Ground Motion Comparison of the 2011 Tohoku, Japan and 2010-2011 Canterbury earthquakes: Implications for large events in New Zealand.

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ABSTRACT: This paper provides a comparison between the strong ground motions observed in the Christchurch central business district in the 4 September 2010 M_w7.1 Darfield, and 22 February 2011 M_w6.3 Christchurch earthquakes with those observed in Tokyo during the 11 March 2011 M_w9.0 Tohoku earthquake. Despite Tokyo being located approximately 110km from the nearest part of the causative rupture, the ground motions observed from the Tohoku earthquake were strong enough to cause structural damage in Tokyo and also significant liquefaction to loose reclaimed soils in Tokyo bay. Comparisons include the strong motion time histories, response spectra, significant durations and arias intensity. The implications for large earthquakes in New Zealand are also briefly discussed.

1 INTRODUCTION

The recent sequence of earthquakes in the Canterbury region has caused widespread damage to commercial, industrial, and residential structures and infrastructure (NZSEE 2010, NZSEE 2011). In the process of reconstruction in Christchurch, it is critical to understand the future hazard posed by the regions active faulting. This hazard is known to be contributed by small-to-moderate earthquakes (i.e. approximately M_w<7) at relatively short distances, as well as the potential for large earthquakes at moderate to large distances.

Figure 1 illustrates the deaggregation of the seismic hazard in Christchurch for an exceedance probability of 2% in 50 years (i.e. an approximately 2475 year return period), which explicitly illustrates the magnitudes and distances of seismic sources, and their contribution to the seismic hazard. It can be seen that for high frequency ground motion (e.g. PGA) the hazard is dominated by small-to-moderate magnitude earthquakes at short distances. In contrast, low frequency ground motion (e.g. SA(2.0)) is dominated by large magnitude earthquakes over a wide range of distances.

Of particular importance in the results of Figure 1 is the large contribution of the SA(2.0) hazard from the large magnitude Alpine fault (Southern and central segments, M_w8.1, R_{rup}=130km), despite its relatively large source-to-site distance (not to mention the M_w7.45 Porters Pass and Hope faults at distances of 43 and 106km, respectively). Such large magnitude events deserve particular attention for several reasons: (i) they will result in large ground motion over a wide spatial region; (ii) due to a lack of historically observed large magnitude events, their characteristics are poorly constrained relative to knowledge for small-to-moderate magnitude events; (iii) large events produce ground motion with long duration, and hence a large number of cycles of significant amplitude, which can cause substantial cumulative effects in degrading structures, and liquefaction/cyclic softening in soils.

The recent 11 March 2011 M_w9.0 Tohoku earthquake illustrated the damage that large magnitudes can cause over a large spatial region. While the predominant cause of damage in this event was a result of tsunami, a substantial number of strong ground motions were recorded in the event. In Tokyo, the world's largest metropolitan area, in particular, the ground motion would be regarded as severe (as will be illustrated in subsequent sections), despite it being located at approximately 110km from the southern extent of the fault rupture. Such a source-to-site distance is similar to the distance from Christchurch to the perceived Alpine Fault earthquake, as demonstrated in Figure 1b. Furthermore, similar to Christchurch, Tokyo is located on deep alluvial deposits which provide significant amplification of long-period ground motion.

While the Tohoku earthquake is larger than that expected from an Alpine fault event, as well as being a subduction event as compared to a shallow crustal Alpine fault event, an analysis of the ground motion severity in Tokyo provides insight as to the implications of an Alpine fault event for Christchurch. The Tohoku earthquake is also of relevance to New Zealand in that the Hikurangi Subduction Zone beneath the central and eastern North Island is inferred to be capable of producing events to up M_w8.8 (Stirling, et al. 2011).

The subsequent sections of this paper provide comparisons between the characteristics (time history, response spectra, significant duration, and arias intensity) of the ground motion observed in the CBD of Christchurch during the 2010 Darfield and 2011 Christchurch earthquakes, and those in Tokyo from the 2011 Tohoku earthquake.

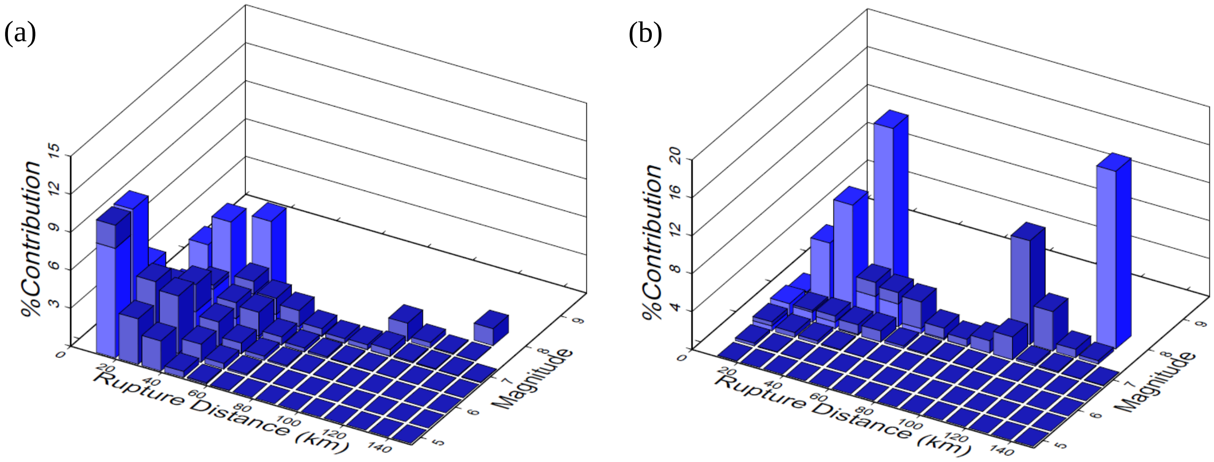

Figure 1: Seismic hazard deaggregation for Christchurch (site class D) for 2% in 50 year exceedance probability: (a) Peak ground acceleration, PGA; and (b) 2-second spectral acceleration, SA(2.0). The results are based on Stirling et al. (2011), and do not include the short-term increased seismicity in the Canterbury region following the Darfield earthquake (which would increase the contribution from small-magnitude near-source events).

2 GROUND MOTION TIME HISTORY COMPARISON

The severity of a ground motion on engineering structures is, in general, a function of its amplitude, frequency and duration. Each of these three general features of a ground motion are strongly affected by the size of the causal earthquake rupture, wave propagation effects such as the distance from source-to-site, and the characteristics of the surficial soils.

Figure 2 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.

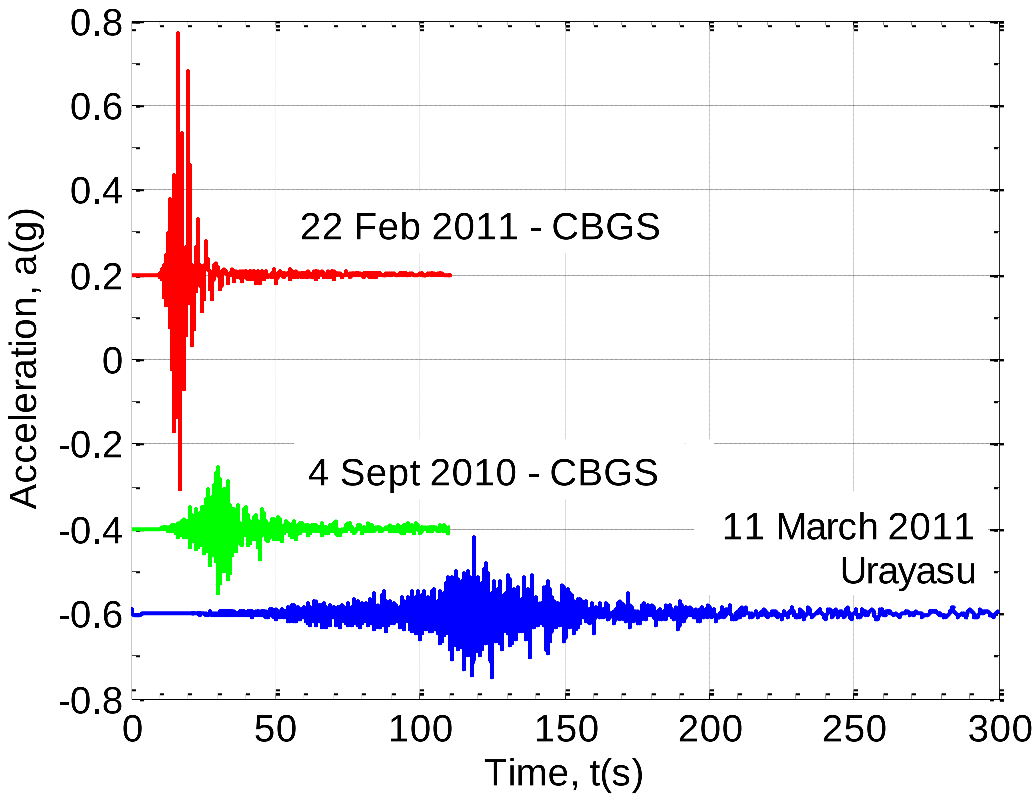

Figure 2: Comparison of the ground motions recorded at Christchurch Botanic Gardens (CBGS) during the 22 February 2011 Christchurch earthquake and the 4 September 2010 Darfield earthquake with the ground motion recorded in Tokyo Bay (Urayasu) during the 11 March 2011 Tohoku earthquake.

3 RESPONSE SPECTRA COMPARISON

Figure 2 illustrated that the CBGS ground motion from the 22 February 2011 earthquake had the largest acceleration amplitude as a result of its close proximity to the causal rupture source. Clearly, therefore such ground motions will be most damaging to stiff structures which are highly excited by such intense high frequency ground motion. On the other hand, the severity of the three ground motions in Figure 2 for moderate- and flexible structures cannot be ascertained from examination of the ground motion acceleration histories alone, and response spectra should be considered.

Figure 3 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 these figures, the ground motions from four locations in the Christchurch CBD were used (CBGS,CCCC,CHHC,REHS – see Bradley and Cubrinovski (2011) for details), while three locations in Tokyo (soil sites) were also examined (Urayasu, Inage, and Hachieda). For reference, the design response spectra provided by NZS1170.5:(2004) is also shown for Christchurch (using Z=0.22, rather than a post-earthquake value of Z=0.3 that has been advised). It can be seen that the ground motion intensity in Tokyo from the 11 March 2011 Tohoku earthquake is below the NZS1170.5:2004 design spectrum for high frequencies (i.e. approximately T<0.8s), but approximately equal to the design spectrum for moderate to low frequencies. It can be seen that the response spectra for T<4 seconds are notably larger from the 22 February 2011 earthquake, for reasons previously noted. 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 (Bradley 2012). Such directivity effects are not present in the Tokyo ground motions due to the large source-to-distance (approx. 110km).

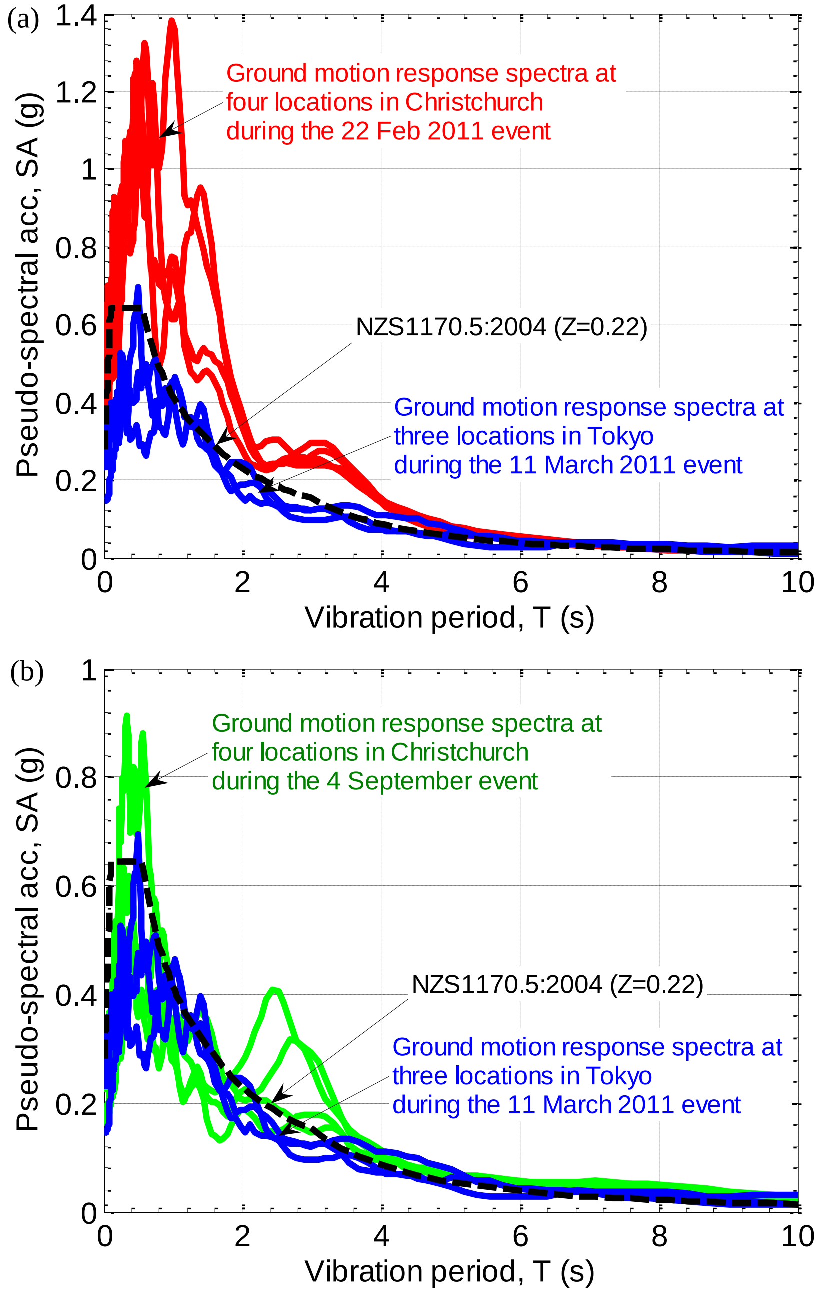

Figure 3: Comparison of ground motions in the Christchurch CBD with those observed in Tokyo from the 11 March 2011 Tohoku earthquake: (a) The 22 February 2011 Christchurch earthquake; and (b) the 4 September 2010 Darfield earthquake. For reference the site class D seismic design spectra for Christchurch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

Figure 4 illustrates the ratio of the response spectra in Figure 3 from the 11 March 2011 Tohoku earthquake with those of the 22 February 2011 and 4 September 2010 earthquakes. In these figures, the mean response spectrum for each event was firstly computed by averaging the various ground motions shown in Figure 3. Figure 4 demonstrates that the ground motions in the Christchurch CBD from the 22 February 2011 earthquake resulted in higher response spectral ordinates than those in Tokyo for vibration periods less than approximately 6.8s, but weaker for longer vibration periods. In contrast, the response spectral amplitudes in the Christchurch CBD from the 4 September 2010 earthquake were larger than those in Tokyo at all vibration periods expect for T=1-2 seconds. For long periods in particular, the ground motions from the 4 September 2011 earthquake are strong due to the near-source forward directivity effect, as discussed in Bradley (2012), and were stronger than from the 22 February 2011 earthquake (Bradley and Cubrinovski 2011).

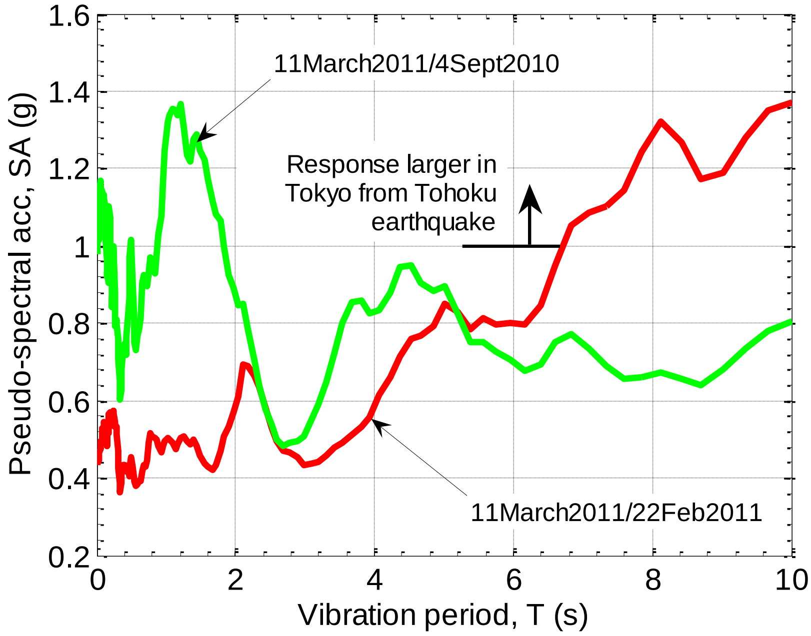

Figure 4: Ratio of ground motion response spectra from the Tohoku earthquake with those from the Canterbury earthquake. The ratio is of the mean of the response spectra shown in Figure 3.

4 COMPARSION OF STRONG GROUND MOTION DURATION

The elastic response spectral accelerations examined in the previous section do not account for the duration of ground motion, which as previously mentioned is important if the amplitude of the ground motion is sufficient to cause nonlinear response in structures and soils.

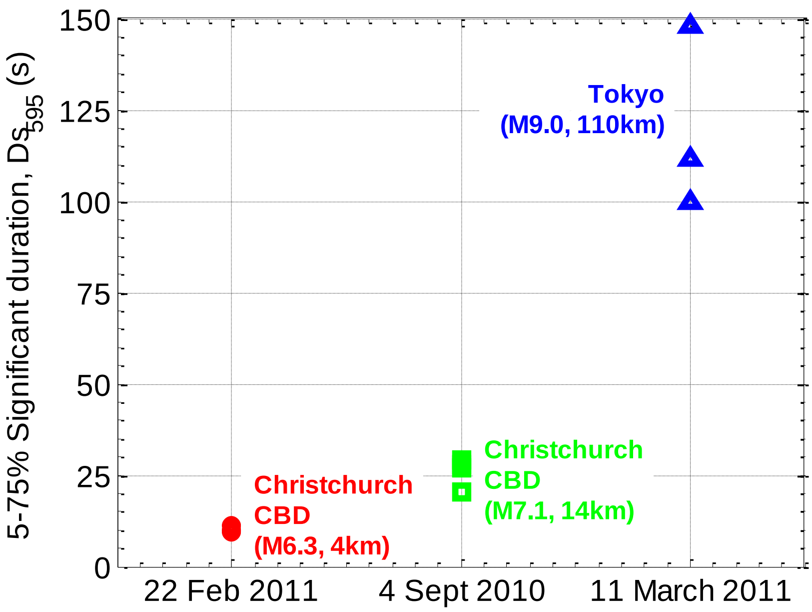

Figure 5: Comparison of the significant duration (5-95% definition) of ground motions in the three different events.

Figure 1 clearly showed that the duration of ground motion is significantly different for the ground motions considered from the three different events. Figure 5 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 (Bommer and Martinez-Pereira 1999). 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).

5 EFFECTS OF STRONG MOTION DURATION ON LIQUEFACTION TRIGGERING

The extremely long duration of ground motion in Tokyo from the Tohoku earthquake, and moderate amplitude (i.e. comparable with that of the Darfield earthquake as Figure 3 illustrates) led to severe liquefaction of reclaimed deposits in the Tokyo bay area as illustrated in Figure 6.

Figure 6: Consequences of liquefaction observed in Urayasu city during the 11 March 2011 Tohoku earthquake (Ishihara, et al. 2011).

Strong motion duration, which is related to the number of cycles of loading is widely recognised as important in soil liquefaction triggering. Using conventional stress-based assessments of liquefaction triggering, strong motion duration is implicitly accounted for using the magnitude scaling factor, MSF. For example, Cubrinovski et al. (2011) compared the ground motion severity in the Christchurch CBD for several of the Canterbury earthquakes in terms of the cyclic stress ratio (CSR), obtained from the PGA of the ground motion, the MSF and other factors related to the soil deposit. However, one of the problems with the MSF is that it is empirically based on historical events. There is no information to provide a precedent for setting an appropriate MSF for $M_w9.0$, and extrapolation of various empirical models for MSF (Architectural Institute of Japan 2001, Youd, et al. 2001) provide magnitude scaling factors which range from 0.6 to 0.8 (i.e. a 25% variation).

One method to account for strong ground motion amplitude and duration explicitly in liquefaction triggering, without the need for extrapolated empirical MSF models, is to perform liquefaction triggering based on Arias intensity as proposed by Kayen and Mitchell (1997). Since Arias intensity considers both ground motion amplitude and duration, then the triggering analysis is based solely on a correlation between soil penetration resistance (e.g. SPT, CPT) and ground motion arias intensity.

Figure 7 provides a comparison between the arias intensities of the ground motions from the three different events that have been previously examined. 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). This is consistent with a factor of approximately 1.6 obtained by Cubrinovski et al. (2011) using the stress-based (i.e. PGA-MSF) approach of liquefaction triggering. 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 liquefaction triggering approach it can therefore be concluded that the ground motion severity, in terms of liquefaction potential, for the Tokyo ground motions is between those ground motions in Christchurch CBD from the 4 September 2010 and 22 February 2011 events.

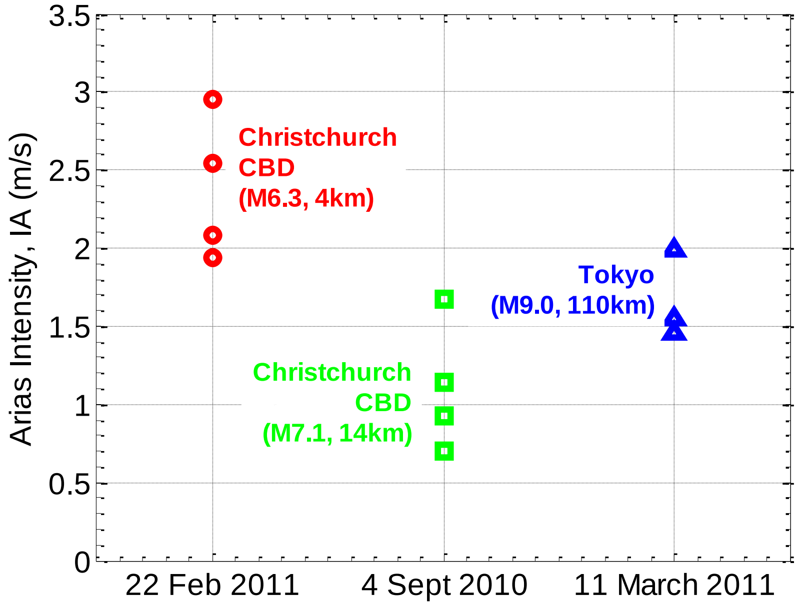

Figure 7: Comparison of the Arias intensity of ground motions in the three different events.

6 IMPLICATIONS FOR LARGE EARTHQUAKES IN NEW ZEALAND

6.1 *Christchurch and the Alpine fault*

The previous sections have illustrated the severity of strong ground motion observed in Tokyo from the 2011 Tohoku earthquake relative to those in the Christchurch CBD during the 22 February 2011 Christchurch and 4 September 2010 Darfield earthquakes. The source to site distance of approximately 110km from Tokyo to the southern extent of the Tohoku earthquake causative rupture is similar to that of Christchurch from a perceived Alpine fault event (130km). Furthermore, both Christchurch and Tokyo are located on deep alluvial deposits which lead to amplification of long period ground motion. Figure 7 illustrated that were these ground motions recorded in Tokyo to occur in Christchurch's CBD they would be of greater liquefaction potential than the 4 September 2010 earthquake, but less potential than the 22 February 2011 earthquake. Given that the Alpine fault is expected to rupture as a M_w8.1 event (Stirling, et al. 2011), then the liquefaction potential of ground motions in Christchurch 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. This is consistent with the liquefaction potential estimate of the Alpine fault for Christchurch by Cubrinovski and McCahon (2011).

Obviously the effect of long duration ground motion from a potential Alpine fault event will also place severe demands on structures which may degrade due to cumulative effects.

6.2 *Potential Subduction Zone earthquakes on the Hikurangi Subduction Zone*

The Hikurangi subduction zone is perceived to be capable of producing earthquakes of M_w8.8 (Stirling, et al. 2011). The results of the previous section illustrate that such earthquakes can produce strong ground motion shaking at distances well beyond 100km from the nearest point on the rupture plane. Given that the interface of the Hikurangi subduction zone is significantly closer to the New Zealand continent than in the case of Japan, it can be envisaged that significant ground motions (capable of causing damage to well engineered structures) would be expected over the majority of the central and southern regions of the North Island and the northern region of the South Island.

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