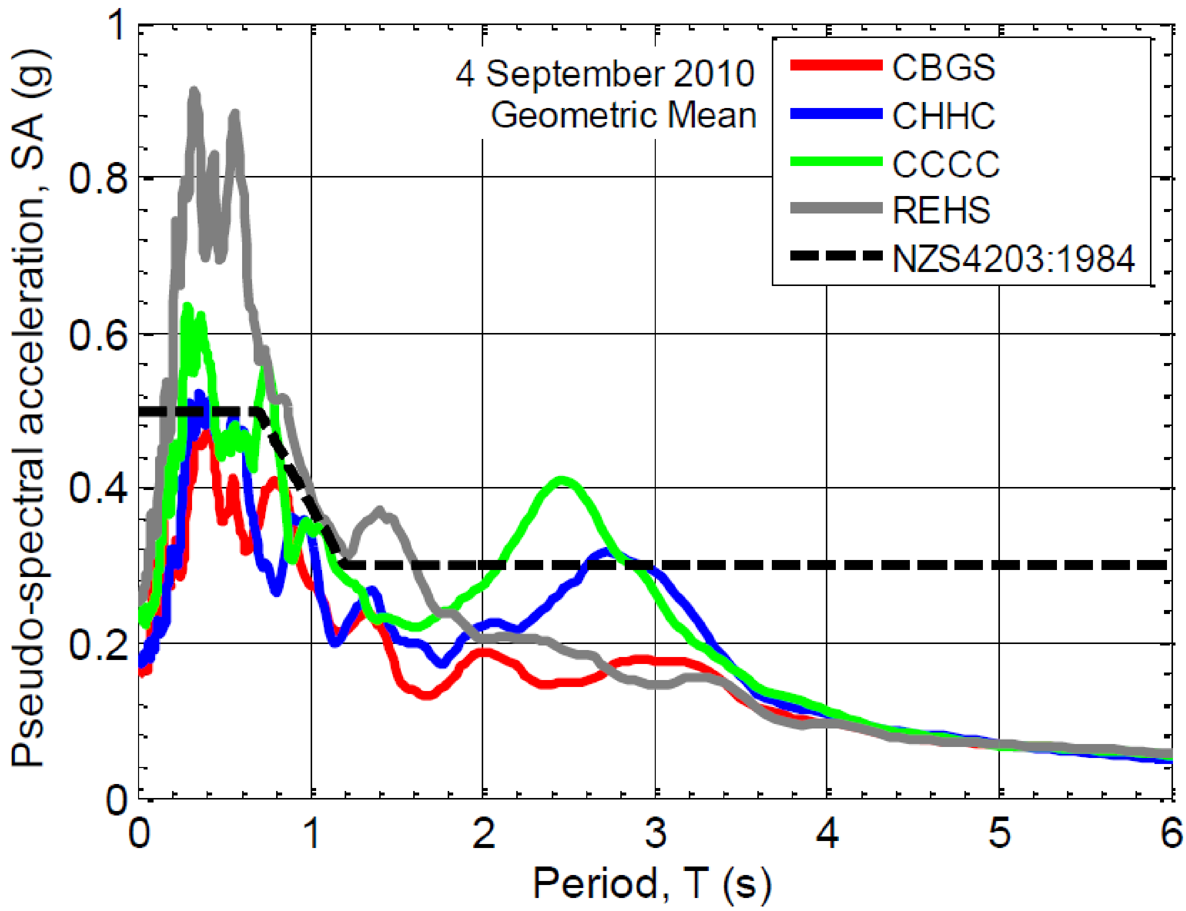
8. Hence, in my opinion the ground motions in the CBD during the 4th September 2010 earthquake were essentially equivalent to a design ground motion for structures with a vibration period of 1 second.

9. A lack of observable damage in the 4th of September 2010 earthquake is, in my opinion, not sufficient evidence to state that the ground motions from the 4th Sept 2010 were not equivalent the design ground motion. This is because the simplified design methods which are conventionally employed contain several locations of conservatism. For example, 5th percentile characteristic strengths of at used, which results in a factor of 1.25 and 1.4 under-prediction of the mean yield strength for grade 275 and 380 steel (Andriono and Park 1986). Another example is the neglect of additional damping which results from the nonlinear response of non-structural elements.

10. Furthermore, the lack of observable damage in post-earthquake inspections does not imply that damage did not actually occur. For example, Prof. Priestley (**WIT.PRIESTLEY.0001[1]**) notes on paragraph 80 of his evidence that crack widths of only 2mm would be required to fracture the mesh in order to commence the disconnection of the floor diaphragms to the North core, and this may not have been easily identified. Analyses for Compusoft Engineering Ltd, both in the initial report, and revision as part of the NLTHA panel indicate that such disconnection is likely to have occurred (specifically they found disconnection in the case in which the input ground motion was that from the CCCC station, but no disconnection in the case of using CBGS ground motion).

References:

Andriono, T., Park, R., (1986). "Seismic design considerations of the properties of New Zealand manufactured steel reinforcing bars", *Bulletin of the New Zealand Society for Earthquake Engineering*, 19, 213-246.
Bradley, B. A., (2012). "Strong ground motion characteristics observed in the 4 September 2010 Darfield, New Zealand earthquake", *Soil Dynamics and Earthquake Engineering*, 42, 32-46. 10.1016/j.soildyn.2012.06.004



Ground motion response spectra from the 4th September 2010 Darfield earthquake (Figure 8 of WIT.BRADLEY.0003.1).

Table 1: Numerical values of the spectral accelerations as shown in the above figure.

	SA(T=1s) (g)	Proportion of design value
Design	0.375	-
CBGS	0.270	0.72
CHHC	0.350	0.93
CCCC	0.350	0.93
REHS	0.400	1.07
Average of recorded	**0.343**	**0.91**
Range of recorded	**0.27-0.40**	**0.72-1.07**

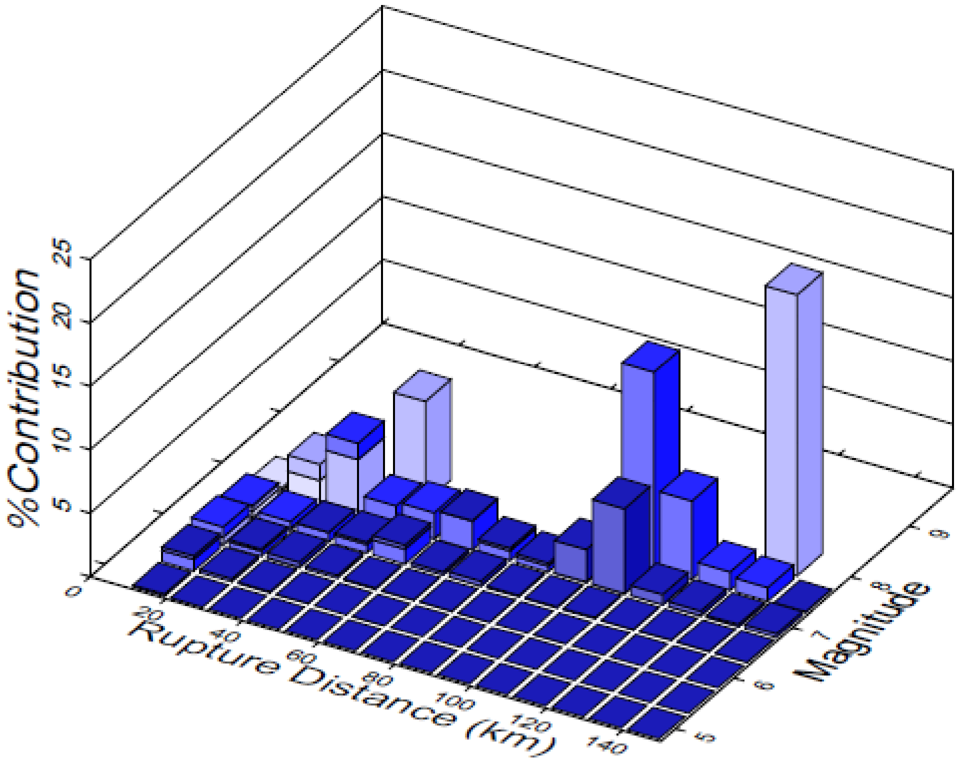


Figure: Contribution of various earthquake sources to the total seismic hazard in central Christchurch. The mean magnitude is M_w7.37.

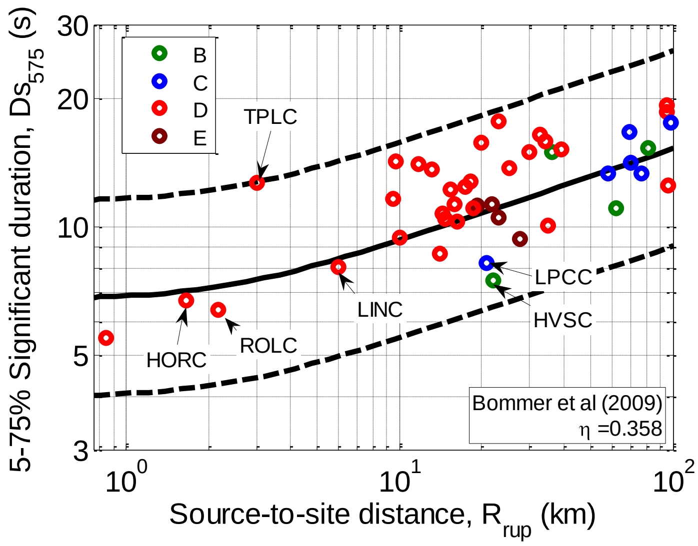


Figure: Comparison of 5-75% significant durations observed in the 4th September 2010 Darfield earthquake and empirical prediction (Figure 18a of Bradley (2012)).

SUPPLEMENTARY STATEMENT OF EVIDENCE OF BRENDON ARCHIE BRADLEY

Comparison of the characteristics of the Christchurch earthquake and a potential alpine fault earthquake for Christchurch city.

16th July 2012.

1. The statements below are principally based on a technical publication in the 2012 New Zealand Earthquake engineering conference (Bradley 2012).

2. Ground motion severity on a structure is a function of its: (i) amplitude; (ii) frequency content; and (iii) duration.

3. The seismic hazard in Christchurch is comprised of larger faults at regional to large distances. For example, the Alpine fault has a postulated rupture magnitude of M_w8.1 at a distance of approximately 130km. Other notable faults include the Porters Pass fault and the Hope fault.

4. Due to a lack of historically observed large magnitude events, their detailed characteristics are poorly understood relative to knowledge for small-to-moderate magnitude events.

5. However, their general characteristics are well known, and can be well illustrated by comparing the ground motions in the Canterbury earthquakes with those observed from the M_w9.0 Tohoku earthquake in Tokyo, which at a source-to-site distance of 110km is similar to the 130km distance from Christchurch to the inferred location of the potential alpine fault rupture.

6. Figure 2 of Bradley (2012), appended here, illustrates the ground motions recorded in the Christchurch CBD in the 22 February 2011 and 4 September 2010 earthquakes, with that recorded in Tokyo Bay in the 11 March 2011 Tohoku earthquake. It is evident that these three ground motions vary widely in their amplitude and duration. The CBGS ground motion from the 22 February 2011 event has a very large amplitude (nearly 0.6g) and short duration (approx. 10s of intense shaking), as a result of the causal M_w6.3 rupture at short distance (R_{rup}=4km). The CBGS ground motion from the 4 September 2010 earthquake has a longer duration (approx. 30s of intense shaking), but reduced acceleration amplitude, as a result of the causal M_w7.1 rupture at a short-to-moderate distance (R_{rup}=14km). Finally, the Urayasu ground motion in Tokyo bay during the 11 March 2011 Tohoku earthquake exhibits an acceleration amplitude similar to the 4 September 2010 CBGS ground motion, but a significantly larger duration (approx 150s of intense shaking). Clearly, these three different ground motions will affect structures and soils in different ways depending on the vibration characteristics of the structures/soil, and the potential for strength and stiffness degradation due to cumulative effects.

7. Figure 3 of Bradley (2012), appended here, provides a comparison of the geometric mean response spectra observed in the Christchurch CBD during the 22 February 2011 and 4 September 2010 earthquakes with those observed in Tokyo during the 11 March 2011 Tohoku earthquake. In this figure, the ground motions from four locations in the Christchurch CBD were used (CBGS,CCCC,CHHC), while three locations in Tokyo (soil sites) are also displayed (Urayasu,

Inage, and Hachieda). It can be seen that the response spectra for T<4 seconds are notably larger from the 22 February 2011 earthquake than those in Tokyo from the Mw9.0 Tohoku earthquake. Also, while the response spectra of ground motions in the Christchurch CBD from the 4 September 2010 earthquake and in Tokyo from the 11 March 2011 earthquake are similar, the effects of near-source forward-directivity can be clearly seen in several of the response spectra from the 4 September 2010 earthquake at T=2-3 seconds. Such directivity effects are not present in the Tokyo ground motions due to the large source-to-distance, and would also not be present in Christchurch from an inferred Alpine fault event.

8. Elastic response spectral accelerations do not explicitly account for the duration of ground motion, which is important if the amplitude of the ground motion is sufficient to cause nonlinear response in structures and soils. Figure 5 of Bradley (2012), appended here, explicitly illustrates the 5-95% significant duration of the ground motions examined in these three different events. The 5-95% significant duration is defined as the time interval over which the arias intensity of the ground motion goes from 5- to 95% of its total value. It can be seen that the ground motions in the Christchurch CBD during the 22 February 2011 earthquake have significant durations on the order to 10 seconds compared to 25 seconds in the 4 September 2010 earthquake. In comparison, the significant duration of ground motions in Tokyo from the 2011 Tohoku earthquake is on the order of 125 seconds (i.e. 13 and 6 times that of the ground motions from the 22 February 2011 and 4 September 2010 earthquakes, respectively).

9. One method to account for strong ground motion amplitude and duration explicitly is to consider the ground motions Arias Intensity, which considers both ground motion amplitude and duration explicitly (and is one method for considering the triggering of liquefaction). Figure 7 of Bradley (2012), appended here, provides a comparison between the arias intensities of the ground motions from the three different events that have been previously discussed. It can be seen that the arias intensities of the ground motions in the Christchurch CBD from the 22 February 2011 earthquake (which is on average AI=2.5m/s) is approximately twice that from the 4 September 2010 earthquake (average AI≈1.25). It can also be seen that the arias intensity of the ground motions recorded in Tokyo during the 2011 Tohoku earthquake are larger than ground motions in the Christchurch CBD from the 4 September 2011 earthquake, but smaller than those of the 22 February 2011 earthquake. Based on the arias intensity it can therefore be concluded that the ground motion severity (in terms of liquefaction potential, for example, as well as structures which may be susceptible to significant strength and stiffness degradation) for the Tokyo ground motions is between those ground motions in Christchurch CBD from the 4 September 2010 and 22 February 2011 events.

10. Recalling that the source to site distance of approximately 110km from Tokyo to the Tohoku earthquake rupture is similar to that of Christchurch from a perceived Alpine fault event (130km) then the severity of ground motions in Christchurch from an Alpine fault event would be expected to be slightly less than those from the Tohoku earthquake in Tokyo, therefore making them more similar to those from the 4 September 2010 earthquake than the 22 February 2011 earthquake. Strictly speaking, the severity will be a function of the vibration period of the considered structure, with long period structures being subjected to greater demands than short period structures.

References:

Bradley, B. A., (2012). "Ground Motion Comparison of the 2011 Tohoku, Japan and 2010-2011 Canterbury earthquakes: Implications for large events in New Zealand", in *New Zealand Society of Earthquake Engineering Annual Conference*: Christchurch, New Zealand. p. 8.

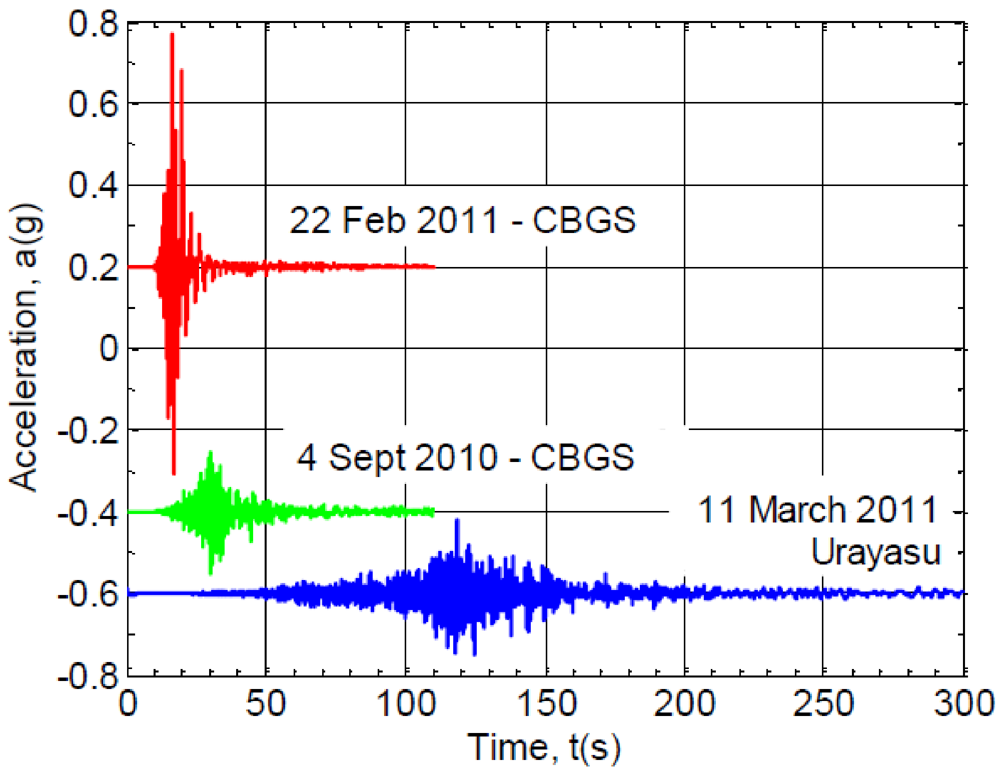


Figure: Comparison of the ground motions recorded at Christchurch Botanic Gardens (CBGS) during the 22 February 2011 Christchurch earthquake and the 4 September 2010 Darfield earthquake with the ground motion recorded in Tokyo Bay (Urayasu) during the 11 March 2011 Tohoku earthquake (Figure 2 of Bradley (2012)).

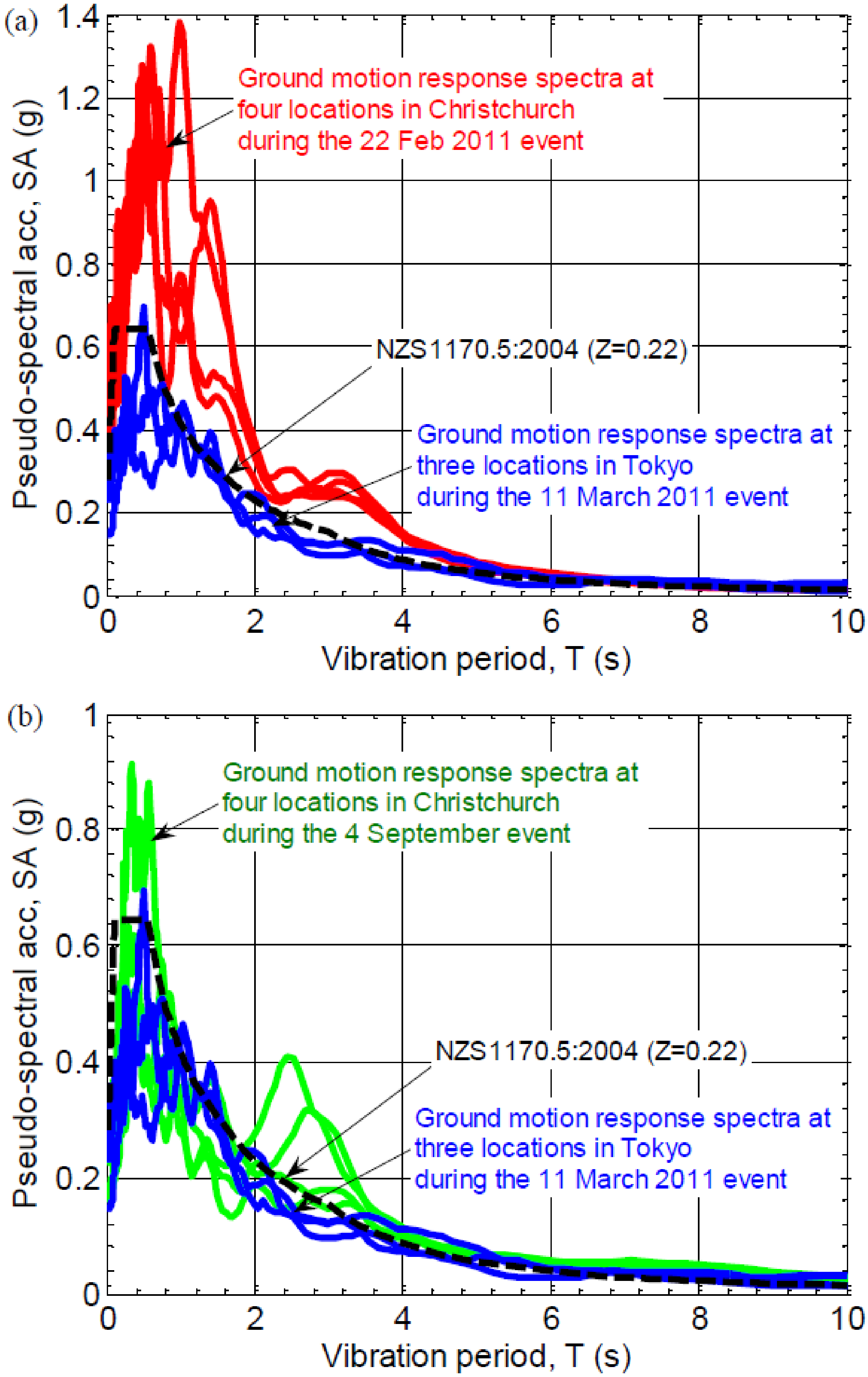


Figure: Comparison of ground motions in the Christchurch CBD with those observed in Tokyo from the 11 March 2011 Tohoku earthquake: (a) The 22 February 2011 Christchurch earthquake; and (b) the 4 September 2010 Darfield earthquake. For reference the site class D seismic design spectra for Christchurch (Z=0.22) as per NZS1170.5:2004 is also shown (Figure 3 of (Bradley 2012)).

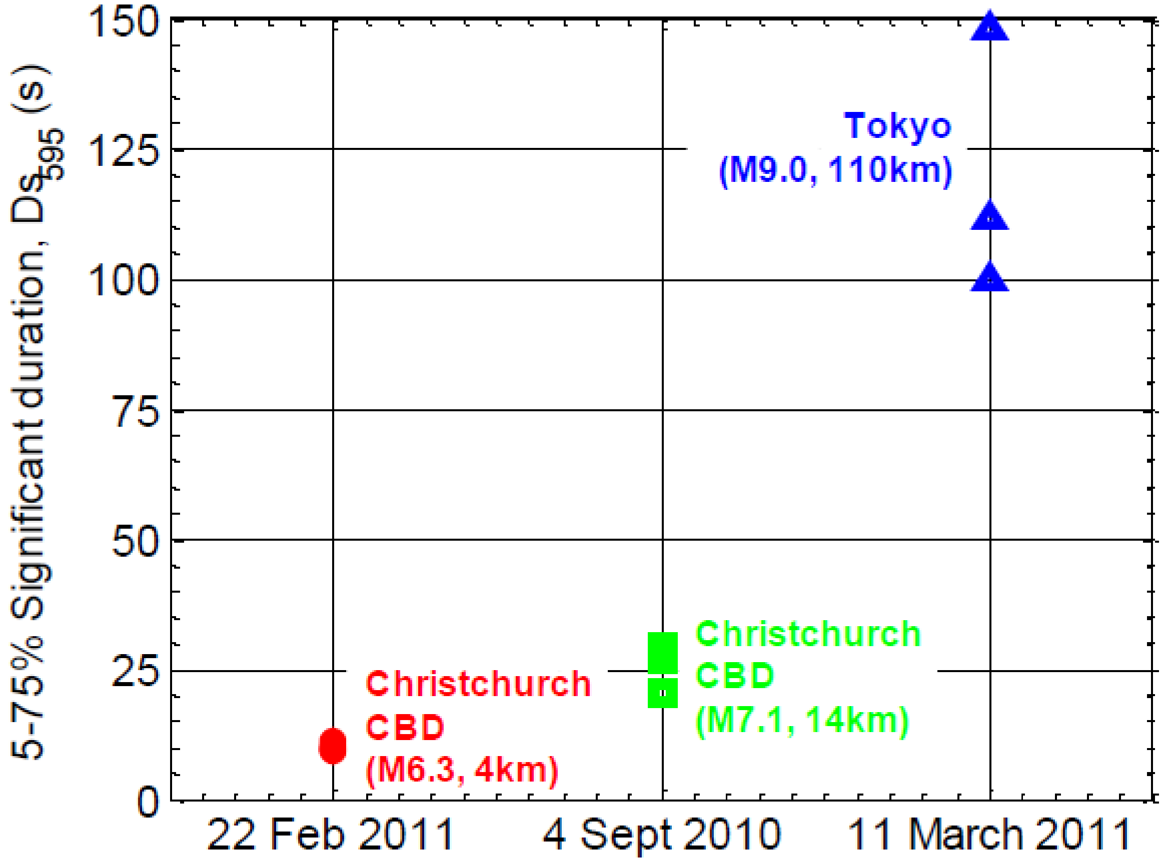


Figure: Comparison of the significant duration (5-95% definition) of ground motions in the three different events **(Figure 3 of (Bradley 2012)).**

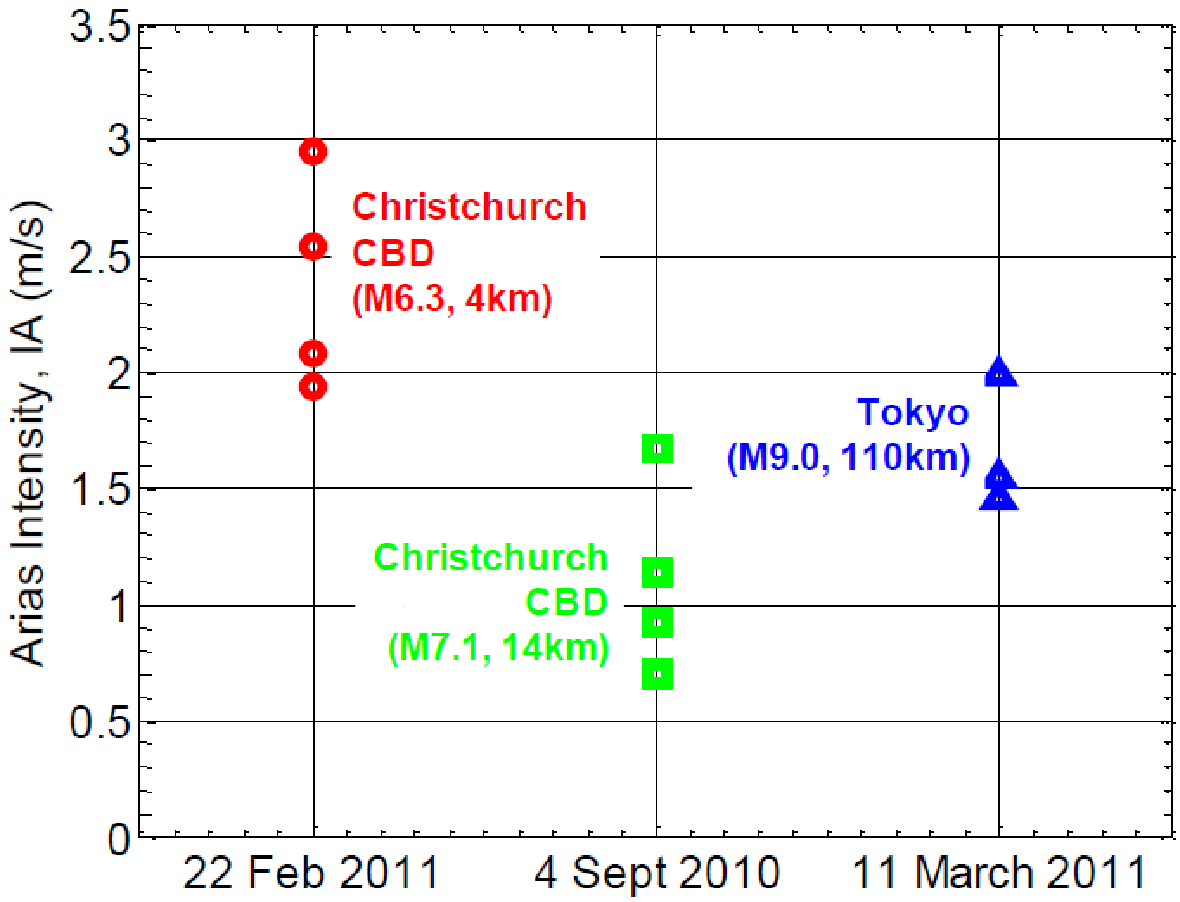


Figure: Comparison of the Arias intensity of ground motions in the three different events (Figure 3 of (Bradley 2012)).

SUPPLEMENTARY STATEMENT OF EVIDENCE OF BRENDON ARCHIE BRADLEY

Vertical ground motion effects in the 22 February 2011 and 4 September 2010 Canterbury earthquakes.

16th July 2012.

1. In both the 22 February 2011 and 4 September 2010 earthquakes, the ground motions in the CBD had vertical response spectral amplitudes which exceeded the vertical design spectra based on the code rule of "Two-thirds" of the horizontal ground motion (which for the New Zealand loadings standard is actually a ratio of 0.7).

2. Note that other structural engineering experts have commented during their testimony (e.g. Prof. Priestley, among others) that the peak accelerations of vertical ground motions in the CBD for the 4 September 2010 earthquake were not significant. That is, presumably to say that they were below two-thirds of the horizontal motion. This is true for the peak ground acceleration, which corresponds to a vibration period of zero, however it is not true for vibration periods in the range of 0.05-0.25 seconds, which often corresponds with the potentially important vertical vibration modes of structures.

3. It is well acknowledged, based on observations of multiple earthquakes worldwide since the 1994 Northridge earthquake (Bozorgnia and Campbell (2004) and references therein), that the rule that the vertical acceleration spectrum is two-thirds of the horizontal spectrum is highly un-conservative in the near-field region for short vibration periods. This un-conservatism was evident in both the 22 February 2011 Christchurch and also 4 September 2010 Darfield earthquakes.

4. The larger vertical ground motions in the CBD during the 22 February 2011 earthquake are simply a result of the close proximity of the CBD to the earthquake source. Comparably large vertical ground motions were also observed in Darfield and Rolleston, among other locations, during the 4 September 2010 Darfield earthquake.

The significance of vertical ground motions on structural response is well recognised, as can be ascertained from the following quote from Elgamal and He (2004): (where the reference to Figure 1 in the quotation is appended) "Papazoglou and Elnashai (1996) drew attention to the significance of studying vertical ground motion and its damaging effects on structures. Indeed, field evidence from recent earthquakes has shown that many buildings and bridges experienced significant damage attributable to high vertical earthquake motions. Papazoglou and Elnashai collated such damaged building and bridge case histories during the 1986 Kalamata earthquake, the 1994 Northridge earthquake, and the 1995 Kobe earthquake. Figure 1 is among the many examples of damage due to vertical motion presented by Papazoglou and Elnashai [1996]. It shows the collapse of the California State University Northridge 3-storey parking structure. Inward bending of the lateral force resisting system occurred as a result of interior columns collapse, very likely due to vertical motion [Papazoglou and Elnashai, 1996]. In this regard, vertical motions may increase axial column forces, causing an increase in moment demand, shear demand, plastic deformation, and extent of plasticised zones in the beams/columns [Papazoglou and Elnashai, 1996; Abdelkareem and Machida, 2000; Diotallevi and Landi, 2000]. Vertical motion may also reduce the ductility level in columns [Abdelkareem and Machida, 2000], and moment/shear capacity in beams [Diotallevi and Landi, 2000]."

References:

Bozorgnia, Y., Campbell, K. W., (2004). "The vertical-to-horizontal response spectral ratio and tentative procedures for developing simplified V/H and vertical design spectra", *Journal of Earthquake Engineering*, 8, 175-207.

Bradley, B. A., (2012). "Ground motion and seismicity aspects of the 4 September 2010 and 22 February 2011 Christchurch earthquakes", *Technical Report Prepared for the Canterbury Earthquakes Royal Commission*, 62pp.

Elgamal, A., He, L., (2004). "Vertical earthquake ground motion records: An overview", *Journal of Earthquake Engineering*, 8, 663-697. 10.1080/13632460409350505

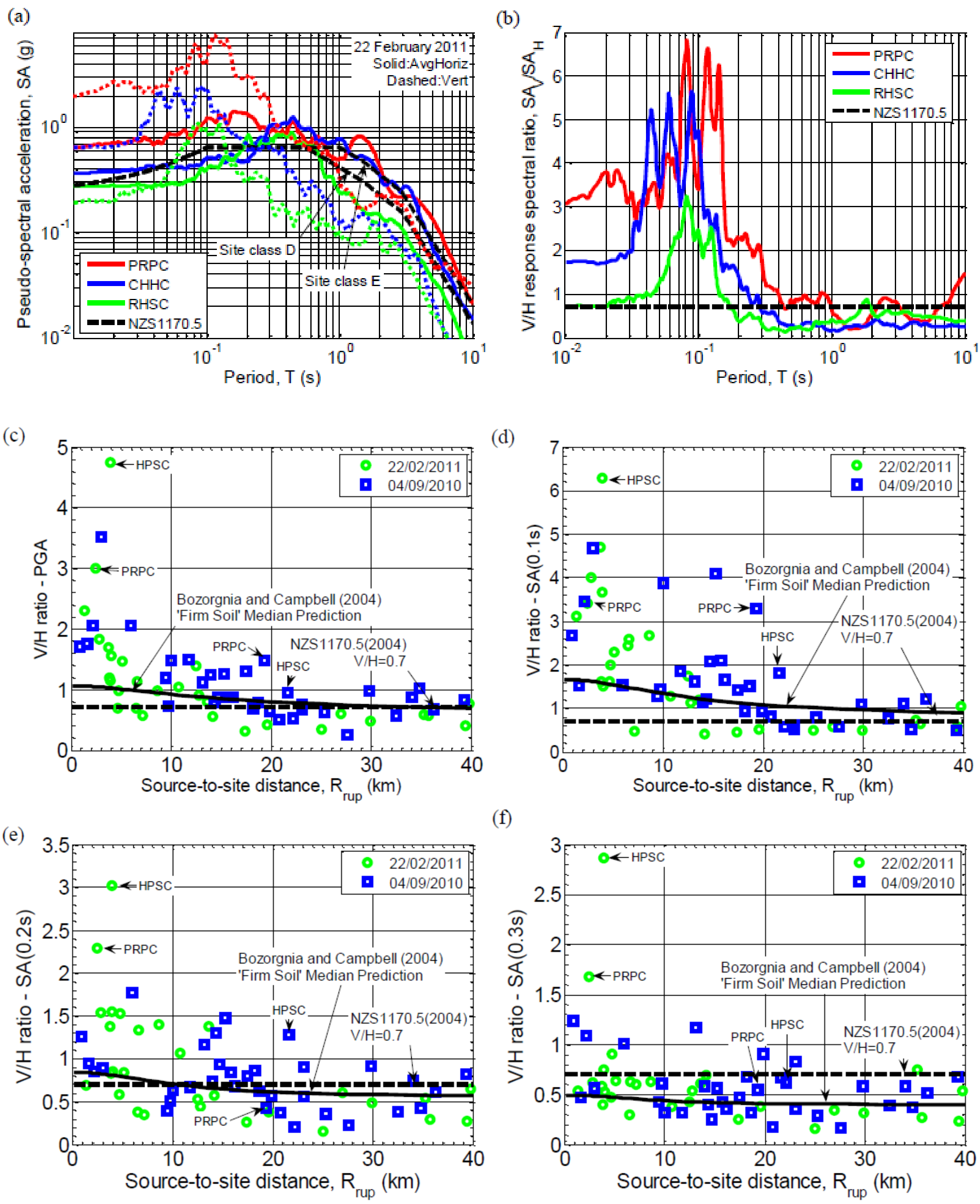


Figure: Vertical ground motion response spectral amplitudes observed: (a)-(b) Example geometric mean horizontal and vertical response spectra and their vertical-to-horizontal ratio; (c)-(e) vertical-to-horizontal response spectral ratios for T = 0.0-0.3s as a function of distance observed in the 4 September 2010 Darfield and 22 February 2011 Christchuch earthquakes and comparison with the empirical prediction of Bozorgnia and Campbell [45]. (Figure 26 of Bradley (2012)).

Fig. 1. Collapsed parking structure of the California State University Northridge [Papazoglou and Elnashai, 1996].

(after Figure 1 of Elgamal and Hue (2004)).