GEOLOGIC, GEOMORPHIC, GEOTECHNICAL, AND DISPLACEMENT MAPS OF LAND AND BUILDINGS AT SELECTED SITES OF CHRISTCHURCH CITY COUNCIL OWNED REINFORCED CONCRETE STRUCTURES DAMAGED DURING THE 2010-2011 CANTERBURY EARTHQUAKES

TIME SERIES OF EARTHQUAKE-INDUCED GROUND MOTIONS AT A GEOGRAPHIC MEAN SITE FOR CCC ASSETS FROM 1939 TO 2014

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1. Introduction

Dr. Bradley and Dr. Quigley were commissioned by Christchurch City Council to assess the possibility that concrete structures and land at seven key Christchurch City Council Asset sites could have experienced damage, total and/or differential settlement, or other forms of structural influence in earthquakes prior to the Canterbury Earthquake Sequence (CES). Specifically, this analysis aimed to understanding whether historical earthquakes prior to the 2010-2011 Canterbury earthquake sequence (Figure 5.1, 5.2) could have induced strong ground motions in Christchurch capable of inducing liquefaction or ground settlement at the locations of key CCC assets.

The seven key asset sites are listed in Table 1, along with their approximate WGS84 coordinates and completion dates for the significant structures at each site.

Table 1 Key Christchurch City Council Assets

ASSET	LATITUDE	LONGITUDE	COMPLETION DATE
Christchurch Art Gallery	-43.530385	172.631448	2003
Manchester street carpark	-43.529597	172.640192	1964
Christchurch City Library	-43.529633	172.635131	1979
Lichfield Street carpark	-43.533845	172.635077	1965/1986 3 floors added to 1965 bldg in 1970's
Old Bus Exchange	-43.53387	172.637407	1999
Old Civic Building	-43.53503	172.637896	1939
Lancaster Park	-43.542031	172.654145	Dean's Stand 2010; Hadlee and Tui Stands 1995; Paul Kelly Stand 2002
Christchurch South Library	-43.561394	172.63805	2002

2. Aims and Methodology

For the purpose of understanding whether historical earthquakes prior to the 2010-2011 Canterbury earthquake sequence (Figure 1, 2) could have induced strong ground motions in Christchurch capable of inducing liquefaction or ground settlement at the locations of key CCC assets, we undertook the following work procedure to define the severity of ground shaking in Christchurch from 1939 to 2013:

(i). <u>CHARACTERISATION OF CANTERBURY EARTHQUAKE SEQUENCE EVENTS (4 SEPTEMBER 2010 to 2013):</u> The ground motion severity is defined explicitly by obtaining geometric mean horizontal peak ground accelerations (PGA_{Hm}) for the largest Canterbury earthquake sequence events recorded at strong ground motion stations CCCC, REHS, CHHC, CMHS, CBGS. Details for each of these strong ground motion stations are presented in Table 2.

Station Name	Code	Network	Latitude	Longitude	Site Class	Geologic conditions**
Christchurch Cathedral College	CCCC	CanNet	-43.538085	172.647427	D	Alluvial sand and silt with gravels > 3 m
Christchurch Resthaven	REHS	NSMN	-43.52194513	172.6351501	D	Peat swamp & unconsolidated sand with gravels > 3 m
Christchurch Hospital	CHHC	CanNet	-43.53592591	172.6275195	D	Alluvial sand and silt
Cashmere High School	CMHS	NSMN	-43.56561744	172.6241694	D	Alluvial sand and silt with gravels > 3m
Christchurch Botanical Gardens	CBGS	CanNet	-43.52934	172.61988	D	Alluvial sand and silt with gravels > 3 m
Geometric mean latitude and longitude for CCC assets considered			-43.53697313	172.6386683		
***from Brown and Weeber;*						

Table 2 Locations and Site Class of strong ground motion stations used in this study

The recorded individual PGA estimates for each station are then used to compute a single 'geographic mean' PGA_{Hm} value at a site centred at the mean latitude and longitude for all CCC assets considered (lat = -43.53697313°, long = 172.6386683°). Data are plotted as open blue circles on Figure 2. Our individual results vary from those published using standard GeoNet processed data (e.g., Wotherspoon et al., 2015) because the latter utilize a filter that cuts out a significant component of high frequency shaking and thus underestimates PGA. Variations in subsurface geology, surface geomorphology and topography, and hydrology amongst strong ground motion sites and CCC asset sites contribute uncertainty to our analyses. However, all strong motion sites used and CCC asset sites considered are on Site Class D soils. Our geographic mean PGA_{Hm} thus provides a meaningful proxy to compare against the pre-Canterbury earthquake sequence event PGAs derived below.

ii. PRE-CANTERBURY EARTHQUAKE SEQUENCE EVENTS (from 1939 to 3 SEPTEMBER 2010): Because of a paucity of strong ground motions in central Christchurch prior to the installation of the dense GeoNet network in the early 2000's, and the lack of strong motions observed in Christchurch since the early 2000's, earthquake epicentre locations and moment magnitude (M_w) (from www.geonet.org.nz) are used to compute estimated ground motion severity from the historical earthquakes with $M_w \geq 5.0$ (Figure 1). Specifically, the Bradley (2013) ground motion prediction equation is used to estimate PGA_{Hm} for historical earthquakes since 1939 at the same Site Class D geographic mean site considered for the CES events described above. These data are plotted as red squares in Figure 5.2. The data from these analyses are provided in the accompanying Excel spreadsheet.

iii. DEFINE LIQUEFACTION TRIGGERING PGA FIELDS USING STRONG MOTION STATION ACCELEROGRAMS: We defined two fields in Figure 2 for the purpose of comparing PGA estimates from 1939 to 2013 with different estimates of the minimum PGA required to induce liquefaction in the sediments underlying CCC assets. We first use the range of estimates of geometric mean PGA at CBD strong ground motion sites in Christchurch presented in Wotherspoon et al. (2015) for earthquakes in which no surface evidence or accelerogram evidence for liquefaction was observed at individual strong ground motion sites in the M_w 7.1 Darfield earthquake. The range of geometric mean PGA for threshold is 0.16g to 0.25 g. This provides a generalized estimate for PGAs required to induce liquefaction at the CCC key asset sites. This proxy is indirect because the individual PGAs used to define this field may *underestimate* actual PGAs due to the filtering described above, and may potentially *overestimate* PGAs required to induce liquefaction in particularly susceptible sediments underlying CCC assets that could have lower liquefaction triggering thresholds than those underlying the strong ground motion sites. Nonetheless, this range is consistent with the absence of observed surface manifestation of liquefaction recorded in the M_w 4.7 Dec 26 2010 earthquake (0.16 – 0.25 g) that similarly did not cause liquefaction surface manifestation at any of the CCC asset sites (Bray et al., 2013).

As an additional constraint on minimum PGAs required to induce liquefaction, we define a second field (Figure 2) using empirical PGA and liquefaction data for a Red Zone residential site in eastern Christchurch with a high liquefaction susceptibility that exceeds any of the strong motion of CCC asset sites (Quigley et al., 2013). At least seven and potentially 10 distinct liquefaction events occurred at this site during the 2010-2011 Canterbury earthquake sequence. The lowest PGA where surface manifestation of liquefaction was recorded was 0.12 g and the highest PGA where no surface manifestation of liquefaction was observed was 0.18 g; these values serve to define the 'Minimum range of geometric mean PGAs in eastern Christchurch to initiate liquefaction' field shown in Figure 2 (Quigley et al., 2013). This can be treated as an 'absolute lower bound' field for liquefaction triggering PGAs required at CCC asset sites.

<u>**5.2. Results**</u>

As shown in Figure 2, 10 CES earthquakes caused PGA ≥0.1 g in the Christchurch CBD. Of these, 5 earthquakes caused PGAs within the range of geometric mean PGAs (0.16g to 0.25 g) at which no

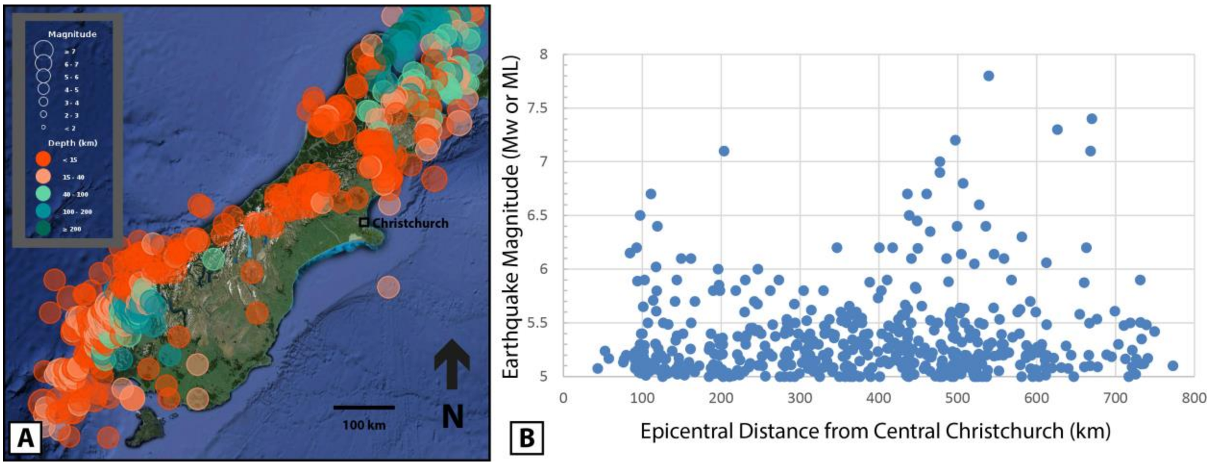

Figure 1. Epicentre locations and magnitudes of pre-CES earthquakes (1939 to 3 September 2010) in the South Island of New Zealand and epicentral distances from the mean latitude and longitude for all CCC assets (lat = -43.53697313°, long = 172.6386683°) in central Christchurch.

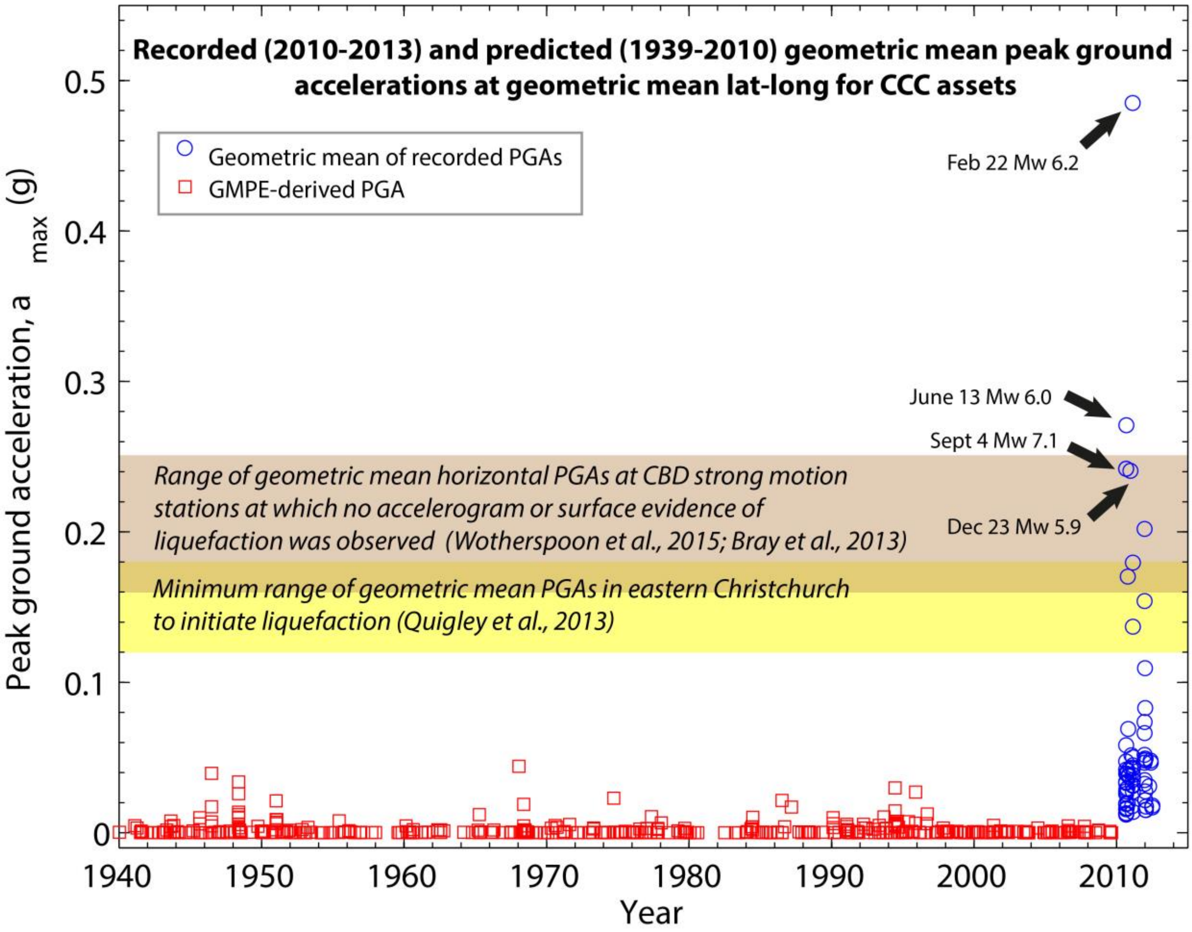

Figure 2. Recorded and predicted geometric mean peak ground accelerations at geometric lat-long for CCC assets and liquefaction triggering fields from Wotherspoon et al. (2015) and Quigley et al. (2013).

surface manifestation of liquefaction was observed and no evidence for liquefaction was detected in strong ground motion waveforms (Wotherspoon et al., 2015). It is likely that some of these earthquakes may have induced minor liquefaction in susceptible layers at depth without surface manifestation. Two earthquakes (M_w 6.2 Feb 2011 and M_w 6.0 June 2011) caused geometric mean PGA above this range; both caused extensive liquefaction and surface manifestations of liquefaction in the Christchurch CBD including at several of the key asset sites (Tonkin and Taylor Report 51845, 2011).

No earthquakes recorded in the period 1939 to August 2010 caused PGA ≥0.05g in the Christchurch CBD (Figure 5.2) and the majority of estimated PGAs are < 0.01 g (see attached Excel spreadsheet).

3. Conclusion

We conclude with a high level of certainty that no earthquakes between 1939 and 3 September 2010 (immediately prior to the M_w 7.1 Darfield earthquake) caused strong ground motions in Christchurch of sufficient shaking intensity to induce ground failure, settlement, and / or liquefaction at any of the sites of CCC assets considered in this investigation. This includes CCC assets situated in the most vulnerable soils to liquefaction in the Christchurch area. We cannot preclude the possibility of pre-CES settlements at any sites of CCC assets on the basis of this analysis alone, however we find no evidence that pre-CES earthquakes could have induced any form of liquefaction-induced pre-CES land or building damage for the assets herein considered. Based on the findings in this report, we find the geometric mean PGA proximal to individual asset sites and the geographic mean PGA we compute for the 22 February 2011 M_w 6.2 Christchurch and the 13 June 2011 M_w 6.0 earthquakes exceeds the minimum range for liquefaction triggering for the site conditions considered (e.g., Wotherspoon et al., 2015). These two events should be considered sufficient to have induced significant liquefaction, ground settlement, and ground failure, particularly the 22 February event, consistent with observed patterns of differential land subsidence (Hughes et al., 2015), and field observations of land and building damage (Cubrinovski et al., 2011).

5.4. References

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