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

INTRODUCTION AND STATEMENT OF KEY FINDINGS

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University of Canterbury Consultancy Report CN4600001360
25 November 2015

INTRODUCTION

The 2010-2011 Canterbury earthquake sequence (CES) in New Zealand's South Island caused extensive and recurrent damage to land and infrastructure within the Central Business District (CBD) of Christchurch.

The University of Canterbury (Dr. Mark Quigley and Dr. Brendon Bradley) and Tonkin and Taylor (Dr. Bruce Deam) was commissioned by Christchurch City Council to investigate land and building damage for seven key CCC assets listed in Table 1. WGS84 coordinates and completion dates for the significant structures are also listed for 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

The specific aims of the project, authors of each report section, and delivery dates for each report are listed below.

<u>(i). Produce detailed geologic, geomorphic, and geotechnical site maps for Council key assets.</u>

AUTHOR: Dr. Mark Quigley (with assistance in map production from Elyse Armstrong)

DATASETS: Geology Maps, Black Maps, DEMs, CPT data, boreholes, auger data

PURPOSE: Document geologic setting of council assets, document heterogeneity of surface and near-surface materials with variable engineering properties

OUTPUT: Suite of 5 reports (i) Art Gallery and Christchurch Central Library, (ii) Manchester St Carpark, (iii) Lichfield St Carpark, Old Bus Exchange, and Old Civic Building, (iv) Lancaster Park (formerly AMI Stadium), and (v) Christchurch South Library. Reports also include material from Part II below.

COMPLETION DATE: Final reports (5) submitted to CCC on 25 November 2015

HOURS: Dr. Quigley = 60 hours.

(ii). Produce earthquake-induced horizontal and vertical displacement maps for ground surface surrounding CCC key assets

AUTHOR: Dr. Mark Quigley (with assistance in map production from Elyse Armstrong)

DATASETS: D-lidar, GPS, Surveying data

PURPOSE: Document 2010-2011 earthquake-induced land elevation and position changes at CCC asset sites to document severity of ground deformation and document geologic/geotechnical controls on ground deformation.

OUTPUT: Combined with Part I into a suite of 5 reports (i) Art Gallery and Christchurch Central Library, (ii) Manchester St Carpark, (iii) Lichfield St Carpark, Old Bus Exchange, and Old Civic Building, (iv) Lancaster Park (formerly AMI Stadium), and (v) Christchurch South Library.

COMPLETION DATE: Final reports (5) submitted to CCC on 25 November 2015

HOURS: Dr. Quigley = 70 hours.

(iii). Extract building settlement and displacements using differential LiDAR, including experimentation with 2003, 2010, and 2011 datasets

AUTHOR: Dr. Bruce Deam

DATASETS: D-lidar

PURPOSE: Document 2010-2011 earthquake-induced building elevation and position changes at CCC asset sites to document severity of building deformation due to CES – compare with (2).

OUTPUT: Report including maps, data and analysis, authored by Dr. Deam. Not included in this suite of reports.

COMPLETION DATE: Final report submitted to CCC on 3 November 2015

HOURS: Dr. Deam (undisclosed, invoice submitted directly to CCC)

(iv). Produce time series of earthquake-induced ground motions at CCC asset sites throughout lifetime of asset

AUTHORS: Dr. Mark Quigley and Dr. Brendon Bradley

DATASETS: Geonet strong ground motion database and Bradley GMPEs

PURPOSE: Quantify history of seismic exposure for key assets over asset lifetime. Produce PGA vs time plots as a function of liquefaction-triggering criteria.

OUTPUT: Report including maps, data, and analysis. Included in this suite of reports.

COMPLETION DATE: Final report submitted to CCC on 12 October 2015

HOURS: Dr. Bradley (undisclosed, submitted invoice directly to CCC); **Dr. Quigley (16 hours)**

(v). Produce site specific ground motion analyses for selected CCC assets (non-Opus) following the methodology used for Opus led assets

AUTHORS: Brendon Bradley

PURPOSE: Determine appropriate strong motion stations to use in the NLTHA at each of the four CCC assets using conditional spectra described in Bradley 2014. Provide comments on suitability of “processed and filtered” or “unprocessed” time-acceleration records from Geonet. Provide comment on the process used to trim, baseline and obtain zero velocity at the end of each time-acceleration record in order to run numerous records from a station in series. Provide comment on the process used to transform two components of the time-acceleration into a single record aligned with the building frame (for 2D NLTHA). Provide an opinion if radiation damping should be considered in the NLTHA with the time-accelerations used.

OUTPUT: Report and advice delivered to CCC and BECA. Not included in this suite of reports.

COMPLETION DATE: Final report submitted to CCC on 1 October 2015.

HOURS: Dr. Bradley (undisclosed, submitted invoice directly to CCC)

The work for parts (i) and (ii) above required the attainment and reproduction of a suite of previously produced maps (Geology Maps, Black Maps, DEMs), reinterpretation of a variety of datasets (CPT data, boreholes, auger data, differential LiDAR data, survey data), and production of a new suite of annotated maps and cross-sections for the CCC key assets.

The purpose of these studies was to (1) document geologic setting of council assets, document heterogeneity of surface and near-surface materials with variable engineering properties, and (2) document 2010-2011 earthquake-induced land elevation and position changes at CCC asset sites to document severity of ground deformation and document geologic/geotechnical controls on ground deformation. The primary purpose of these reports is to synthesize geologic, geomorphic, geotechnical, and geophysical data into a unified model that best explains the patterns and origin of land and building deformation in the 2010-2011 Canterbury earthquake sequence.

STATEMENT OF KEY FINDINGS

1. The 2010-2011 Canterbury earthquake sequence (CES) in New Zealand's South Island caused extensive and recurrent damage to land and infrastructure within the Central Business District (CBD) of Christchurch. The most significant liquefaction, subsidence, and lateral spreading occurred at the sites of several Christchurch City Council (CCC) owned assets in the 22 February 2011 M_w 6.2 Christchurch earthquake. New mapping confirms prior mapping results in some instances and provides new evidence for previously unidentified liquefaction surface ejecta proximal to many CCC assets following the 22 February earthquake, consistent with subsurface and seismologic evidence for major liquefaction in this earthquake.

2. No earthquakes since the completion of the oldest of Christchurch's key assets (1939) and prior to the 2010 Mw 7.1 Darfield earthquake caused peak ground accelerations at the site of Christchurch's key assets of >0.05 g. The minimum threshold to trigger liquefaction and related ground settlement at the site of CCC assets is in the range of ~0.1 to 0.17g. Historical earthquakes prior to the Darfield earthquake can be confidentially precluded as culpable liquefaction sources. If the observed land and building damage is attributable to earthquake-induced liquefaction and associated ground failure, this must have occurred during or after the 2010 Mw 7.1 Darfield earthquake, with the most likely cause the 22 February 2011 M_w 6.2 Christchurch earthquake, and with possible contributing events including the 13 June 2011 M_w 6.0 and 23 December 2011 M_w 5.9 earthquakes.

3. Cumulative horizontal land movements (after removal of tectonic displacements) in the area beneath and surrounding the locations of CCC assets are consistent with liquefaction and associated ground failure. Specifically, broad patterns of horizontal displacements are primarily consistent with a mechanism of liquefaction-induced gravitational sliding in deep (e.g. >8-10 m below land surface) liquefiable layers. With some exceptions, variations in extent of land displacements and damage related primarily to changes in the extent and geometry of deep liquefiable layers. For example, land typically spread 'down-slope' within the deep liquefiable layers (irrespective of surface slope). However, the location of liquefaction surface ejecta and locations and types of vertical displacements (e.g. uplift or subsidence) appear more controlled by the distribution and geometry of shallower (depths of ~2-5 m below surface) liquefiable sedimentary layers with some influence from anthropogenic structures.

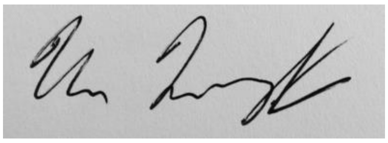
4. The patterns of land and building damage in the Lichfield St Carpark, Old Bus Exchange, and Old Civic Building area are well-explained by the area-wide seismic induction of cyclic strains in liquefiable sediments which subsequently caused ground failure downslope by gravitational flow within liquefiable sediments. Modern surface topography did not exert a first-order influence on the azimuth or magnitude of surface displacements. The patterns are in general not consistent with contributions from static loading in the absence of earthquake-induced strong ground motions and associated liquefaction. However, in some heavily structures including the Lancaster Park stadium and the Art Gallery, it appears that loading from the structure on to the liquefiable layers created anomalous land displacement patterns, including 'inflationary' surface uplift as liquefied sediment was transported outward from beneath the structures.

5. Readers are turned to the following suite of reports for specific information for each Asset.

7. APPLICABILITY

This report has been prepared for the benefit of Christchurch City Council with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.

Report prepared by:



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Dr. Mark Quigley

University of Canterbury

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GEOLOGIC SETTING OF CHRISTCHURCH AND SEISMIC ASPECTS OF THE 2010-2011 CANTERBURY EARTHQUAKE SEQUENCE

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University of Canterbury Consultancy Report CN4600001360
25 November 2015

1. Tectonic and geologic setting

The CES occurred in the Canterbury region of the eastern South Island of New Zealand (Fig. 1). CES epicenter locations span an area of ~1800 km^2 (~100 km E-W; ~13 to 35 km N-S) extending from the eastern margin of the Southern Alps to approximately 10 km offshore into the Pacific Ocean in Pegasus Bay (Fig. 1). The western fringe of the CES region is approximately 80 km east of the Alpine Fault, which accommodates ~ 75% of the ~38 mm yr^{-1} of relative Pacific-Australian plate motion, and east of the Southern Alps, which accommodate a further ~20% of plate motion via distributed active faulting (Wallace et al., 2007; Stirling et al., 2012; Litchfield et al., 2014). Global positioning system measurements indicate regional strain rates of ~16 nanostrain yr^{-1} (~2mm yr^{-1}) shortening with a (σ1) azimuth of 110-120^{o} over a ~150 km wide region defined as the Canterbury Block (Wallace et al., 2007) that includes the CES area (Fig. 1). Strain rates (Wallace et al., 2007), pre-CES historical seismicity rates (Stirling et al., 2012), and fault slip rates and earthquake recurrence intervals (e.g., Hornblow et al., 2014) are lower in the CES region compared to more tectonically active parts of the diffuse plate boundary zone (Howard et al., 2005) but higher than seismically active 'intraplate' settings more distal from plate boundary zones (e.g. Quigley et al., 2006; 2010a). The CES region is thus best typified as a tectonically active but comparatively low strain rate domain at the periphery of a diffuse plate boundary orogen.

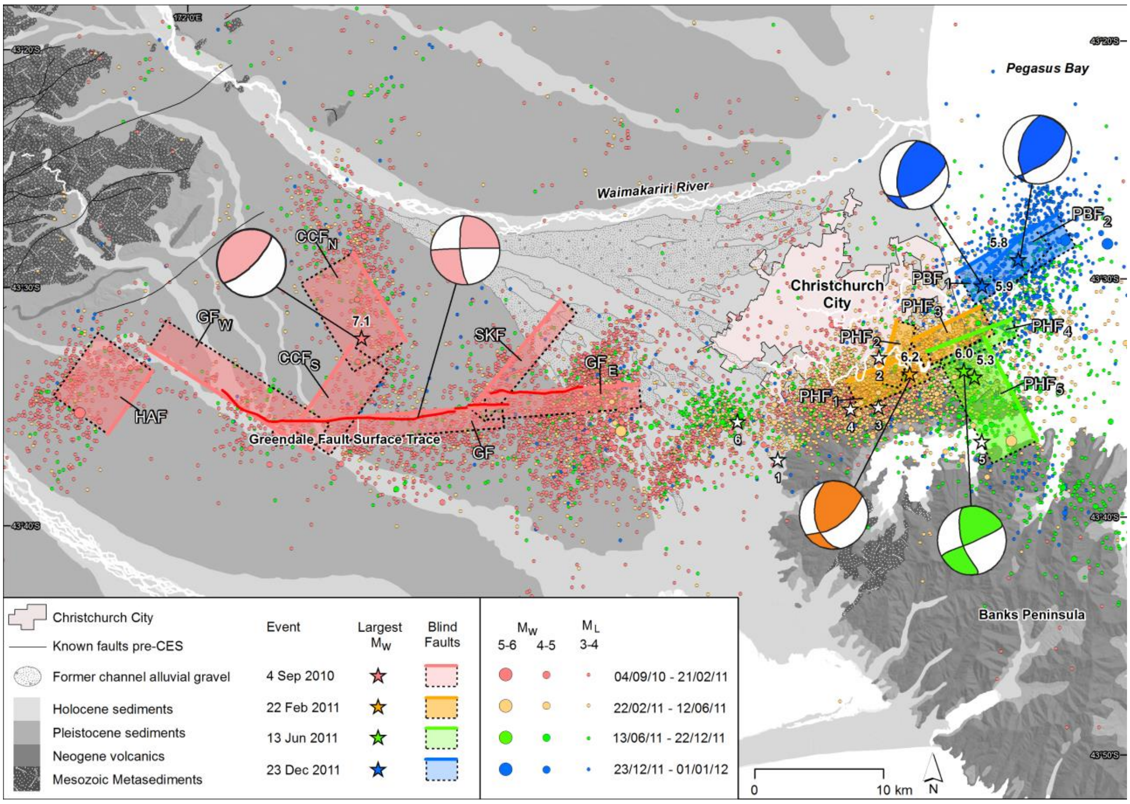


Figure 1: Regional surficial geology, seismicity and fault location map of the Canterbury region affected by the CES. Epicentre locations for M_L≥3.0 events from 4 September 2010 to 10 February 2013 (data from www.geonet.org.nz). Projected surface locations of major blind faults in bold, projected base of all major faults shown by dotted lines (from Beavan et al. 2012). Earthquakes colour-coded by time as indicated by legend. Location of mapped Greendale Fault surface ruptures in red (from Quigley et al. 2012). Epicentres of most significant earthquakes are indicated with stars for 4 September 2010 (pink), 22 February 2011 (orange), 13 June 2011 (green) and 23 December 2011 (blue), with additional significant epicentres indicated by white

stars: (1) October aftershock, (2) Boxing Day aftershock, (3) February aftershock I, (4) February aftershock II, (5) April aftershock, (6) June 21 aftershock (Table 1). Earthquake focal mechanisms from Bannister and Gledhill (2012). For the Darfield earthquake, both P-wave first motion (reverse faulting) and centroid moment tensor (strike-slip faulting) are shown.

The city of Christchurch is located primarily upon a low relief, low elevation (0-20 m asl) alluvial landscape (Fig. 2). Much of the central and eastern city is built upon a progradational coast sequence of alluvial silt and sand deposits, drained peat swamps and estuaries, sand of fixed to semi-fixed dunes, and underlying marine sands (collectively referred to as the Christchurch Formation) that formed as sea levels transgressed then regressed from a mid-Holocene highstand that reached up to ~ 1 km west of the current position of the CBD at ~ 6.5 ka (Fig. 2) (Browne et al., 1995). The Christchurch Formation is underlain by glacial-outwash gravels (Riccarton Formation) at depths of 20-40 m in the central and eastern city (Cubrinovski and McCahon, 2011). Quaternary alluvial deposits interfinger with estuarine and shallow marine deposits to depths of approximately 240 m under eastern Christchurch (Browne et al. 1995). The hillslope suburbs of southern Christchurch are situated on Miocene volcanic rocks, draping loess, and shallow sandy bays in Banks Peninsula (Figs. 2, 4). The volcanic rocks are mantled by Quaternary loess and colluvially-reworked loess mixed with boulders; the loessic sequence where preserved is typically > 1m thick and locally > 5 m thick (Bell and Trangmar, 1987). The geology of Christchurch is described in detail in Browne et al. (1995, 2012), Forsyth et al. (2008), and Begg et al., (2015).

2.2 The 2010-2011 Canterbury earthquake sequence

The CES initiated with the Mw 7.1 Darfield earthquake with an epicentre located approximately 44 km west of the Christchurch CBD (Gledhill et al., 2011) (Fig. 1). Between September 2010 and September 2012, the CES had 45 ML ≥ 5.0 and 3 ML ≥ 6.0 aftershocks (Figs. 3, 5), or 12 Mw ≥ 5.0 and 3 Mw ≥ 6.0 events (Table 1). The post-Darfield earthquake CES events including the Mw ≥ 5.0 events were classified as 'aftershocks' because (i) they were smaller in magnitude than the Mw 7.1 Darfield mainshock, (ii) they occurred in close temporal succession to the mainshock (i.e. within seconds to months), (iii) they followed classical G-R scaling aftershock frequency-magnitude distributions, modified Omori's law aftershock decay rates (Fig. 5B), and a modified version of Bath's law for the largest magnitude aftershock (Scherbakov et al., 2012), and (iv) they occurred primarily in areas of modelled increases in Coulomb (static) stress changes due to the mainshock (e.g., Steacy et al., 2013), although the correlation between cumulative aftershock activity and positive static stress lobes has been debated (Bebbington et al., 2015). The sequence was highly 'clustered' in the sense that the post-mainshock (2010-2012) average annual earthquake seismicity rate for Mw 3-5 earthquakes was ~ 500 x greater than the average pre-mainshock (1940-2010) annual seismicity rate for the same spatial domain (Fig. 3A). Earthquake decay rates consistent with modified Omori law behaviour were also observed following the largest aftershocks in the sequence (Fig. 3B inset) (Scherbakov et al., 2012; Gerstenberger et al., 2014).

The spatial-temporal evolution of CES seismicity (Fig. 1) has been studied by Bannister and Gledhill (2012). Early aftershocks were particularly concentrated at the eastern end of the Greendale Fault, although all of the causative faults for the Mw 7.1 Darfield earthquake had some activity (Fig. 3).

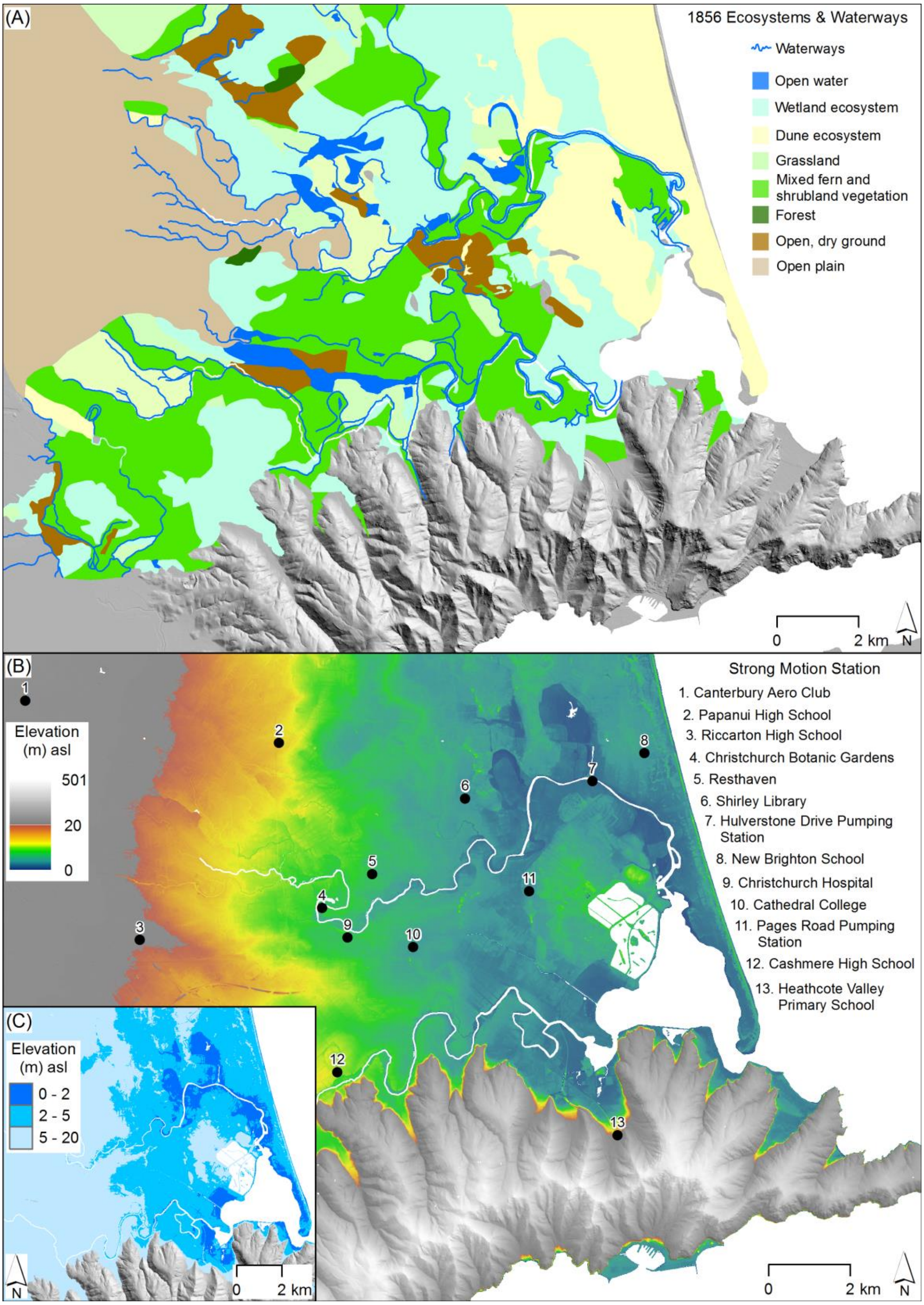


Figure 2: (A) Ecosystems and waterways in the Christchurch area as depicted in the Black Maps, 1856. From White et al. (2007). (B) Digital elevation model of the Christchurch area, showing paleochannels, paleodune systems and anthropogenic geomorphic features. Also shown are seismic strong motion stations. (C) Elevation classes in the Christchurch area showing 0-2 m, 2-5 m and 5-20 m.

One of the largest early aftershocks (ML 5.0; 8 Sept 2010) occurred in close proximity to the hypocenter of the Mw 6.2 Christchurch earthquake. A Mw 4.7 aftershock on 26 Dec 2010 (Boxing Day aftershock, Table 1) on a steeply dipping blind fault beneath central Christchurch caused vertical PGAs locally exceeding 0.5g and caused some damage in Christchurch's CBD. The Mw 6.2 Christchurch earthquake was composed of successive ML 6.3, 5.8, and 5.9 earthquakes and numerous aftershocks over 2 hours (Table 1); subsequent aftershocks were largely concentrated in the vicinity of the Mw 6.2 source faults (e.g., Port Hills Faults 1-3; Fig. 1) and in the area between these and the eastern tip of the Greendale Fault. The Mw 6.0 (ML 6.4) Christchurch earthquake was preceded by a ML 5.6 earthquake 1h20min prior; these events and related aftershocks were primarily located in southeast Christchurch along a NNW-trending alignment, although some large aftershocks (e.g., 21 June 2011 ML 5.4; Table 1) continued to occur in the intervening area between the Port Hills and Greendale Faults. Following the December Mw 5.8 and 5.9 earthquakes (ML 5.8 and 6.0 within 1h20min), aftershocks shifted primarily to a NE-striking alignment offshore of Christchurch in Pegasus Bay. The overall pattern of the CES is that of successive eastward propagating seismic activity with concentrations closely tracking the geometry of orientation of the fault sources of the major (i.e. ML ≥ 5.5) earthquakes (Fig. 1).

A high density of strong ground motion instruments in the Canterbury region (Fig. 2) resulted in a wealth of well-recorded CES earthquake-induced ground motions, including many near-fault ground motions (Bradley 2012b, Bradley and Cubrinovski 2011a, Bradley et al. 2014). Prior to the CES there was a paucity of high amplitude recorded strong ground motions in New Zealand, primarily as a result of a sparse instrumentation network before the commencement of GeoNet in 2001 (www.geonet.org.nz). Prior to 2009, the maximum PGA recorded in New Zealand was 0.39g, with only 7 observed ground motions exceeding 0.2g PGA (Bradley and Cubrinovski 2011a). During the CES, ground motions of up to 1.51g PGA were recorded, with over 20 ground motions exceeding 0.4g PGA and over 80 ground motions exceeding 0.2g PGA (Bradley et al. 2014).

Fig. 4 illustrates the ground motions recorded for the largest earthquakes in the CES that occurred during the Mw 7.1 Darfield, Mw 6.2 and 6.0 Christchurch, and Mw 5.9 and 5.8 December earthquakes. This data is shown in terms of the spatial distribution of PGA over the region and the specific PGA values recorded at strong motion stations in comparison to NZ-specific empirical ground motion predictions (Bradley 2010, Bradley 2013). Because of the proximity of the Mw 6.2 Christchurch earthquake to Christchurch, it produced the strongest ground motion shaking over the urban Christchurch city region, as can be seen from comparison of the spatial distribution of PGA shown in Fig. 6. The largest instrumental PGAs and PGVs were observed at Godley Head station (GODS) during the Mw 6.0 June earthquake (horizontal PGA =1.51g), Heathcote Valley (HVSC) station during the Mw 6.2 Christchurch earthquake (vertical PGA = 2.21g), and Greendale (GDLC) during the Mw 7.1 Darfield earthquake (PGV = 115cm/s) (locations of selected seismometers shown in Fig. 2B and 4B).

Areal extents of PGA ≥ 0.1, 0.2, and 0.3g within the Christchurch area shown in Fig. 4 appear for the four largest events. Collectively these reveal the importance of source location in addition to Mw and other factors (Fig. 1) when considering ground motion histories for a specific study area; for example the ≥ 0.1g and ≥ 0.3g areas of the Fig. 4 extent were similar for the Darfield and Mw 6.2 Christchurch earthquakes despite the significant difference in Mw between these events. Magnitude weighted PGAs (PGA7.5) are also shown.

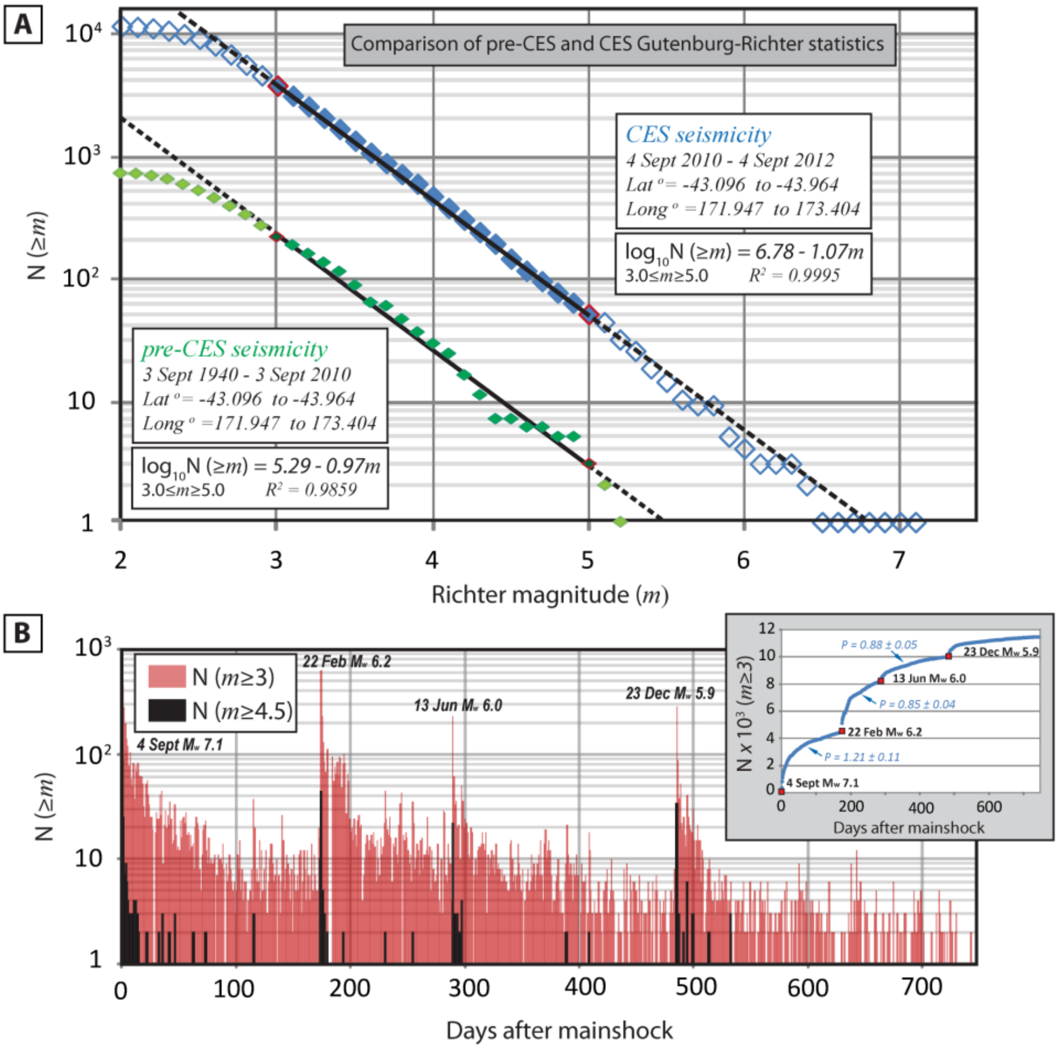


Figure 3: (A) Comparison of frequency-magnitude (G-R) relationship for seismicity in the CES region (see lat-long values for spatial extent) in the 70 years prior and two years after the Darfield earthquake. B-values as reported determined for Richter magnitudes between 3.0 and 5.0 and subject to curve fitting uncertainties of ~10%, both datasets adhere well to G-R relationship (R^2 as shown). Any possible data completeness issues are not addressed in this study. Post Darfield annual seismicity rates between M_L 3 to 5 increase from pre-CES rates by an average of 4.2 x 10^4 %.

(B) Temporal distribution of ML ≥ 3.0 and ML ≥ 4.5 earthquakes during the CES, binned into 24 hr increments and reported in days after the Darfield earthquake (4:35 am NZ standard time).

(B Inset) shows cumulative total of ML ≥ 3.0 earthquakes with time, showing punctuated rate changes immediately preceding the four largest CES earthquakes, in accordance with Omori's Law. P-values describing seismicity decay rate exponent from Shcherbakov et al. (2012). All seismic data from www.geonet.org.nz

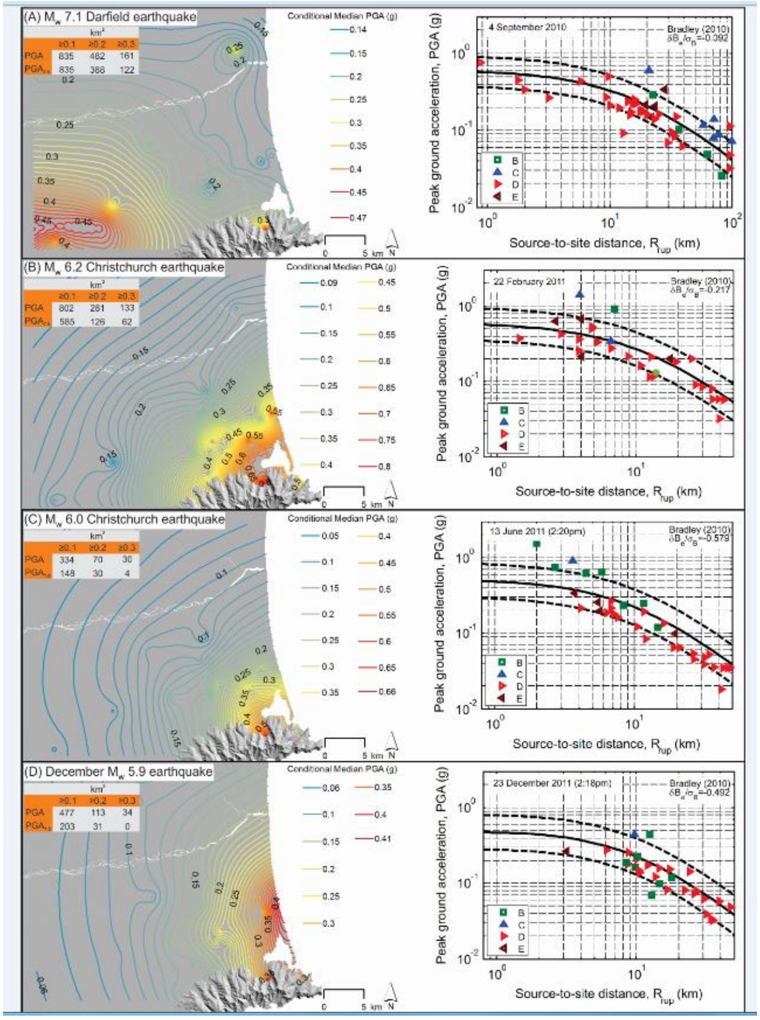


Figure 4: Peak Ground Acceleration (PGA) data in the Christchurch area for the (A) M_w 7.1 Darfield earthquake, (B) M_w 6.2 Christchurch earthquake, (C) M_w 6.0 Christchurch earthquake and (D) December M_w 5.9 earthquake. Left panels: PGA contours across the analysis domain of Bradley and Hughes (2012a,b), inset tables show km^2 of the analysis domain experiencing PGA and $PGA_{7.5}$ ≥0.1, ≥0.2 and ≥0.3. Right panels: Comparison of the Bradley (2010) Ground Motion Prediction Equations (prediction shown for geotechnical site class D) with PGA observations from the shown CES events. Denoted values of the between-event residual, δB_e, are normalized by the between-event standard deviation, σ_B, so that $\delta B_e/\sigma_B$ = 1.0 implies observations with a between-event residual which is one standard deviation above zero. From Bradley (2014).

3. Strong earthquakes affecting Christchurch prior to the 2010-2011 Canterbury earthquake sequence

Written accounts of felt earthquakes in Christchurch extend back to 1844, when one of the early European settlers wrote that ‘there was very little noise but a curious trembling feeling for a few seconds’ (Deans, 1937). Earthquakes were also felt locally in 1851, 1855, and 1868 (http://lostchristchurch.org.nz/a-history-of-quakes-in-christchurch). Two proximal, moderate-magnitude historical earthquakes caused damage to buildings and contents in the 19th Century; the 1869 Mw 4.7-4.9 Christchurch earthquake and 1870 Mw 5.6-5.8 Lake Ellesmere earthquake (Fig. 2).

The former generated Modified Mercalli Intensity (MMI) shaking of up to MMI 7 (PGA ~ 0.24 g; converted using Wald et al., 1999) in the Christchurch CBD and eastern suburbs and caused damage to unreinforced masonry. It was reported by the Weekly News (26 June 1869; cited by Downes and Yetton, 2012) that '[after the earthquake] the tide runs higher up the Heathcote River than formerly', indicating that this earthquake may have caused surface subsidence. The 1870 earthquake caused shaking up to MMI 6 (PGA ~ 0.13g) and minor infrastructural damage in central and eastern Christchurch, Banks Peninsula, and South Canterbury. 'Tons of loose rockfall' were observed to fall from coastal cliffs on the southern side of Lyttelton harbour (The Christchurch Star, Sunday Sept 3 1870), although the extent and severity of mass movements were not systematically documented. The lack of hypocentre spatial resolution precludes assignment of the 1869 and 1870 earthquakes to a source fault.

Regional earthquakes including the 1881 Mw ~ 6 Castle Hill, 1888 Mw 7.1-7.3 North Canterbury, 1901 Mw 6.9 Cheviot, 1922 Mw 6.4 Motunau, and 1929 Mw 7.1 Arthur's Pass earthquakes all caused MMI ≥ 6 shaking and damage to stone and unreinforced masonry structures in Christchurch (Fig. 2A) (Pettinga et al., 2001; Cowan et al. 1991). No ground surface manifestation of liquefaction or extensive severe rockfall was reported in Christchurch from these events, although in the 1888 earthquake 'on the Sumner Road, near Lyttelton, blocks of rocks 10 tons in weight gave way, and went into the harbour with a great crash, carrying fences and other obstructions before them' (New Zealand Herald, Volume XXV, Issue 9149, 3 September 1888, Page 3). The 1901 Cheviot earthquake caused ground surface manifestation of liquefaction in Kaiapoi (Fig. 2) (Mulqueen et al., 1994). A ML 5.0 earthquake occurred in the vicinity of the Greendale Fault in 1968 (Fig. 2), but no damage was reported. The lack of spatial resolution of epicentre location precludes reliable assignment of this earthquake to the Greendale Fault. A clustered sequence of earthquakes beginning with the 1994 Mw 6.7 Arthurs Pass earthquake and including the 1994 Mw 6.0, 1995 Mw 6.0, and 1995 Mw 6.2 Cass earthquakes occurred with epicentres <40 km apart in the eastern Southern Alps (Fig. 2A) (Gledhill et al., 2000; Robinson and McGinty, 2000) and generated up to MMI ~5 in Christchurch (Pettinga et al., 2001).

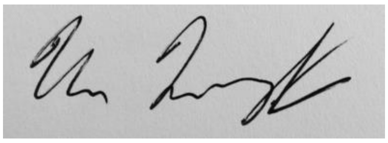
In the 70 years preceding the CES, regional seismicity exhibited G-R frequency magnitude scaling behavior with a 'b value' ≈ 1 that included three ML≥ 5 and 30 ML≥ 4 events (Fig. 3). Although the seismic catalogue is variably incomplete for ML≤4 earthquakes prior to 1964, it is unlikely that any ML≥5 events are missing for this time period. Return periods of ML 6 and 7 earthquakes based on this data are ~ 200 yr and ~ 1800 yr, respectively, for the specified region. Pre-CES PGA (Period T= 0.0 sec, shallow 'site class C' soils with site period T ≤ 0.6 s) estimates for Christchurch were 0.11g for 50 yr return times and 0.22 g for 200 yr return times (Stirling et al., 2008). Prior to the CES, the 475-year PGA hazard for Christchurch of ~0.3 g (Stirling et al., 2008) was dominated by distributed seismicity (Mw 5–6.8 at distances of less than 50 km) with further significant contributions from identified regional fault systems capable of Mw ≥ 7.0 earthquakes.

Of particular interest to this investigation is the seismicity affecting the Christchurch area, and specifically affecting the sites of Christchurch City Council's key assets, over the lifetime of each asset.

APPLICABILITY

This report has been prepared for the benefit of Christchurch City Council with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.

Report prepared by:



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Dr. Mark Quigley

University of Canterbury

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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University of Canterbury Consultancy Report CN4600001360

October 2015

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

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). CHARACTERISATION OF CANTERBURY EARTHQUAKE SEQUENCE EVENTS (4 SEPTEMBER 2010 to 2013): 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.

5.2. Results

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

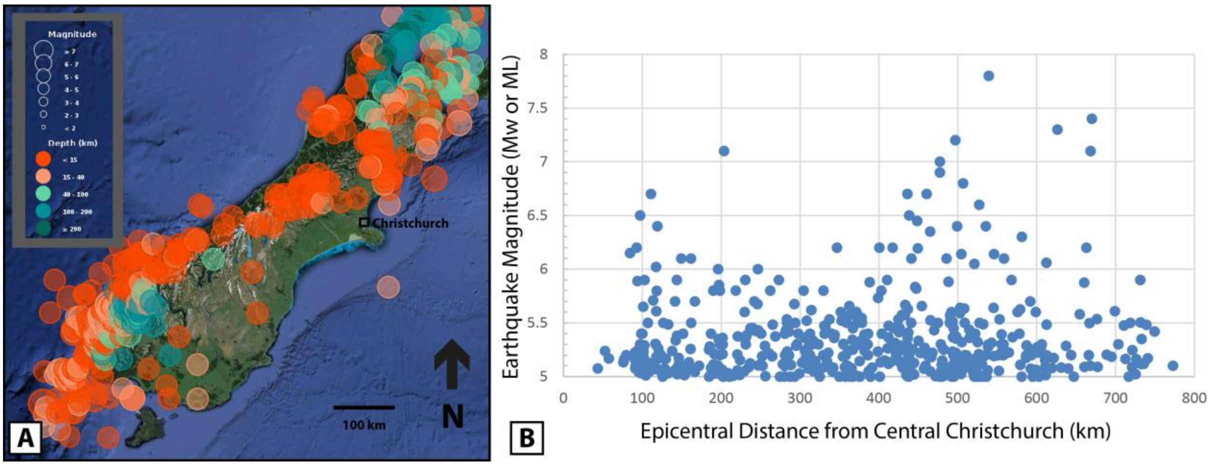

Figure 1. Epicentre locations and magnitudes of pre-CES earthquakes (1939 to 3 September 2010) in the South Island of New Zealand and epicentral distances from the mean latitude and longitude for all CCC assets (lat = -43.53697313º, long = 172.6386683º) in central Christchurch.

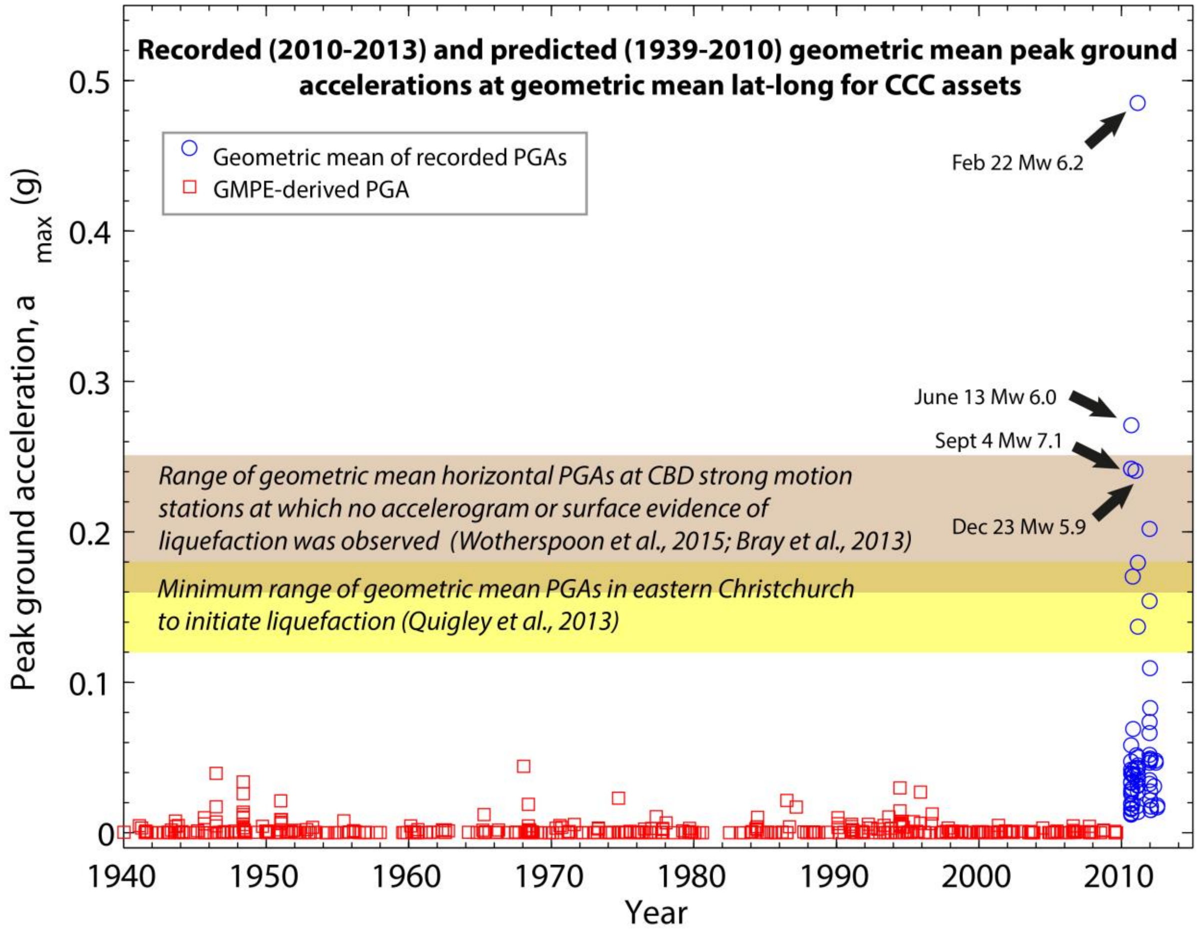

Figure 2. Recorded and predicted geometric mean peak ground accelerations at geometric lat-long for CCC assets and liquefaction triggering fields from Wotherspoon et al. (2015) and Quigley et al. (2013).

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).

4. References

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Bradley, B. A., (2013). A New Zealand-specific pseudo-spectral acceleration ground-motion prediction equation for active shallow crustal earthquakes based on foreign models, Bulletin of the Seismological Society of America v. 103.

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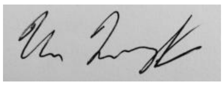
Wotherspoon, L. M., Orense, R. P., Green, R. A., Bradley, B. A., Cox, B. R., & Wood, C. M. (2015). Assessment of liquefaction evaluation procedures and severity index frameworks at Christchurch strong motion stations. Soil Dynamics and Earthquake Engineering.

5. Applicability

This report has been prepared for the benefit of Christchurch City Council with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.

Report prepared by:



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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

CHRISTCHURCH ART GALLERY AND CHRISTCHURCH CITY LIBRARY STUDY

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University of Canterbury Consultancy Report CN4600001360

25 November 2015

EXECUTIVE SUMMARY

The land surrounding the Christchurch Art Gallery and Central City Library was disturbed as a result of earthquake-induced liquefaction, lateral spreading, and subsidence during the 2010-2011 Canterbury earthquake sequence. When the tectonic component of horizontal displacement is removed, the Art Gallery property was horizontally displaced ~200-400 mm in a SW direction and the City Library property was horizontally displaced ~400-500 mm in a SW direction. Differential lidar suggests that the eastern side of the Art Gallery may have subsided ~ 400 mm relative to the western part of the property (west of the building footprint, above the underground carpark). Differential lidar suggests that the area NE of the City Library may similarly have subsided up to ~400 mm. More detailed analysis of the building damage using multi-temporal LiDAR (Deam, 2015) suggests slight eastward tilting to the Art Gallery and uniform (minor) subsidence of the City Library. Inspection of MASW profiles, and geologic and liquefaction-hazard cross-sections provide insight into the origin of regional land damage. The patterns of ground deformation appear to reflect the following phenomena: (1) SW-directed lateral displacements driven by slope and distribution changes in deep (e.g., >8 m depth) liquefiable layers, (2) some differential subsidence of ground and buildings above liquefiable sediment due to variations in distribution of shallow and deep liquefiable sediments, (3) some uplift of ground surrounding buildings (e.g. parking lots) due to differential loading and consequent outward expulsion of liquefied sediment from beneath buildings. The direction and modes of ground deformation at the sites of CCC assets considered in this study are consistent with earthquake-induced liquefaction and associated ground failure.

1. SCOPE

The University of Canterbury (Dr. Mark Quigley) was commissioned by Christchurch City Council to (1) Produce detailed geologic, geomorphic, and geotechnical site maps for Council key assets, and (2) Produce earthquake-induced horizontal and vertical displacement maps for ground surface surrounding CCC key assets.

The seven key asset sites to be considered in this suite of reports 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
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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

This work required the attainment and reproduction of a suite of previously produced maps (Geology Maps, Black Maps, DEMs), reinterpretation of a variety of datasets (CPT data, boreholes, auger data, differential LiDAR data, survey data), and production of a new suite of annotated maps and cross-sections for the CCC key assets.

The purpose of these studies was to (1) document geologic setting of council assets, document heterogeneity of surface and near-surface materials with variable engineering properties, and (2) document 2010-2011 earthquake-induced land elevation and position changes at CCC asset sites to document severity of ground deformation and document geologic/geotechnical controls on ground deformation. The primary purpose of these reports is to synthesize geologic, geomorphic, geotechnical, and geophysical data into a unified model that best explains the patterns and origin of land and building deformation in the 2010-2011 Canterbury earthquake sequence.

This report focuses on the Christchurch Art Gallery and Christchurch City Library.

2. LOCATION AND PRIOR WORK

The Christchurch Art Gallery is located in central Christchurch immediately east of Montreal St (Fig. 1). The central lat-long of the site is -43.530385, 172.631448.

The site formerly occupied by the Christchurch Central Library is east of Oxford Terrace and north of Gloucester St (Fig. 1). The central lat-long of the site is -43.529633, 172.635131.

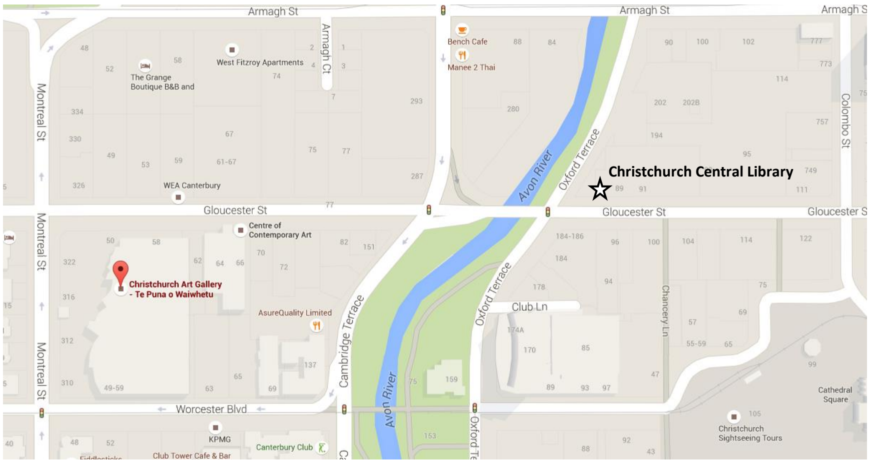


Figure 1. Location of Christchurch Art Gallery and Christchurch City Library shown on Google Maps.

T&T conducted mapping (Fig. 2), and CPT investigations (Fig. 3) in close proximity to these sites.

Horizontal and vertical displacement data was derived using differential lidar and airphoto interpretations throughout the Canterbury earthquake sequence (Fig. 5,6) and plotted on digital elevation model underlays. From these data, the tectonic component of displacement was removed (using tectonic displacements inferred from geodetic seismic source models presented in Beavan et al., 2012), with the residual displacements interpreted to reflect shaking-induced permanent ground displacements relating to liquefaction and ground failure. See “Evaluation of Building Settlements during the Canterbury Earthquake Sequence using LiDAR” (T&T Ref # 53841) (see References) for further detail on how horizontal and vertical land displacements were obtained from differential LiDAR.

Individual horizontal displacement measurements reported in the displacement maps have an error range of ± 200 mm that corresponds to the lidar pixel resolution. The relatively large error compared to individual displacements requires that displacements be used only to provide a general picture of progressive land deformation through the Canterbury earthquake sequence and that individual measurements are not over-interpreted. However, added confidence to the cited displacements is found in the general agreement between cumulative displacements inferred from differential lidar and (i) cumulative displacements of LINZ benchmarks (Deam, 2015), and (ii) cumulative displacements from field measurements (Hughes et al., 2015). For these reasons, we use our horizontal displacement maps to make general conclusions regarding cumulative land deformation throughout the Canterbury earthquake sequence with an emphasis on relative horizontal land deformation variability on the m to 10s of metres scale, rather than emphasizing any individual measurement on the pixel scale. We do not use them to characterise strain on the scale of an individual building in this study; this could perhaps serve as a focus for further investigation however, particularly where individual measurements show large (e.g., >200-300 mm) variations in displacement across a building site.

The vertical displacement measurements reported in cumulative differential lidar displacement maps likely have an error of ± 300 mm. Errors accumulate due to varying quality of lidar data acquired (2003 vs 2011) and apparent 'tilt effects' corresponding to swath edges in the data. The reliability of these data for many individual locations (Hughes et al., 2015) is confirmed by field observations (Quigley et al., 2013; Hughes et al., 2015) and LINZ benchmarks (Deam, 2015). We thus use the differential lidar vertical displacement maps to make general conclusions regarding cumulative vertical land deformation throughout the Canterbury earthquake sequence with an emphasis on relative vertical land deformation variability on the m to 10s of metres scale, rather than emphasizing any individual measurement on the pixel scale.

Ecological maps (pre-development vegetation and waterways) were reproduced by T&T for Christchurch area (Fig. 7) from historic "Black Maps".

A series of MASW surveys were conducted by T&T in the vicinity of these sites (Fig. 8,9). By combining topographic data, borehole data, CPT data, and MASW data, T&T constructed a suite of geologic cross-sections in this area (Fig. 10). Please see Christchurch Central City Geologic Interpretative Report" (T&T Ref REP-CCC-INT) for details including location of geotechnical sampling sites, raw and interpreted data, complete cross-sections, and preliminary geologic interpretations.

The richness of data obtained from these prior investigations provides the basis for our integrated geologic and geomorphic models for the Art Gallery and City Library sites, and our interpretations of how seismic loading and geology influenced the patterns of deformation.

Figure 2: Area reconnaissance mapping of liquefaction and lateral spreading in the vicinity of the Christchurch Art Gallery (1) and City Library (2) following the 22 Feb 2011 Christchurch Mw 6.2

earthquake (mapping by Tonkin and Taylor Ltd). More detailed mapping (this report) is presented in Fig. 11 and 12.

Figure 3: Location of CPT, borehole, and other geotechnical sampling sites in the vicinity of the Christchurch Art Gallery (1) and City Library (2). These data were variably used to construct geologic cross-sections (e.g., Fig. X).

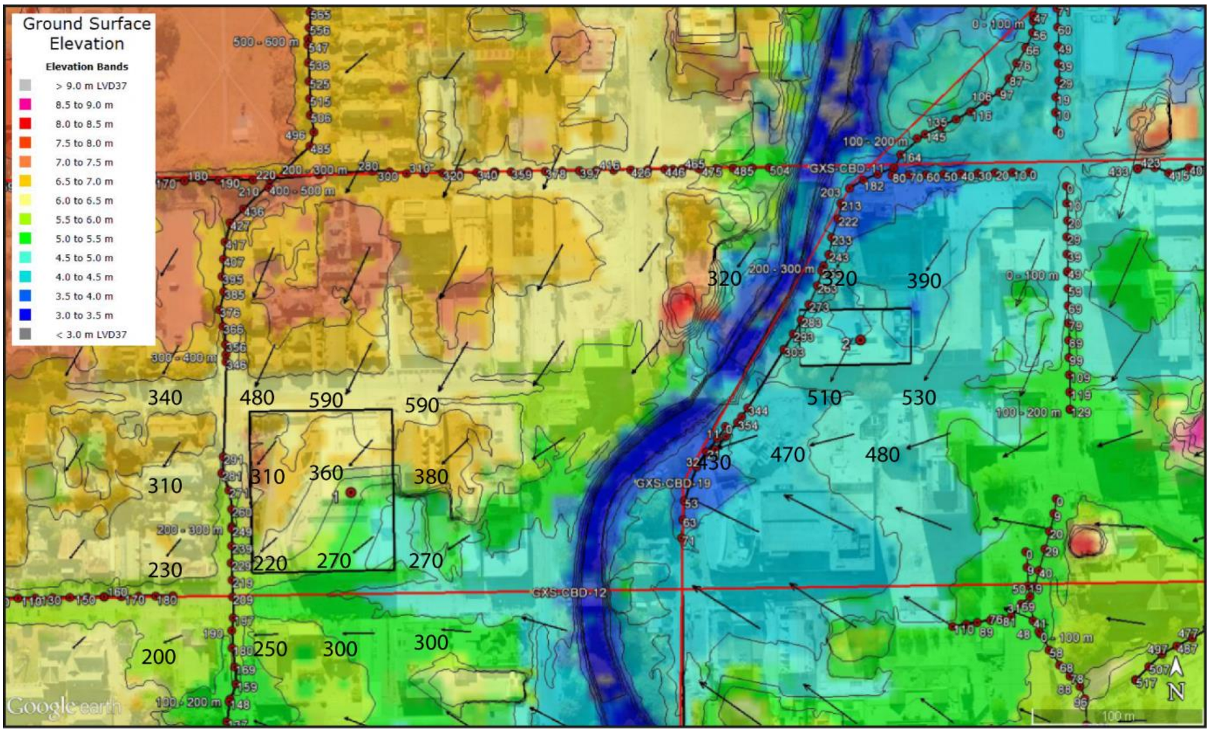


Figure 4: Cumulative horizontal permanent land displacements in mm with tectonic component removed for the Art Gallery and Christchurch City Library area, superimposed on DEM underlay. Location of MASW surveys and geologic cross-sections shown.

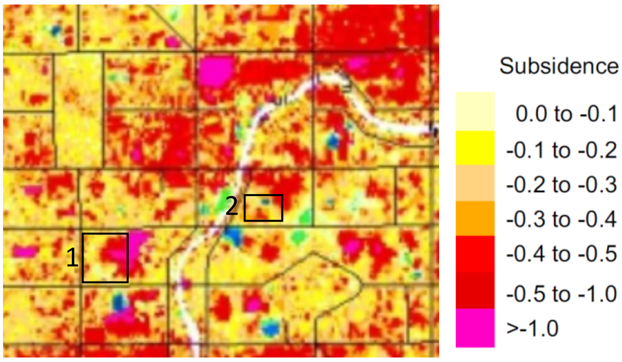


Figure 5: Permanent vertical land displacements from 2003 to December 2011 in metres for the Lancaster Park area. Image from Hughes et al. (2015). Location of Christchurch Art Gallery (1) and City Library (2) as shown.

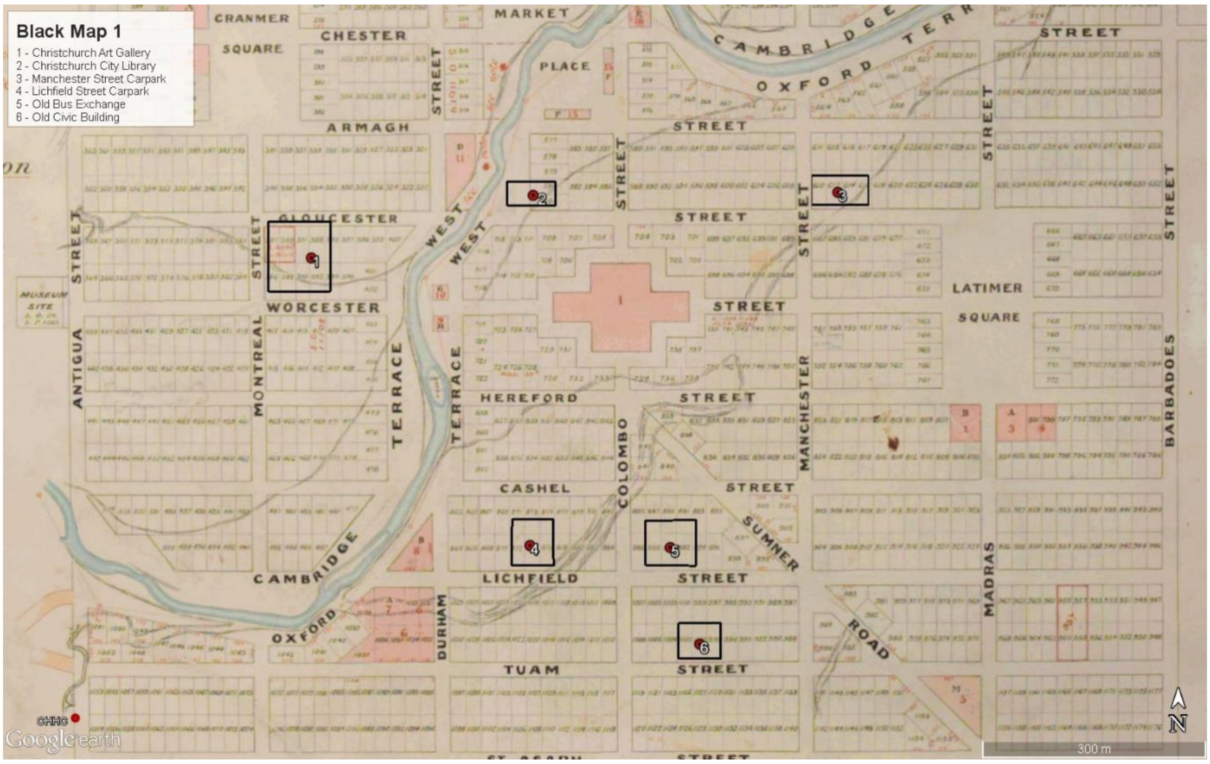


Figure 6: Paleo-drainages in Christchurch including the Christchurch Art Gallery (1) and City Library sites (2).

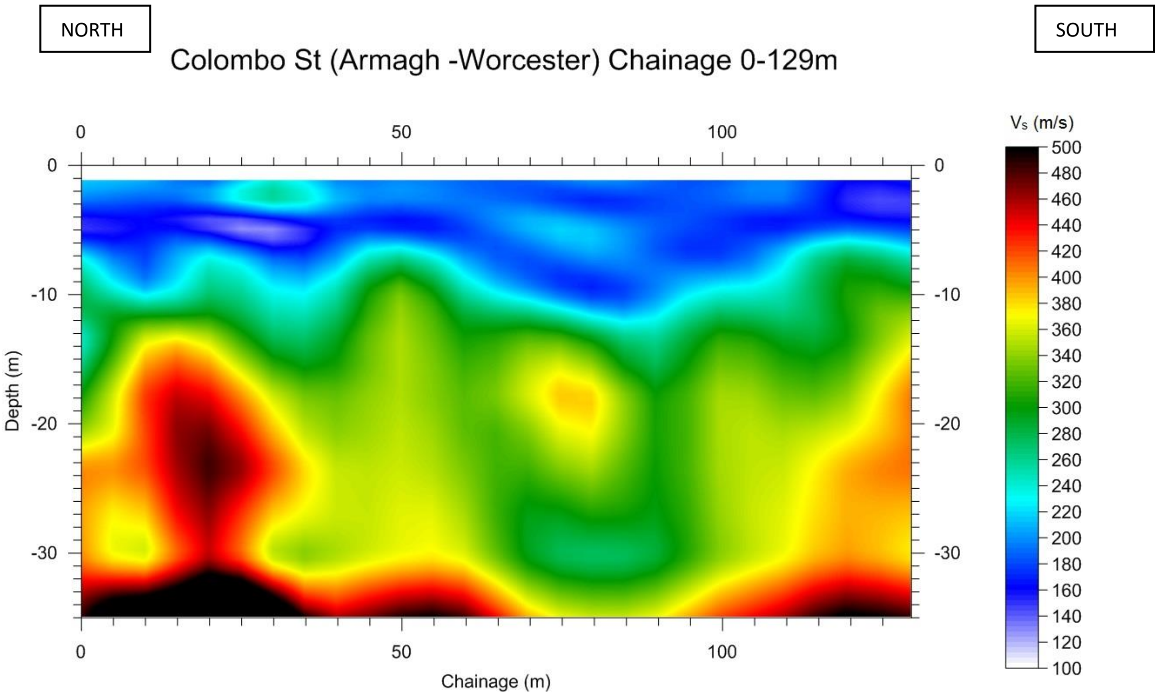


Figure 7: MASW survey for Colombo St, east of Art Gallery and City Library. See Fig. 4 for corresponding chainage.

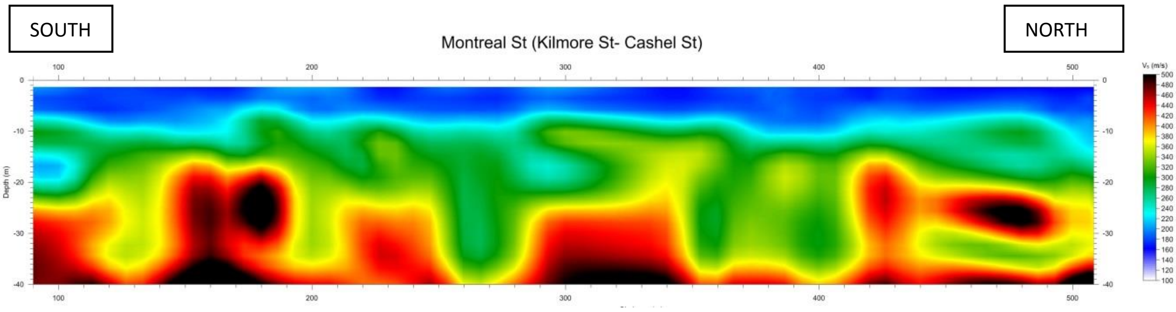


Figure 8: MASW survey for Montreal Street, west of Art Gallery. See Fig. 5 for corresponding chainage.

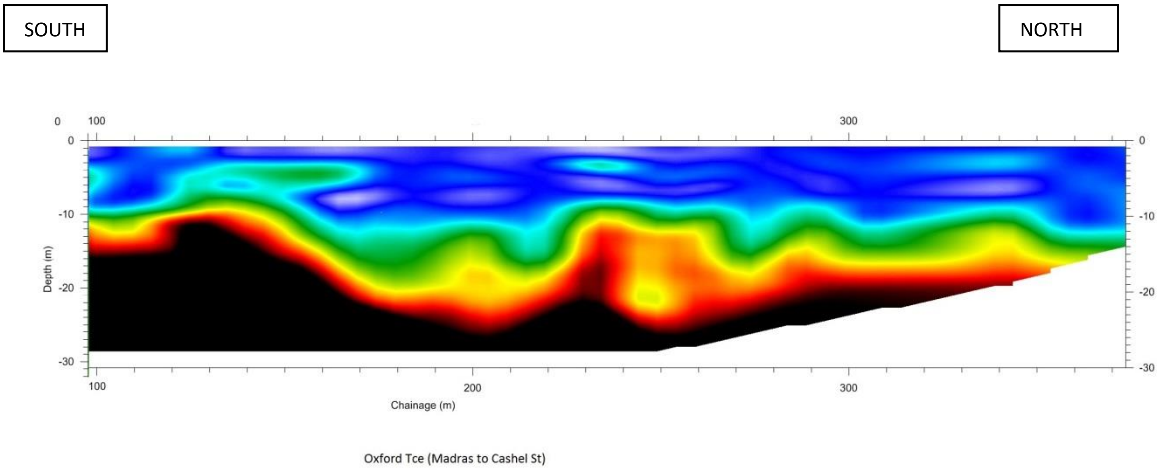


Figure 9: MASW survey for Oxford Terrace, between Art Gallery and central Library. See Fig. 5 for corresponding chainage.

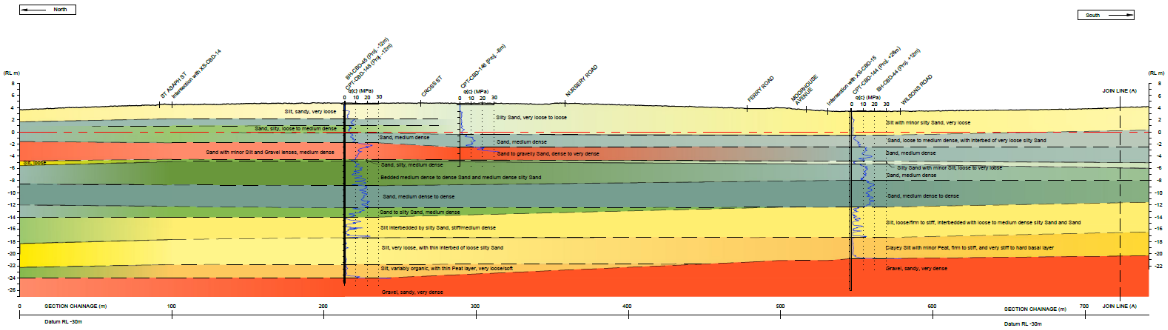


Figure 10: Example of geologic cross-section prepared for the Christchurch City by Tonkin and Taylor Ltd.

3. THIS WORK

3.1. MAPPING OF LIQUEFACTION EJECTA

The first part of our analysis was to produce detailed maps of liquefaction surface ejecta (Fig. 11,12) using airphotos obtained immediately following the 22 February earthquake in order to better quantify the extent of liquefaction surface ejecta. Distributions of liquefaction were characterised as definite or inferred. Former (historic) stream channels were added to maps where present.

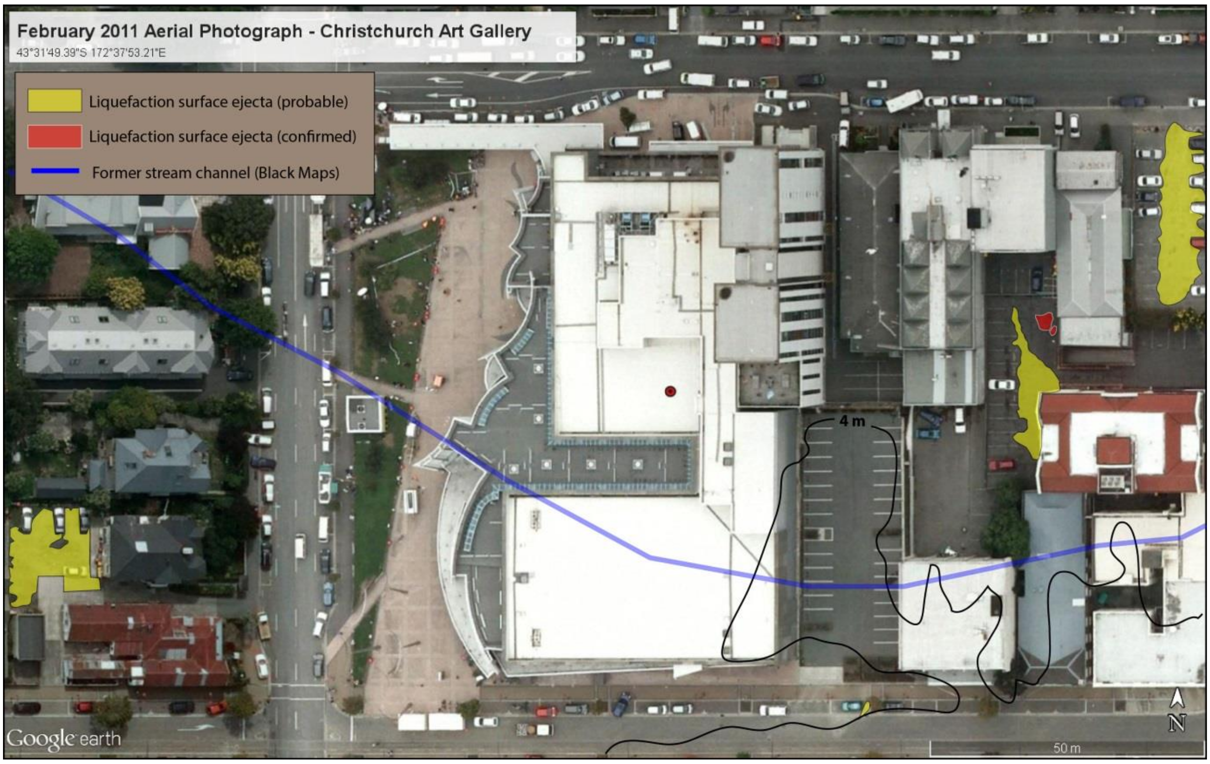


Figure 11: Map of liquefaction surface ejecta in the vicinity of the Christchurch Art Gallery following the 22 February 2011 Mw 6.2 Christchurch earthquake.

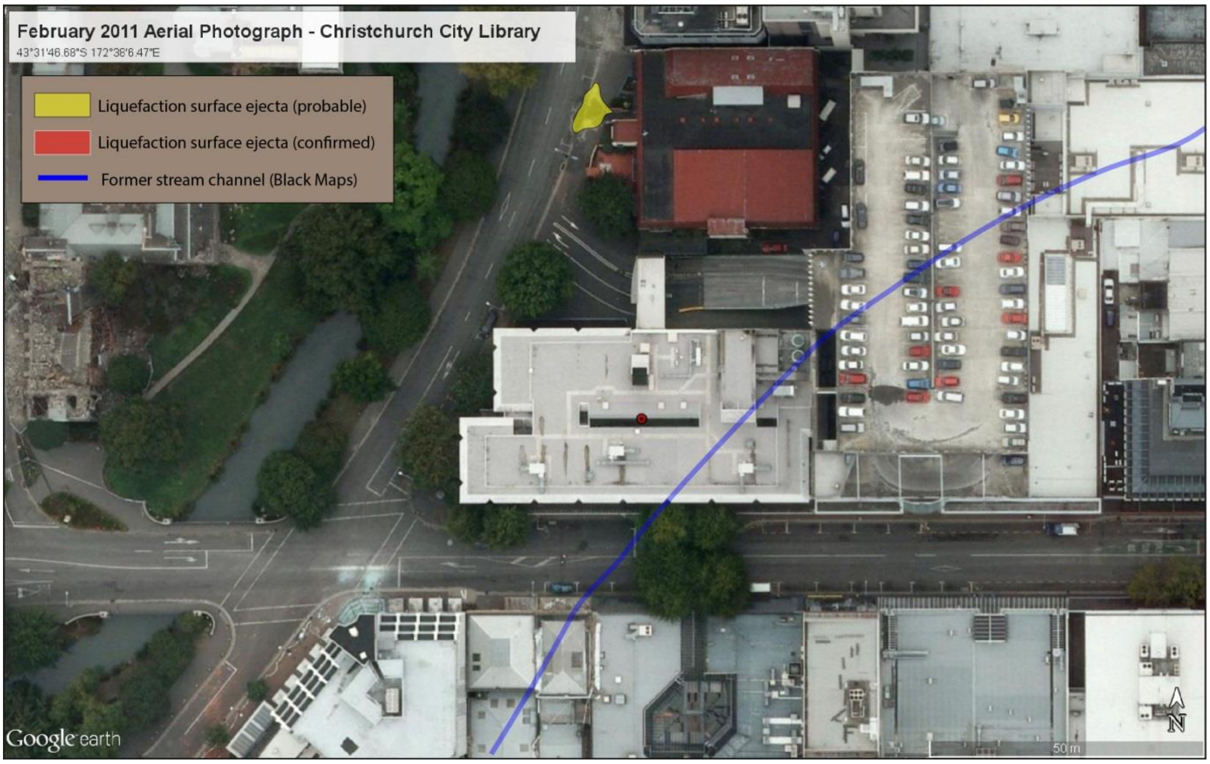


Figure 12: Map of liquefaction surface ejecta in the vicinity of the Christchurch City Library following the 22 February 2011 Mw 6.2 Christchurch earthquake.

The maps presented in Figs. 11, 12 provide higher resolution and improved accuracy compared to previously published maps (Fig. 2), which were undertaken at the suburb-scale for general land-damage and liquefaction severity purposes. The following conclusions can be drawn from the mapping.

1. No surface manifestation of liquefaction was identified proximal to the Art Gallery, however some probable (and an isolated pocket of confirmed) liquefaction ejecta was identified in parking lots to the east and west of the Art Gallery (Fig. 11) in areas that also experienced vertical subsidence (Fig. 5).
2. No surface manifestation of liquefaction was identified proximal to the Christchurch City Library, however some probable liquefaction ejecta was identified north of the City Library (Fig. 12) in areas that also experienced minor lateral spreading and vertical subsidence (Fig. 5).

A comparison of liquefaction ejecta distributions with land and building damage is presented in Section 3.2.

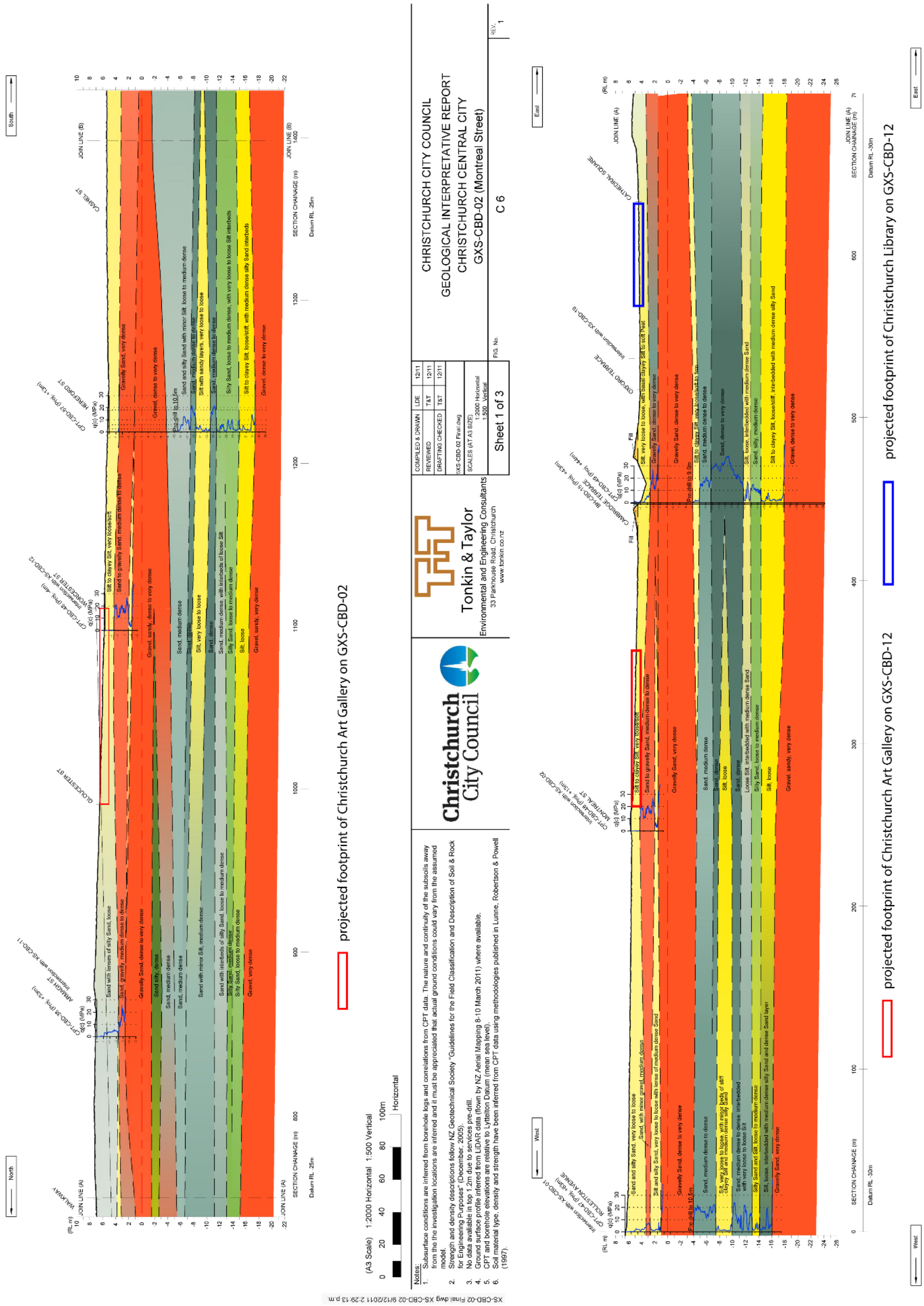


Figure 12: Geologic cross-section, showing subsurface geology projected from survey lines to beneath the Art Gallery and City Library. See text for discussion of survey results and geologic interpretations.

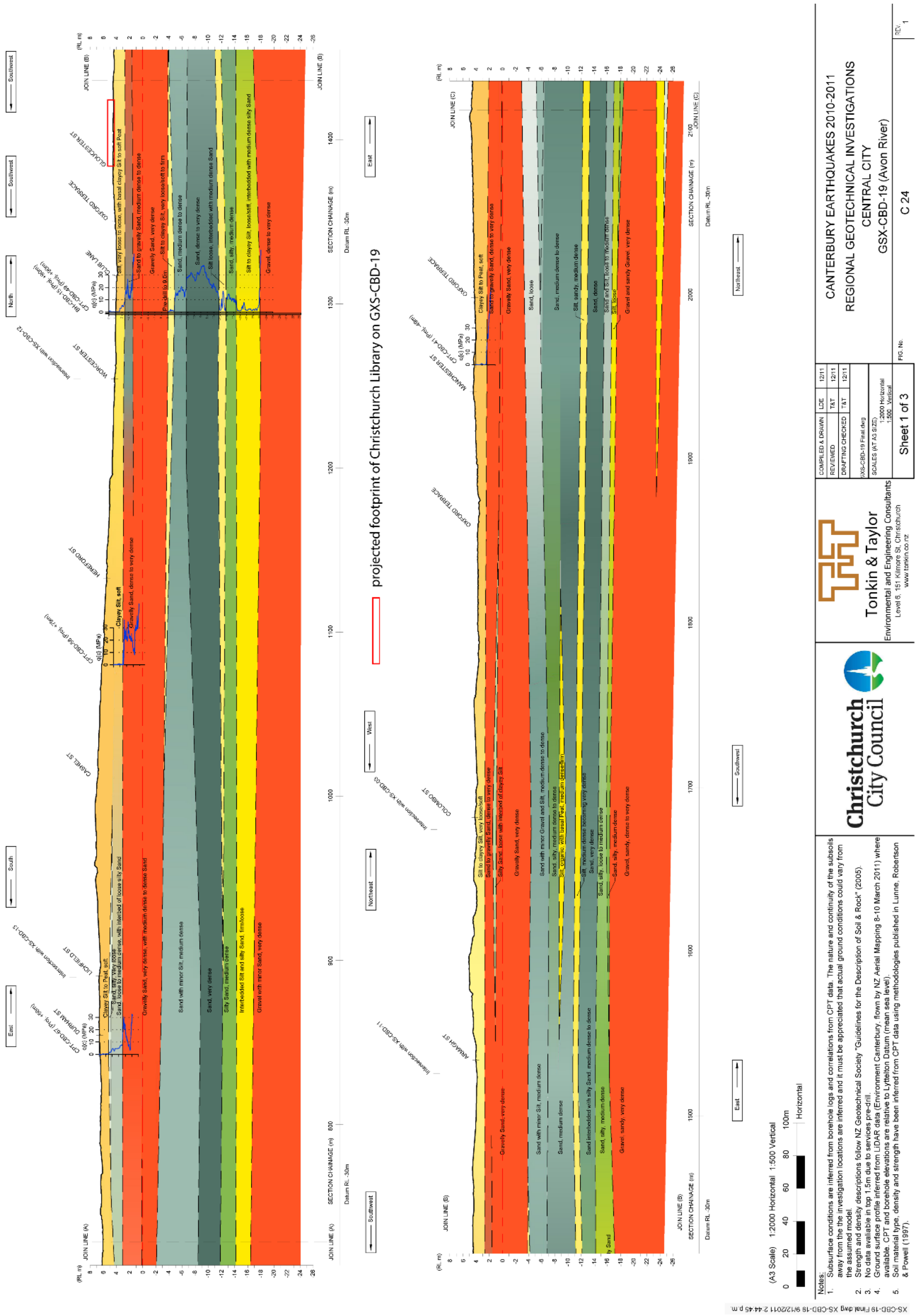
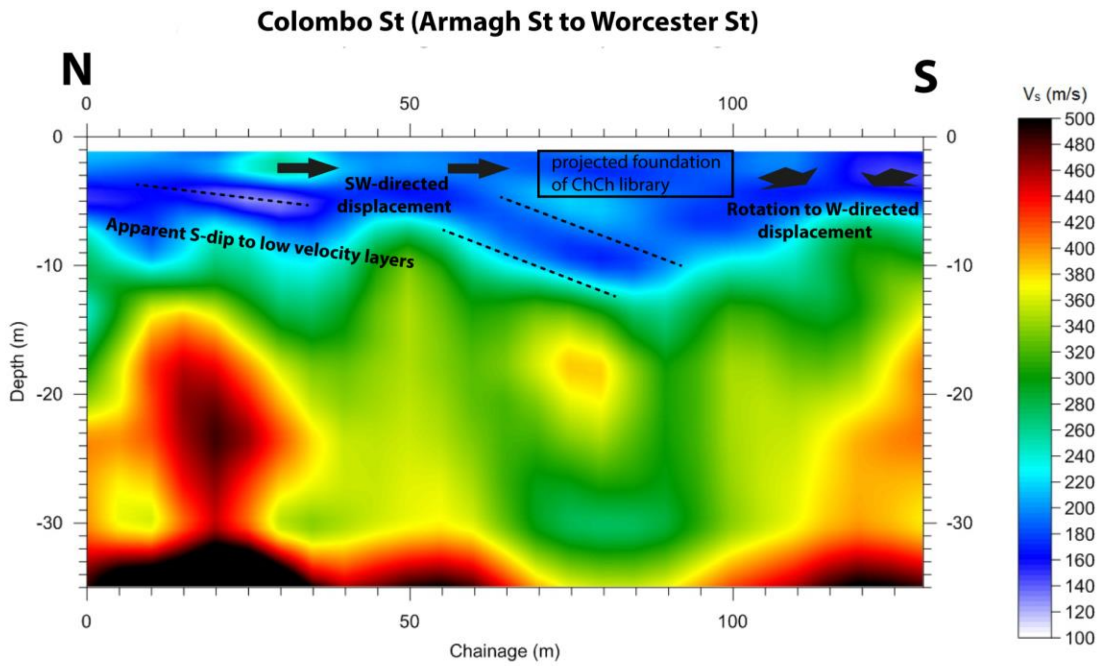


Figure 13: Geologic cross-section, showing subsurface geology projected from survey lines to beneath the Art Gallery and City Library. See text for discussion of survey results and geologic interpretations.



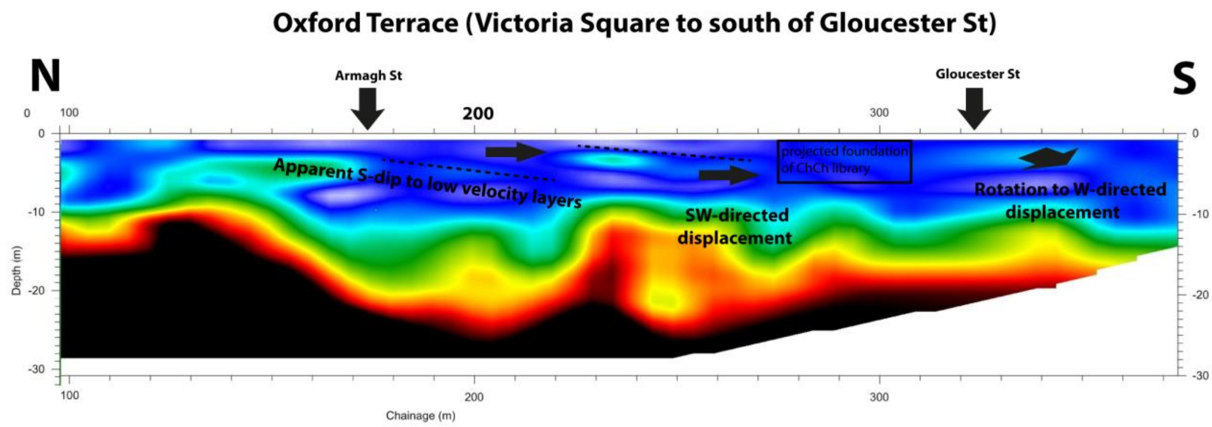


Figure 14: Interpreted MASW profiles showing apparent N-S changes in the geometry of lower velocity sediments beneath the projected locations of the Christchurch City Library.

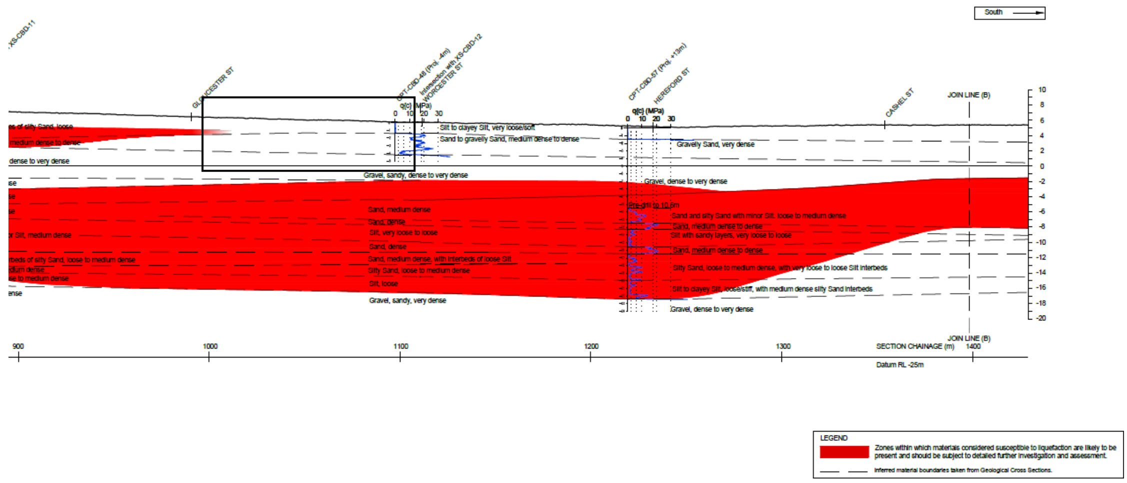


Figure 15: Projected footprint of the Christchurch Art Gallery on to LHXS-CBD-02 (Montreal St). Cross-section showing zones susceptible to liquefaction (RED) from T&T Ref # 51845. *Note regional southward thickening of liquefaction-susceptible zones from north of Gloucester St to Hereford St.*

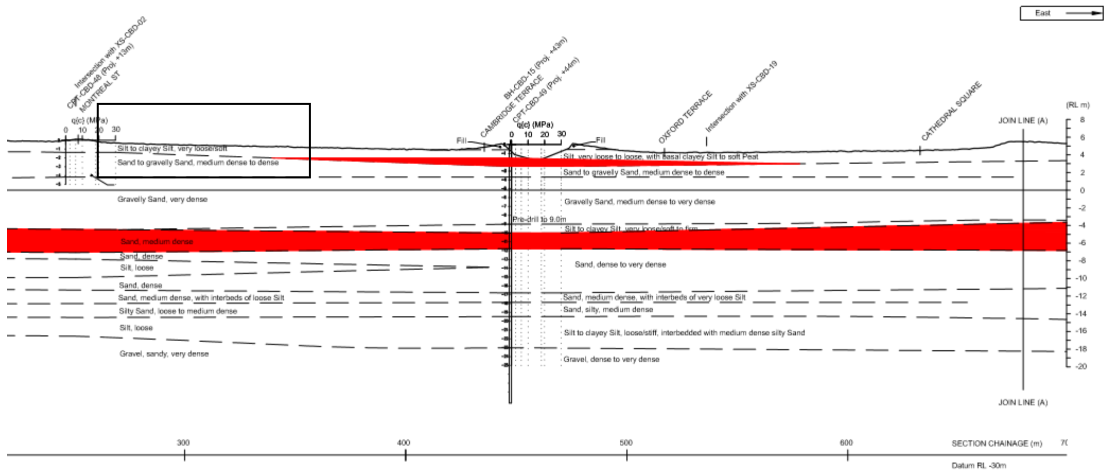


Figure 16: Projected footprint of the Christchurch Art Gallery on to LHXS-CBD-12 (Worcester St). Cross-section showing zones most susceptible to liquefaction (RED) from T&T Ref # 51845. East edge of Art Gallery overlaps with shallow channel of increased liquefaction hazard.

3.2. UNIFIED SYNTHESIS OF CHRISTCHURCH ART GALLERY AND CITY LIBRARY DATA AND MODEL FOR GEOLOGIC CONTROLS ON BUILDING PERFORMANCE IN THE 2010-2011 CANTERBURY EARTHQUAKES

Geologic cross-sections in the vicinity of the Art Gallery and City Library (Fig. 12, 13) show (i) westward increasing thickness of deep loose silts (-8 to -10 m RL; GXS-CBD-12), (ii) southward increasing thickness of deep liquefiable sediments (-1 to -17 m RL; LXHS-CBD-02) from north of the Art Gallery to south (Fig. 15), (iii) shallow layers (5 to 2 m RL) of liquefiable sediments present beneath the northern (LXHS-CBD-02) and eastern (LXHS-CBD-12) edges of the Art Gallery that are not present beneath the southern and western edges of the Gallery, and (iv) a shallow (4-3 m RL) channel of liquefiable sands and silts beneath the current position of the Avon River and extending ~100m beyond the channel, including beneath the site formerly occupied by the City Library (Fig. 16)

Fig. 17: Shallow liquefaction zones (~1.2 to 3m depth) beneath the Art Gallery and City Library.

MASW profiles (Fig. 14) appear to show a southward dip and apparent thickening of low velocity sediments to a maximum beneath the projected location of the City Library, and subsequent shallowing south of this location.

Horizontal displacements (Fig. 5) in the vicinity of the Art Gallery and City Library are consistent with southwest-directed lateral transport in the direction of increased deep liquefaction susceptibility and thickening of low velocity sediments. Surface subsidence is highest towards the east and northeast side of the Art Gallery and northeast side of the City Library (Fig. 6). Area-wide subsidence correlates generally with increased distribution and susceptibility of liquefiable sediments (Fig. 6).

Differential lidar analysis (Deam, 2015) suggests that the land west of the Art Gallery building (above the underground carpark) uplifted (about 0.1 m) during the February 2011 earthquake and that part of the parking lot east of the Art Gallery uplifted by up to 0.5 m in this earthquake. The roof of the Art Gallery subsided slightly (<0.2m) in the east and south. The City Library subsided relatively uniformly by 0.05m.

The patterns of ground deformation appear to reflect the following phenomena: (1) SW-directed lateral displacements driven by slope and distribution changes in deep (e.g., >8 m depth) liquefiable layers, (2) some differential subsidence of ground and buildings above liquefiable sediment due to variations in distribution of shallow and deep liquefiable sediments, (3) some uplift of ground surrounding buildings (e.g. parking lots) due to differential loading and consequent outward expulsion of liquefied sediment from beneath buildings. The direction and modes of ground deformation at the sites of CCC assets considered in this study are consistent with earthquake-induced liquefaction and associated ground failure.

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"Historical channels" – former, historical stream channels in Christchurch that were infilled during urban development

"LiDAR" – Light Detection And Ranging; in this report used to refer to laser scanning data obtained through airborne laser scanning

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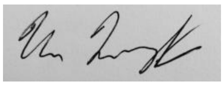

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GEOLOGIC, GEOMORPHIC, GEOTECHNICAL, AND DISPLACEMENT MAPS OF LAND AND BUILDINGS AT SELECTED SITES OF CHRISTCHURCH CITY COUNCIL OWNED REINFORCED CONCRETE STRUCTURES DAMAGED DURING THE 2010-2011 CANTERBURY EARTHQUAKES

MANCHESTER ST CARPARK STUDY

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University of Canterbury Consultancy Report CN4600001360

25 November 2015

EXECUTIVE SUMMARY

The 2010-2011 Canterbury earthquake sequence (CES) in New Zealand's South Island caused extensive and recurrent damage to land and infrastructure within the Central Business District (CBD) of Christchurch. In this report we consider the effects of the CES on ground deformations and building deformations at the Manchester St Carpark site. We present geologic, geotechnical, geophysical and geomorphic data in the form of series of interpreted maps. Minimal land and building surface subsidence occurred at this site through the CES. This is consistent with the near-absence of liquefaction surface ejecta at the site and the scarcity of liquefiable sediments at depth beneath the site as revealed from geologic cross-sections and CPT data. However, large (>20-40 cm) west-to-southwest directed cumulative lateral displacements are suggested from differential air photo analysis. We speculate that these lateral displacements, if they can be validated, could reflect a mixture of gravitational creep in southward dipping shallow (<10 m below surface) strata and westward dip in deeper strata (~15 m below surface). This hypothesis requires further testing. A larger component of the observed damage at the Manchester St Carpark and surrounding buildings is likely to relate to transient strong ground motions, rather than liquefaction-induced differential land damage.

1. SCOPE

The University of Canterbury (Dr. Mark Quigley) was commissioned by Christchurch City Council to (1) Produce detailed geologic, geomorphic, and geotechnical site maps for Council key assets, and (2) Produce earthquake-induced horizontal and vertical displacement maps for ground surface surrounding CCC key assets.

The seven key asset sites to be considered in this suite of reports 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
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Christchurch South Library	-43.561394	172.63805	2002

This work required the attainment and reproduction of a suite of previously produced maps (Geology Maps, Black Maps, DEMs), reinterpretation of a variety of datasets (CPT data, boreholes, auger data, differential LiDAR data, survey data), and production of a new suite of annotated maps and cross-sections for the CCC key assets.

The purpose of these studies was to (1) document geologic setting of council assets, document heterogeneity of surface and near-surface materials with variable engineering properties, and (2) document 2010-2011 earthquake-induced land elevation and position changes at CCC asset sites to document severity of ground deformation and document geologic/geotechnical controls on ground deformation. The primary purpose of these reports is to synthesize geologic, geomorphic, geotechnical, and geophysical data into a unified model that best explains the patterns and origin of land and building deformation in the 2010-2011 Canterbury earthquake sequence.

The focus of this report is MANCHESTER ST CARPARK.

2. LOCATION AND PRIOR WORK

Manchester Street Carpark is located in central Christchurch (Fig. 1). The central lat-long of the site is -43.529597, 172.640192.

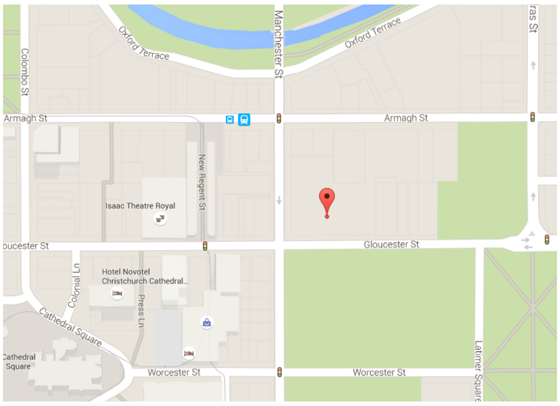

Figure 1. Location of Manchester St Carpark shown on Google Maps.

T&T conducted mapping (Fig. 2), and CPT investigations (Fig. 3) in close proximity to this site.

Horizontal and vertical displacement data was derived using differential lidar and airphoto interpretations throughout the Canterbury earthquake sequence (Fig. 4,5) and plotted on digital elevation model underlays. From these data, the tectonic component of displacement was removed (using tectonic displacements inferred geodetic seismic source models presented in Beavan et al., 2012), with the residual displacements interpreted to reflect shaking-induced permanent ground displacements relating to liquefaction and ground failure. See “Evaluation of Building Settlements during the Canterbury Earthquake Sequence using LiDAR” (T&T Ref # 53841) (see References) for further detail on how horizontal and vertical land displacements were obtained from differential LiDAR.

Individual horizontal displacement measurements reported in the displacement maps have an error range of ± 200 mm that corresponds to the lidar pixel resolution. The relatively large error compared to individual displacements requires that displacements be used only to provide a general picture of progressive land deformation through the Canterbury earthquake sequence and that individual measurements are not over-interpreted. However, added confidence to the cited displacements is found in the general agreement between cumulative displacements inferred from differential lidar and (i) cumulative displacements of LINZ benchmarks (Deam, 2015), and (ii) cumulative displacements from field measurements (Hughes et al., 2015). For these reasons, we use our horizontal displacement maps to make general conclusions regarding cumulative land deformation throughout the Canterbury earthquake sequence with an emphasis on relative horizontal land deformation variability on the m to 10s of metres scale, rather than emphasizing any individual measurement on the pixel scale. We do not use them to characterise strain on the scale of an individual building in this study; this could perhaps serve as a focus for further investigation however, particularly where individual measurements show large (e.g., >200-300 mm) variations in displacement across a building site.

The vertical displacement measurements reported in cumulative differential lidar displacement maps likely have an error of ± 300 mm. Errors accumulate due to varying quality of lidar data acquired (2003 vs 2011) and apparent ‘tilt effects’ corresponding to swath edges in the data. The reliability of these data for many individual locations (Hughes et al., 2015) is confirmed by field observations (Quigley et al., 2013; Hughes et al., 2015) and LINZ benchmarks (Deam, 2015). We thus use the differential lidar vertical displacement maps to make general conclusions regarding cumulative vertical land deformation throughout the Canterbury earthquake sequence with an emphasis on relative vertical land deformation variability on the m to 10s of metres scale, rather than emphasizing any individual measurement on the pixel scale.

A map showing pre-development waterways from historic “Black Maps” is shown in Fig. 6.

A series of MASW surveys were conducted by T&T in the vicinity of the Manchester St Carpark (Fig. 7,8). By combining topographic data, borehole data, CPT data, and MASW data, T&T constructed a suite of geologic cross-sections in this area (Fig. 9,10). Please see Christchurch Central City Geologic Interpretative Report” (T&T Ref REP-CCC-INT) for details including location of geotechnical sampling sites, raw and interpreted data, complete cross-sections, and preliminary geologic interpretations.

The richness of data obtained from these prior investigations provides the basis for our integrated geologic and geomorphic models for the Manchester St Carpark and our interpretations of how seismic loading and geology influenced the patterns of deformation.

Figure 2: Area reconnaissance mapping of liquefaction and lateral spreading in the vicinity of Manchester St Carpark following the 22 Feb 2011 Christchurch Mw 6.2 earthquake (mapping by Tonkin and Taylor Ltd). More detailed mapping (this report) is presented in Fig. 11

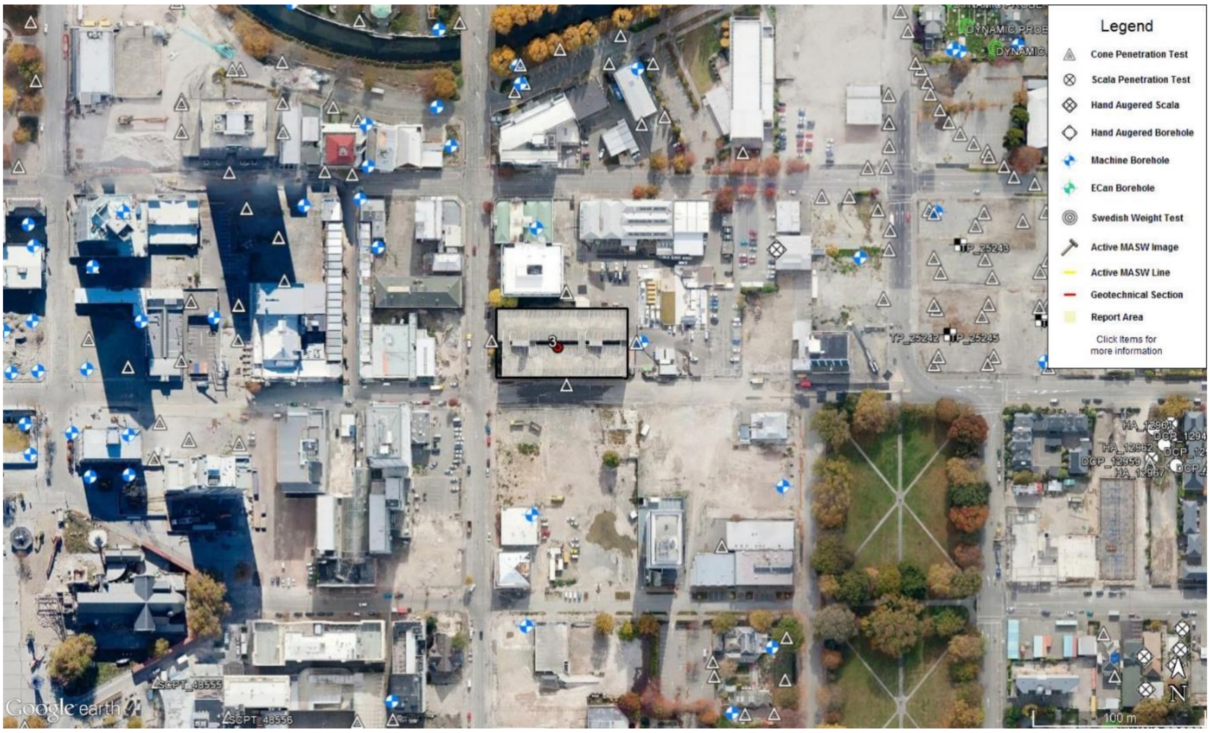

Figure 3: Location of CPT, borehole, and other geotechnical sampling sites in the vicinity of Manchester St Carpark. These data were variably used to construct geologic cross-sections (e.g., Fig. 9-11).

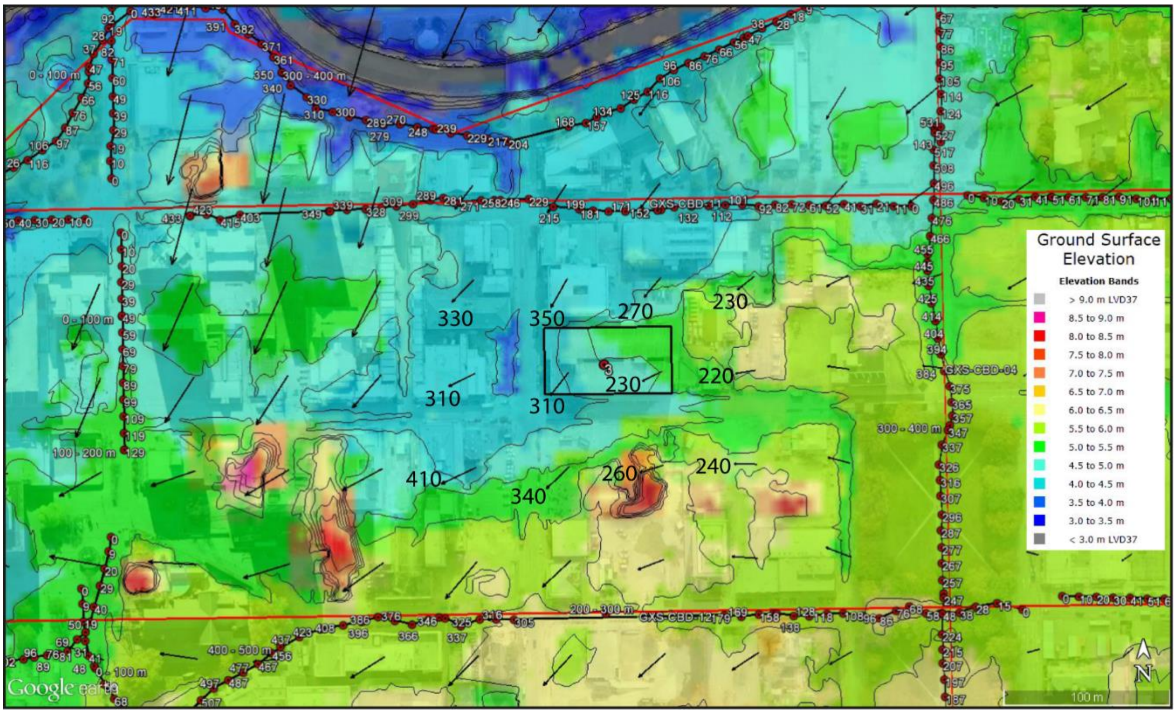

Figure 4: Cumulative horizontal permanent land displacements in mm with tectonic component removed for the Manchester St Carpark area, superimposed on DEM underlay. Location of MASW surveys and geologic cross-sections shown.

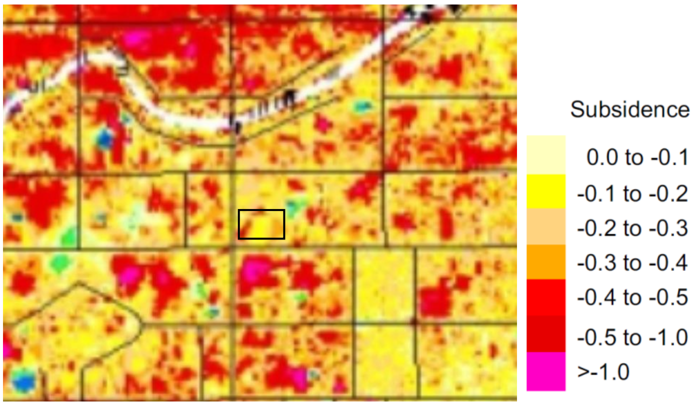

Figure 5: Permanent vertical land displacements from 2003 to December 2011 in metres for the Manchester St Carpark area. Image from Hughes et al. (2015)

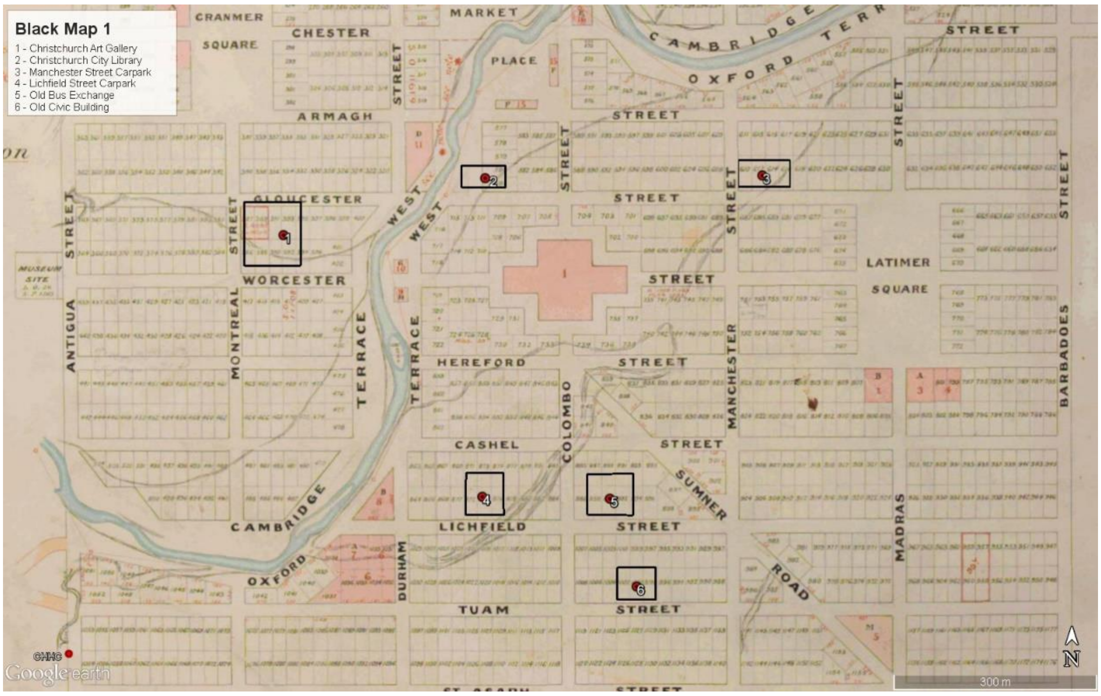

Figure 6: Historic drainage in Christchurch, showing location of historic channel beneath present-day southeast corner of Manchester St Carpark (3).

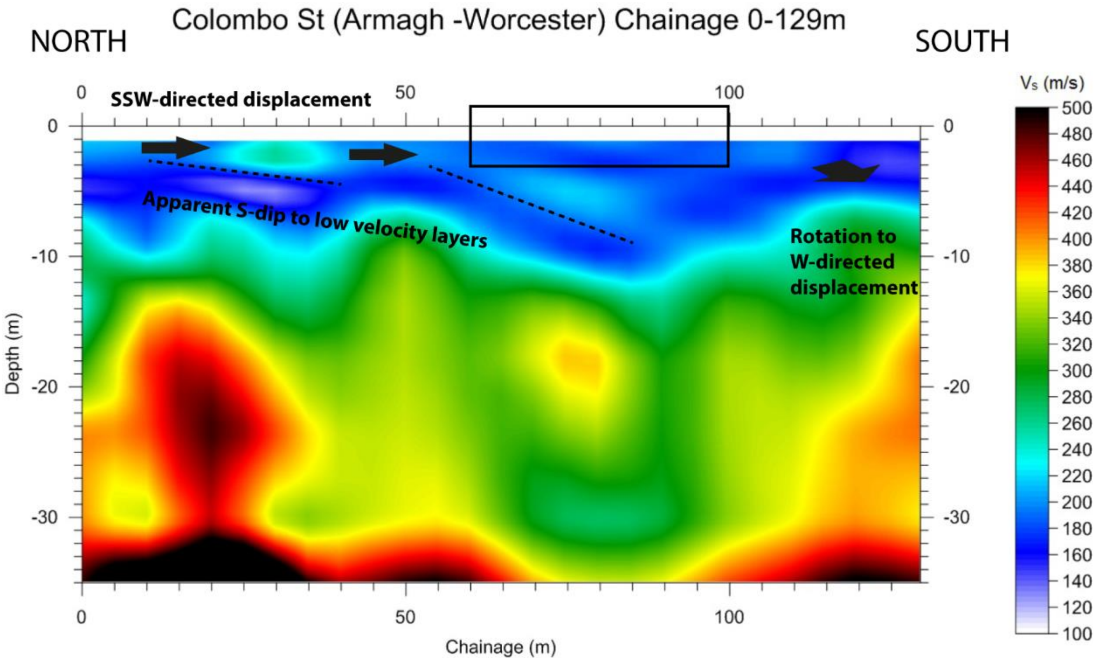

Figure 7: Interpreted MASW survey for Colombo St between Armagh St and Worcester St, immediately west of the Manchester St Carpark. See Fig. 4 for corresponding chainage.

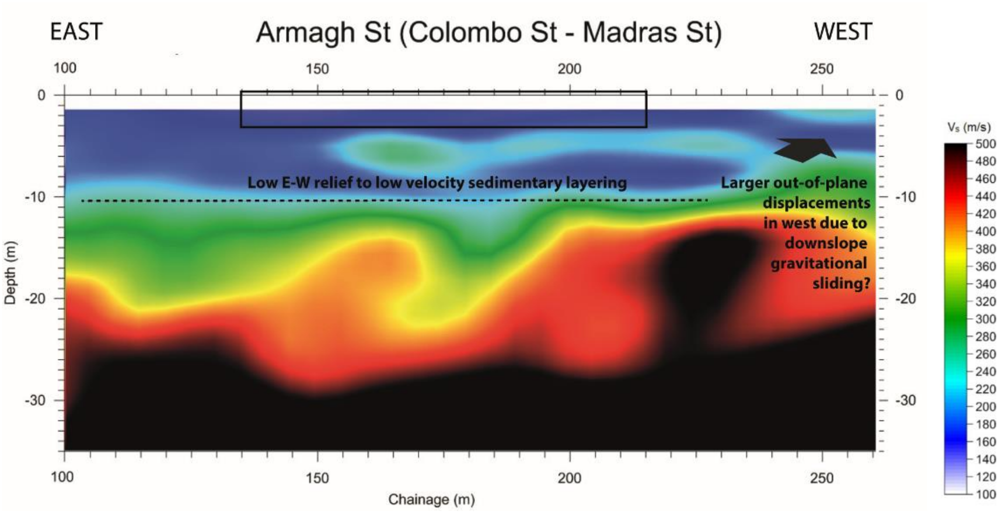

Figure 8: MASW survey for Armagh St, immediately north of the Manchester St Carpark (looking direction to the south). See Fig. 4 for corresponding chainage.

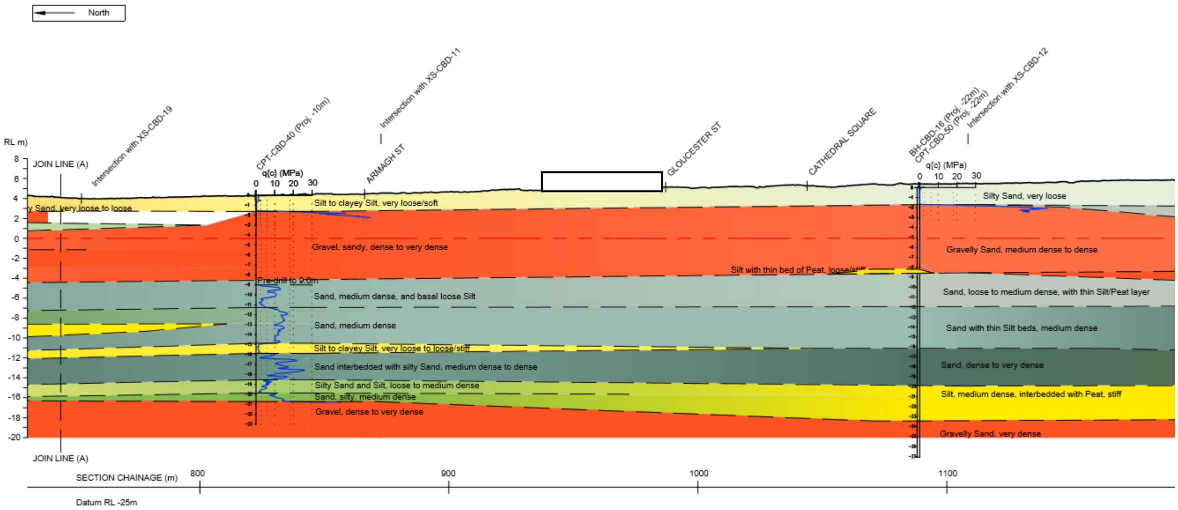

Figure 9: Geologic cross-section GXS-CBD-03 (Colombo St) showing projected position of Manchester Cark Park.

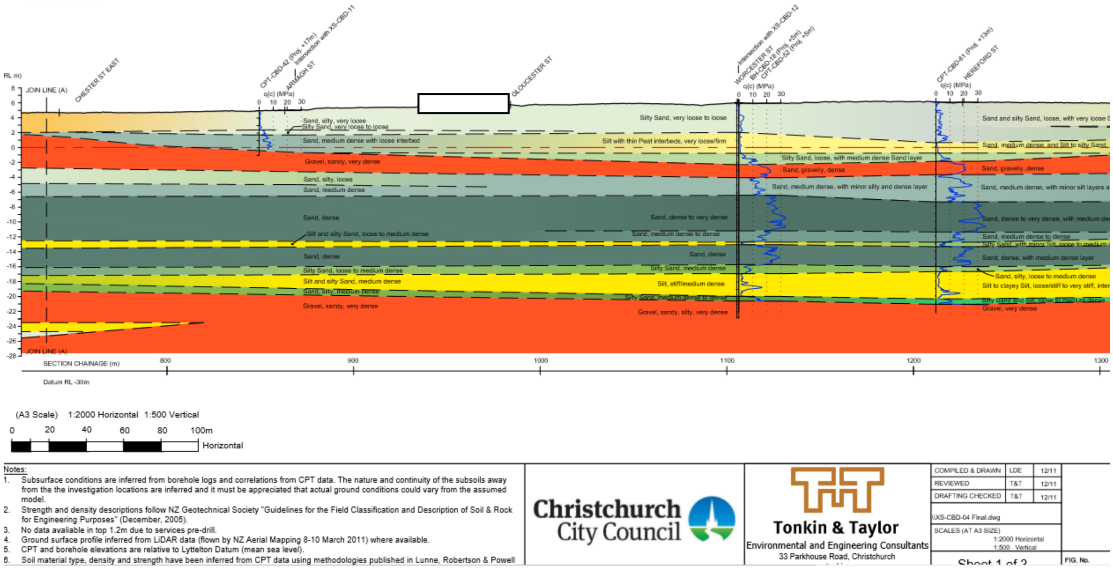

Figure 10: Geologic cross-section GXS-CBD-04 (Madras St) showing projected position of Manchester Cark Park.

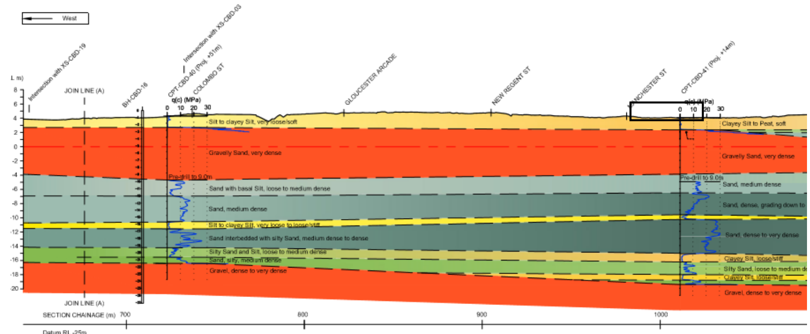

Figure 11: Geologic cross-section GXS-CBD-11 (Armagh St) showing projected position of Manchester Cark Park. Note westward slope and thickening of deep (~10-12m bsl), thin, very loose, highly liquefiable yellow unit, through to perhaps provide an explanation for west-directed lateral displacements in the absence of surface ejecta (further hypothesis testing required).

3. THIS WORK

3.1. MAPPING OF LIQUEFACTION EJECTA

The first part of our analysis was to produce detailed maps of liquefaction surface ejecta (Fig. 11) using airphotos obtained immediately following the 22 February earthquake in order to better quantify the extent of liquefaction surface ejecta. Distributions of liquefaction were characterised as definite or inferred. Former (historic) stream channels were added to maps where present. Liquefaction ejecta were rare in the vicinity of the Manchester St Carpark. The small, circular shape of possible or confirmed ejecta suggest anthropogenic control; it is possible that shallow infrastructure provide conduits for localized pockets of liquefiable material to reach the surface. Fig. 12 highlights the abundance of building damage in the area surrounding the Manchester St Carpark in the absence of abundant surface ejecta and scarcity of liquefiable material at depth; strong transient ground shaking during the 22 Feb Christchurch earthquake is suggested to be the primary cause of observed damage surrounding this site, rather than ground failure.

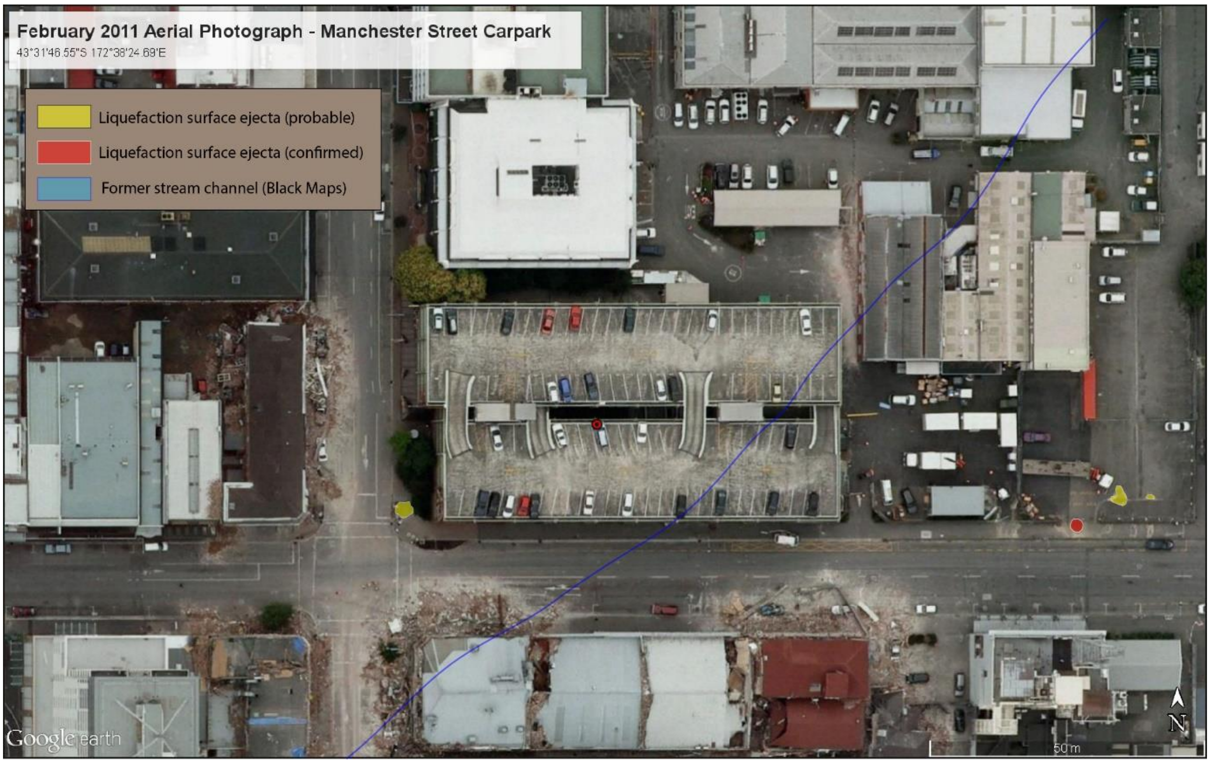

Figure 12: Map of liquefaction surface ejecta in the Manchester St Carkpark site following the 22 February 2011 Mw 6.2 Christchurch earthquake.

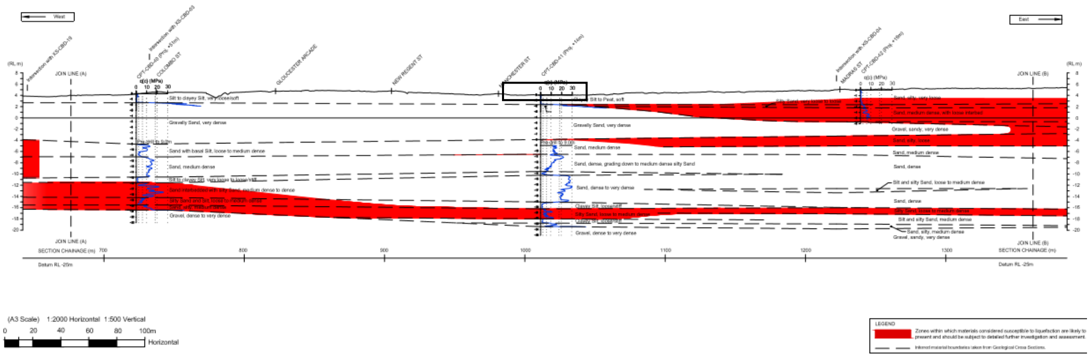

Figure 13: Projected footprint of Manchester Carkpark on to LHXS-CBD-11 (Armagh St). Cross-section showing zones susceptible to liquefaction (RED) from T&T Ref # 51845. *Note eastward thickening of liquefaction-susceptible zones in shallow levels (1-10 m below surface) and westward thickening of liquefaction-susceptible deep zones (15-20 m below surface). It is possible that the regional westward-directed lateral displacements reflect translational slip of the capping units above a deep liquefiable layer.*

4. CONCLUSIONS

Mapping of the Manchester St Carpark site confirms that surface manifestation of liquefaction was minimal at this site. This is consistent with constraints on the subsurface distribution of liquefiable sediments from CPT and borehole data, which are minimal at this location, and the apparent lack of surface subsidence at the site above the resolution of lidar data. However, large (>20-40 cm) west-to-southwest directed cumulative lateral displacements are suggested from differential air photo analysis. We speculate that these lateral displacements, if they can be validated, could reflect a mixture of gravitational creep in southward dipping shallow (<10 m below surface) strata and westward dip in deeper strata (~15 m below surface). This hypothesis requires further testing. A larger component of the observed damage at the Manchester St Carpark and surrounding buildings is likely to relate to transient strong ground motions, rather than liquefaction-induced differential land damage.

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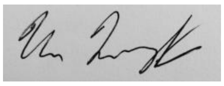

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LICHFIELD ST CARPARK, OLD BUS EXCHANGE, and OLD CIVIC BUILDING STUDY

Dr. Mark Quigley
Associate Professor of Active Tectonics and Geomorphology
School of Earth Sciences at the University of Melbourne, and
Department of Geological Sciences, University of Canterbury

With assistance in map production from

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25 November 2015

EXECUTIVE SUMMARY

The 2010-2011 Canterbury earthquake sequence (CES) in New Zealand's South Island caused extensive and recurrent damage to land and infrastructure within the Central Business District (CBD) of Christchurch. In this report we consider the effects of the CES on land and building deformations for an area that includes the Lichfield St Carpark, Old Bus Exchange, and Old Civic Building in central Christchurch. We present geologic, geotechnical, geophysical and geomorphic data in the form of series of interpreted maps. We draw the following conclusions for our analyses:

- Cumulative horizontal land surface displacements with tectonic components removed range from >100 to >500 mm in the area considered. Horizontal surface displacement vectors are oriented SE. Area-wide displacements are driven by liquefaction-induced gravitational displacements associated with (i) increasing thicknesses of liquefiable sediments at depths of ~2-5 m below surface towards the South and East associated with sedimentary facies changes, and (ii) South and East sloping sedimentary layers in liquefiable sediments ate depths of ~2-5 m below surface associated with Holocene paleo-geographic evolution of this area. It is possible that increased abundance of low seismic velocity, liquefiable sediments at ~10 m and ~18-22 m depths may also have enabled southward-directed displacements.
- Localized perturbations to surface displacements reflect the geometric configuration of shallow (i.e. 2-5 m) sedimentary units with varying liquefaction susceptibilities. Sediments with highest liquefaction susceptibility tend to have highest lateral displacements.
- Areas with most abundant identified surface manifestations of liquefaction (e.g., sand blows and fissures) generally coincide with areas with largest cumulative vertical subsidence, largest differential horizontal displacements (i.e. horizontal stretching strains), increased abundance of highly susceptible sediments, and possibly the proximal presence of shallow historical channels. Localized patterns of liquefaction surface manifestation at the small scale (e.g., individual sand blows) are frequently influenced by anthropogenic structures (e.g., piles, lamp posts) that provide efficient conduits for upward transport of liquefiable material from depth.
- The patterns of land and building damage in the Lichfield St Carpark, Old Bus Exchange, and Old Civic Building area are well-explained by the area-wide seismic induction of cyclic strains in liquefiable sediments which subsequently caused ground failure downslope by gravitational flow within liquefiable sediments. Modern surface topography did not exert a first-order influence on the azimuth or magnitude of surface displacements. The patterns are not consistent with contributions from static loading in the absence of earthquake-induced strong ground motions and associated liquefaction.

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This work required the attainment and reproduction of a suite of previously produced maps (Geology Maps, Black Maps, DEMs), reinterpretation of a variety of datasets (CPT data, boreholes, auger data, differential LiDAR data, survey data), and production of a new suite of annotated maps and cross-sections for the CCC key assets.

The purpose of these studies was to (1) document geologic and geomorphic setting of council assets, (2) document heterogeneity of surface and near-surface materials with variable engineering properties, and (3) document 2010-2011 earthquake-induced land elevation and position changes at CCC asset sites to quantify severity of ground deformation and relationship to topography, geology, and geotechnical characteristics of underlying sediments in this area. The primary purpose of these reports is to synthesize geologic, geomorphic, geotechnical, and geophysical data into a unified model that best explains the patterns and origin of land and building deformation in the 2010-2011 Canterbury earthquake sequence.

This report focuses on the LICHFIELD ST CARPARK, OLD BUS EXCHANGE, and OLD CIVIC BUILDING sites.

2. LOCATION AND PRIOR WORK

The Lichfield St Carpark site is located in central Christchurch immediately north of Lichfield St (Fig. 1). The central lat-long of the site is -43.533845, 172.635077.

The Old Civic Building site is immediately north of Tuam Street (Fig. 1). The central lat-long of the site is -43.53503, 172.637896.

The Old Bus Exchange site is immediately north of Lichfield St (Fig. 1). The central lat-long of the site is -43.53387, 172.637407.

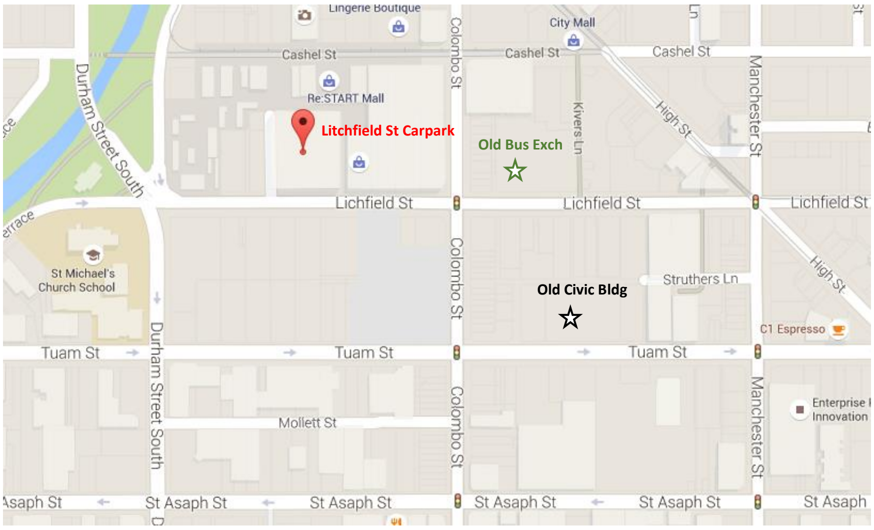

Figure 1. Location of Lichfield St carpark, Old Civic Building, and Old Bus Exchange sites shown on Google Maps.

T&T conducted reconnaissance liquefaction mapping of the area following major CES earthquakes including the 22 February 2011 Mw 6.2 Christchurch earthquake (Fig. 2). A variety of other subsurface sampling investigations including CPT tests (Fig. 3) have been conducted in this area.

Horizontal and vertical displacement data was derived using differential lidar and airphoto interpretations throughout the Canterbury earthquake sequence (Fig. 5,6) and plotted on digital elevation model underlays. From these data, the tectonic component of displacement was removed (using tectonic displacements inferred geodetic seismic source models presented in Beavan et al., 2012), with the residual displacements interpreted to reflect shaking-induced permanent ground displacements relating to liquefaction and ground failure. See “Evaluation of Building Settlements during the Canterbury Earthquake Sequence using LiDAR” (T&T Ref # 53841) (see References) for further detail on how horizontal and vertical land displacements were obtained from differential LiDAR.

Individual horizontal displacement measurements reported in the displacement maps have an error range of ± 200 mm that corresponds to the lidar pixel resolution. The relatively large error compared to individual displacements requires that displacements be used only to provide a general picture of progressive land deformation through the Canterbury earthquake sequence and that individual measurements are not over-interpreted. However, added confidence to the cited displacements is found in the general agreement between cumulative displacements inferred from differential lidar and (i) cumulative displacements of LINZ benchmarks (Deam, 2015), and (ii) cumulative displacements from field measurements (Hughes et al., 2015). For these reasons, we use our horizontal displacement maps to make general conclusions regarding cumulative land deformation throughout the Canterbury earthquake sequence with an emphasis on relative horizontal land deformation variability on the m to 10s of metres scale, rather than emphasizing any individual measurement on the pixel scale. We do not use them to characterise strain on the scale of an individual building in this study; this could perhaps serve as a focus for further investigation however, particularly where individual measurements show large (e.g., >200-300 mm) variations in displacement across a building site.

The vertical displacement measurements reported in cumulative differential lidar displacement maps likely have an error of ± 300 mm. Errors accumulate due to varying quality of lidar data acquired (2003 vs 2011) and apparent 'tilt effects' corresponding to swath edges in the data. The reliability of these data for many individual locations (Hughes et al., 2015) is confirmed by field observations (Quigley et al., 2013; Hughes et al., 2015) and LINZ benchmarks (Deam, 2015). We thus use the differential lidar vertical displacement maps to make general conclusions regarding cumulative vertical land deformation throughout the Canterbury earthquake sequence with an emphasis on relative vertical land deformation variability on the m to 10s of metres scale, rather than emphasizing any individual measurement on the pixel scale.

Ecological maps (pre-development vegetation and waterways; Fig. 7,8) were reproduced by T&T from compilations of Christchurch Drainage Board 1856 "Black Maps" consequently reproduced by Di Lucas for Christchurch area.

Figure 2: Area reconnaissance mapping of liquefaction and lateral spreading in the vicinity of Litchfield St carpark (4), Old Bus Exchange (5), and Old Civic Building (6) following the 22 Feb 2011

Christchurch Mw 6.2 earthquake (mapping by Tonkin and Taylor Ltd). More detailed mapping (this report) is presented in Fig. 11

Figure 3: Location of CPT, borehole, and other geotechnical sampling sites in the vicinity of the Lichfield St carpark (4), Old Bus Exchange (5), and Old Civic Building (6). These data were variably used to construct geologic cross-sections (e.g., Fig. 10).

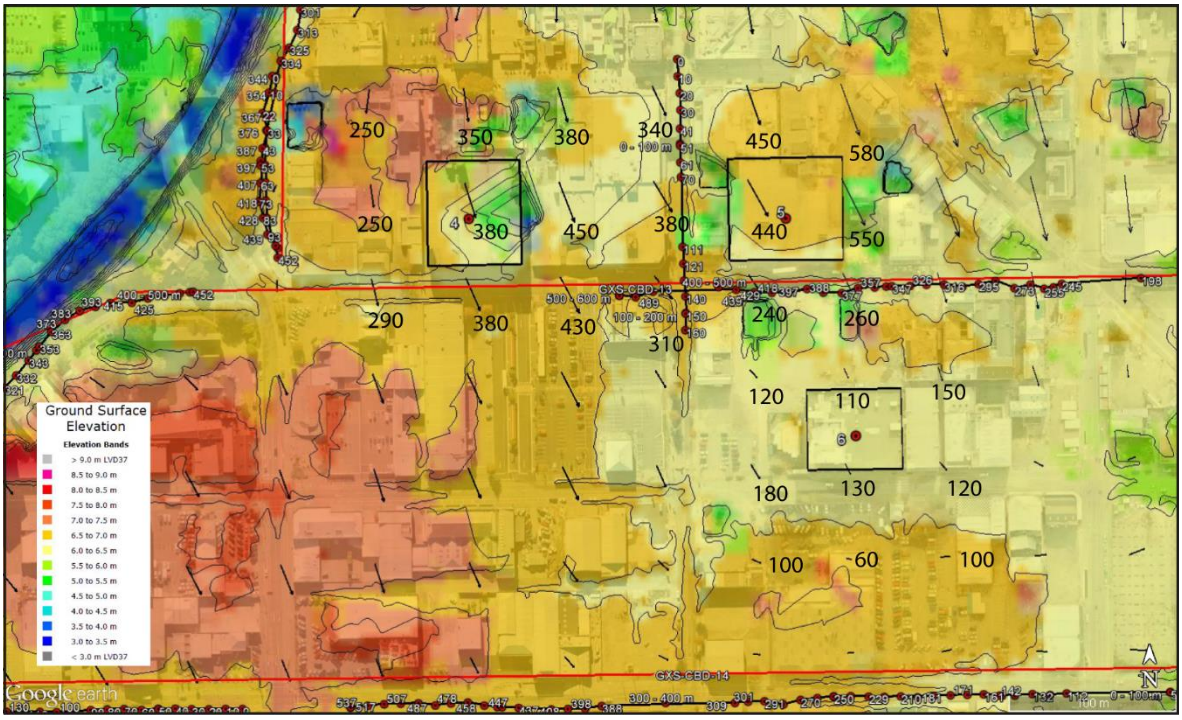

Figure 5: Cumulative horizontal permanent land displacements in mm with tectonic component removed for the Lichfield St Carpark (4), Old Bus Exchange (5), and Old Civic Building (6) area, superimposed on DEM underlay. Location of MASW surveys and geologic cross-sections shown

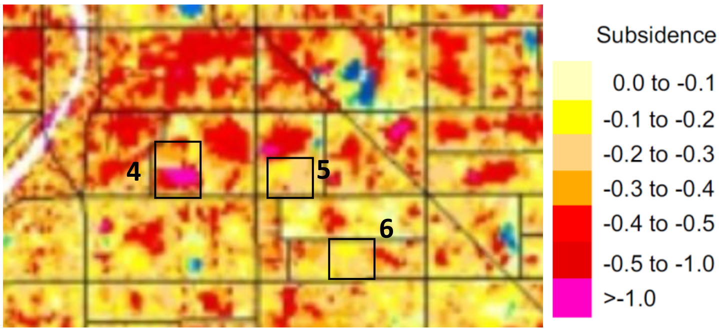

Figure 6: Permanent vertical land displacements from 2003 to December 2011 in metres in the vicinity of the Lichfield St carpark (4), Old Bus Exchange (5), and Old Civic Building (6). Image from Hughes et al. (2015)

Figure 7: Paleo-ecology of the Lichfield St carpark (4), Old Bus Exchange (5), and Old Civic Building (6) sites.

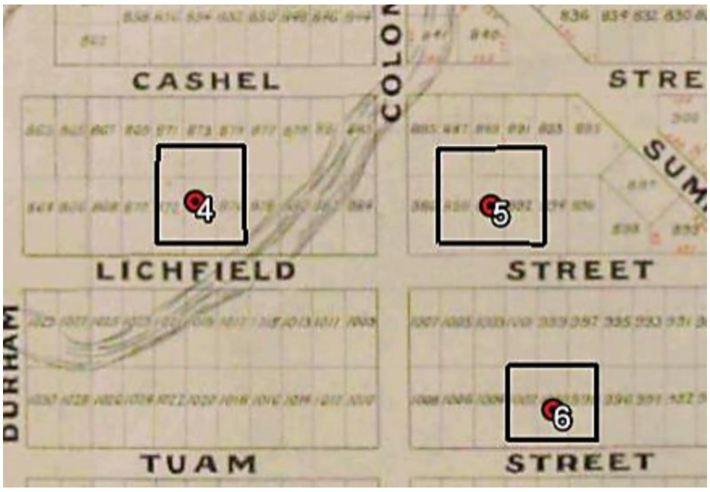

Figure 8: Black Maps historic stream channel in the Lichfield St carpark (4), Old Bus Exchange (5), and Old Civic Building (6) area.

A series of MASW surveys were conducted by T&T in the vicinity of these sites (Fig. 9). I have annotated these MASW surveys with some of the key features of the study area below.

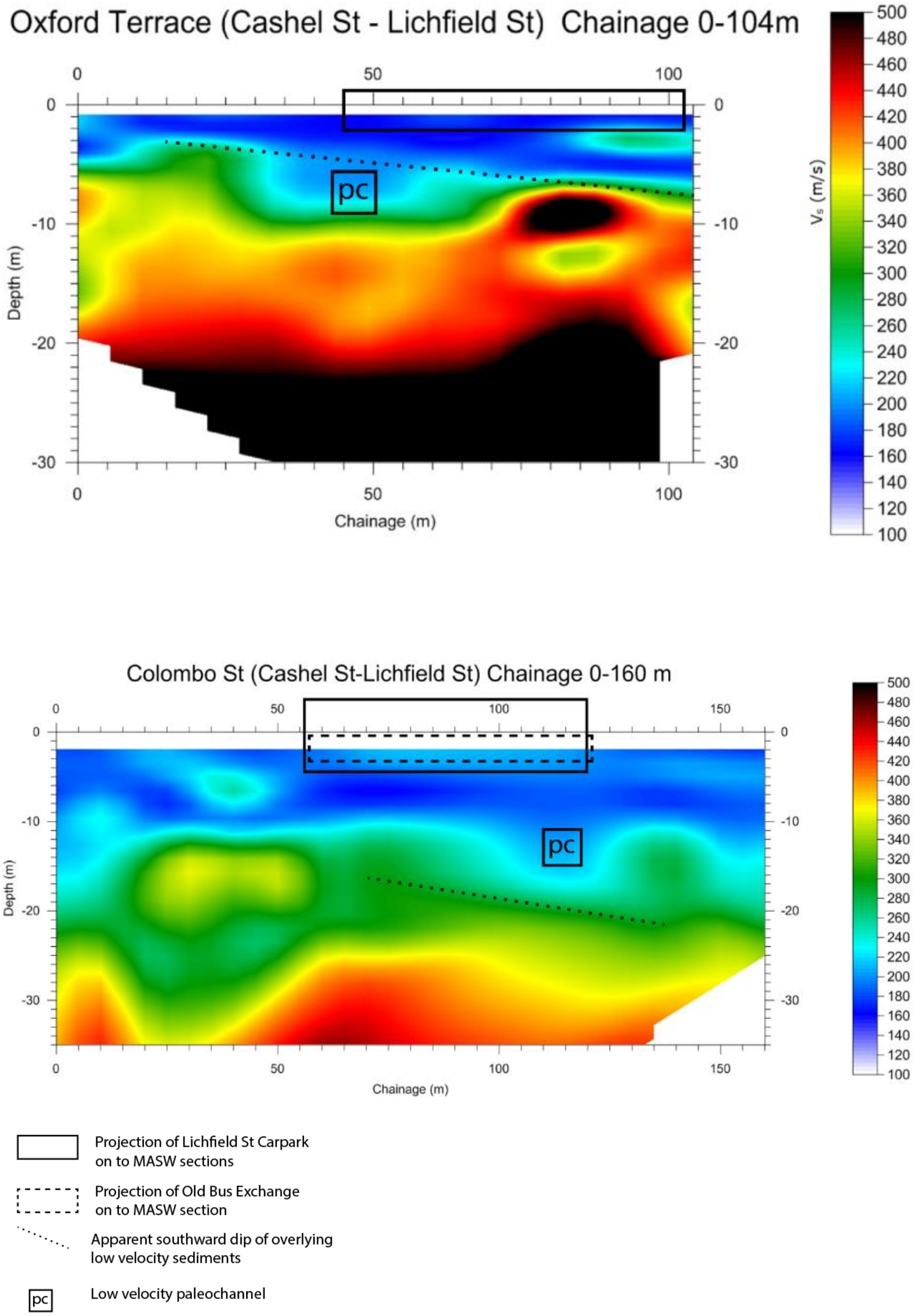

Figure 9: MASW profiles with annotated features, including southward slope and southward thickening of low shear wave velocity sediments in the vicinity of the assets considered (see Fig. 5 for MASW profile locations), and topographic depressions in low velocity sediment interpreted as buried ancient stream channels (i.e. paleochannels).

By combining topographic data, borehole data, CPT data, and MASW data, T&T constructed a suite of geologic cross-sections in this area (Fig. 10, 11). Please see Christchurch Central City Geologic Interpretative Report" (T&T Ref REP-CCC-INT) for details including location of geotechnical sampling sites, raw and interpreted data, complete cross-sections, and preliminary geologic interpretations.

The richness of data obtained from these prior investigations provides the basis for our integrated geologic and geomorphic models for the Lichfield St Carpark, Old Civic Building, and Old Bus Exchange sites, and our interpretations of how seismic loading and geology influenced the patterns of deformation.

3. THIS WORK

3.1. MAPPING OF LIQUEFACTION EJECTA

The first part of our analysis was to produce detailed maps of liquefaction surface ejecta (Fig. 12-14) using airphotos obtained immediately following the 22 February earthquake in order to better quantify the extent of liquefaction surface ejecta. Distributions of liquefaction were characterised as definite or inferred. Former (historic) stream channels were added to maps where present.

The maps presented in Fig. 12-14 present higher resolution and improved accuracy compared to previously published maps (Fig. 2), which were undertaken at a coarser scale for general land-damage and liquefaction severity purposes.

The next step was to compare liquefaction ejecta distributions to surface topography (Fig. 5), horizontal displacements (Fig. 5), CES-induced subsidence (Fig. 6), and the subsurface geology (Fig. 9-11) including planar geologic maps (Fig. 15).

The following conclusions can be drawn from the mapping.

1. My new maps show small pockets of liquefaction surface ejecta not identified on prior liquefaction maps. The most extensive manifestations of mapped surface ejecta occur northwest of the Old Bus Exchange, in an area previously identified as having 'minor to moderate quantities of surface ejecta' by Tonkin and Taylor (Fig. 2).
2. The general areas with most abundant identified surface manifestations of liquefaction (e.g., sand blows and fissures) generally coincide with areas with largest cumulative vertical subsidence (Fig. 6), largest differential horizontal displacements (i.e. horizontal stretching strains, as indicated from lateral displacement increases in the direction of displacement, Fig. 5), and increased abundance of highly susceptible sediments at shallow depths (2-5 m; Fig. 15).
3. Localized patterns of liquefaction surface manifestation at the small scale (e.g., individual sand blows) are frequently influenced by anthropogenic structures (e.g., piles, lamp posts) that provide efficient conduits for upward transport of liquefiable material from depth. Specific locations and geometries of individual liquefaction surface ejecta appear to be largely controlled by anthropogenic structures including the edges of buildings, parking lots, and edges of roads and laneways where the junctions of different materials may have provided efficient conduits for liquefied material at depth to reach the surface. An absence of surface ejecta does not indicate an absence of major liquefaction at depth.

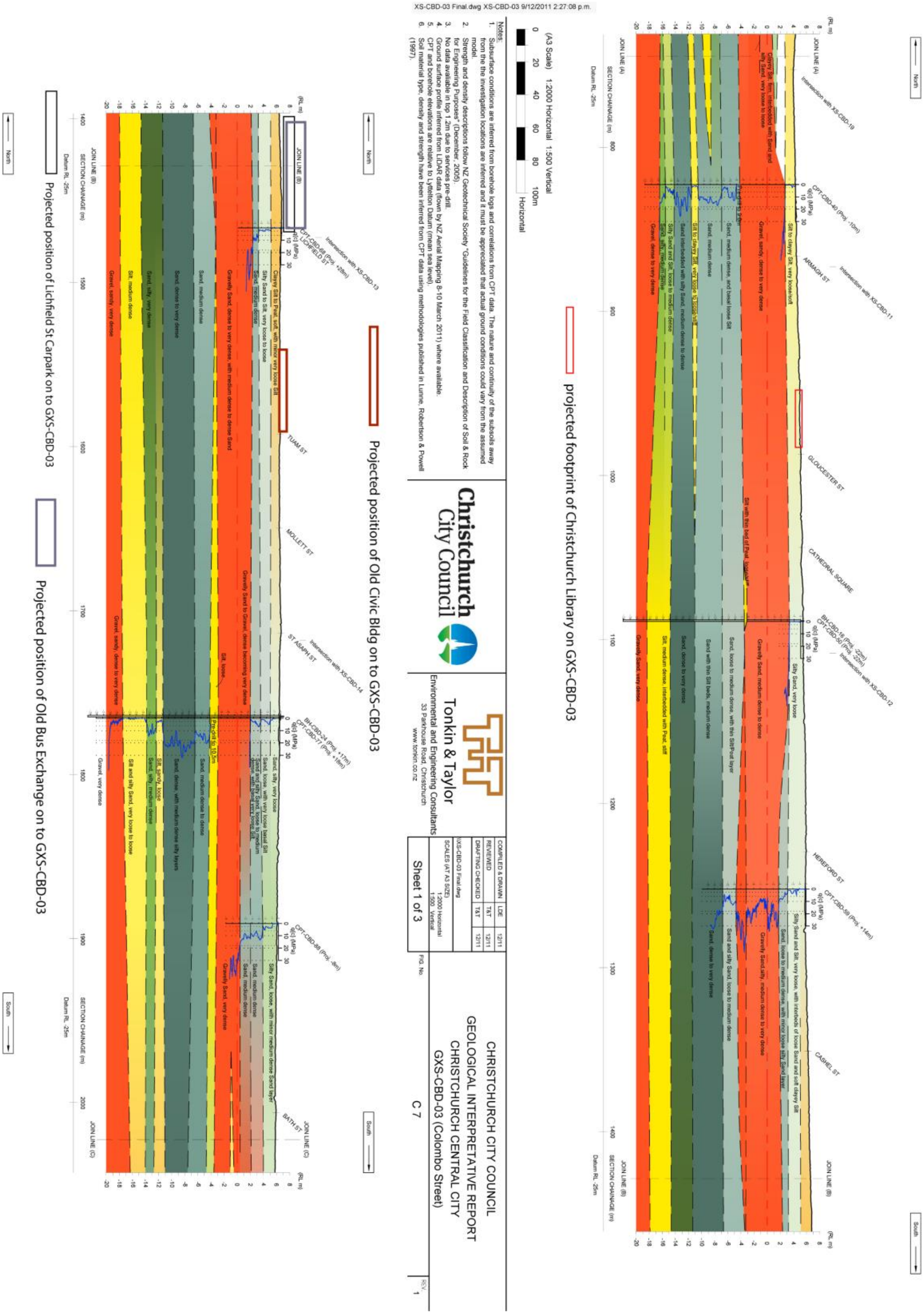

Figure 10: Geologic cross-sections reproduced from Tonkin and Taylor showing projected locations of assets considered in this report. Cross-sections and CPT data indicate apparent southward thickening of liquefiable sediments due to facies changes and southward slope of sedimentary strata due to sloping paleotopography.

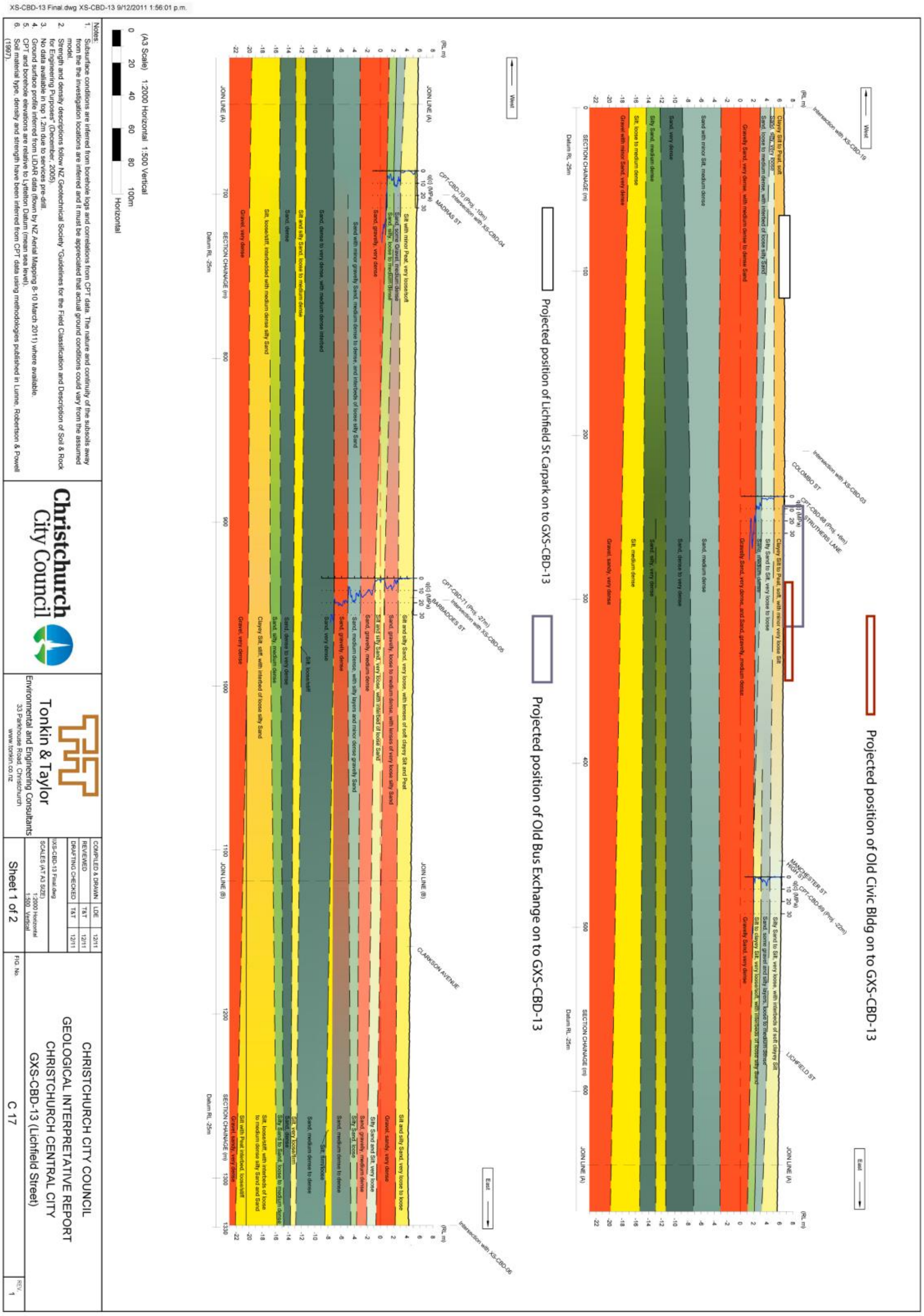

Figure 11: Geologic cross-sections reproduced from Tonkin and Taylor showing projected locations of assets considered in this report. Cross-sections and CPT data indicate apparent eastward thickening of liquefiable sediments due to facies changes.

Figure 12: Map of liquefaction surface ejecta surrounding Lichfield Car Park following the 22 February 2011 Mw 6.2 Christchurch earthquake. Position of waterway identified from Black Maps as shown.

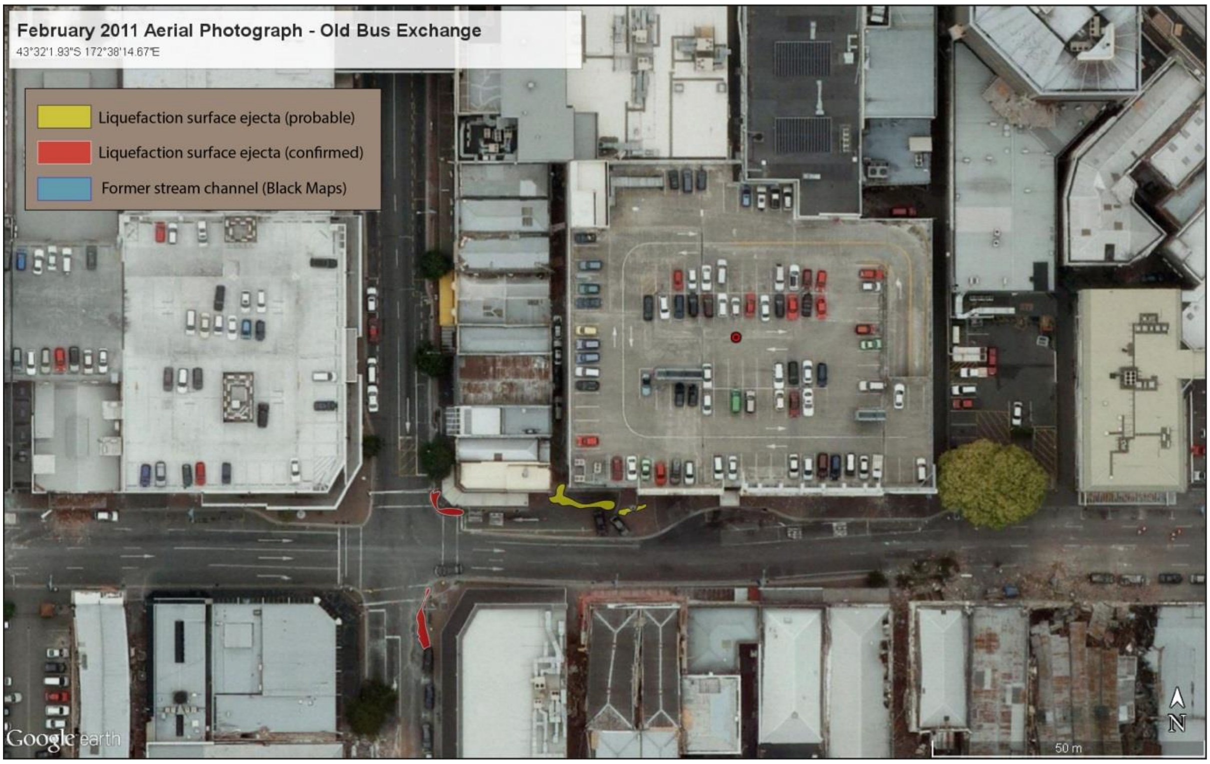

Figure 13: Map of liquefaction surface ejecta surrounding the Old Bus Exchange following the 22 February 2011 Mw 6.2 Christchurch earthquake.

Figure 14: Map of liquefaction surface ejecta surrounding the Old Civic Building following the 22 February 2011 Mw 6.2 Christchurch earthquake

3.2. COMPARISON OF LAND DISPLACEMENTS WITH TOPOGRAPHY, GEOMORPHOLOGY, GEOLOGY, AND GEOTECHNICAL DATA

Cumulative horizontal land surface displacements with tectonic components removed range from >100 to >500 mm in the area considered (Fig. 5). Horizontal surface displacement vectors are primarily oriented SE and exhibit counter-clockwise rotation to E in the southeast part of the study area. Area-wide displacements are driven by liquefaction-induced gravitational displacements associated with increasing thicknesses of liquefiable sediments at depths of ~2-5 m below surface towards the South and East associated with sedimentary facies changes (Fig. 10, 11, 16) and South and East sloping sedimentary layers in liquefiable sediments ate depths of ~2-5 m below the surface (Fig. 10, 11) associated with the Holocene paleo-geographic evolution of this area (Fig. 15). It is possible that increased abundance of low seismic velocity, liquefiable sediments at ~10 m and ~18-22 m depths may also have enabled southward-directed displacements (Fig. 9).

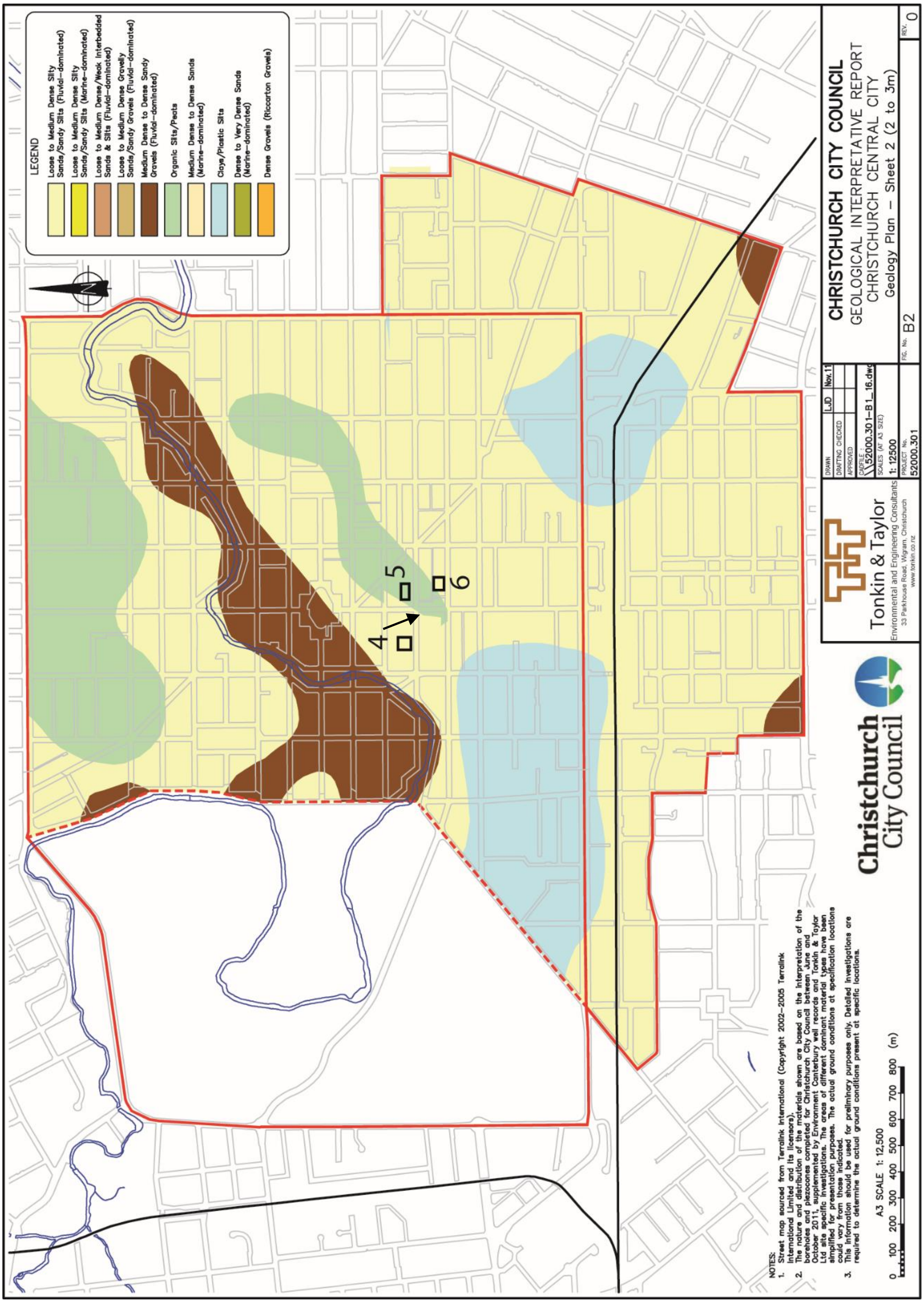

Figure 15: Planar geologic map of liquefaction surface ejecta surrounding the Old Civic Building following the 22 February 2011 Mw 6.2 Christchurch earthquake. Note SE displacements in liquefiable sediment (black arrow) towards paleodepressions (organic silts and peats) and away from dense sand units.

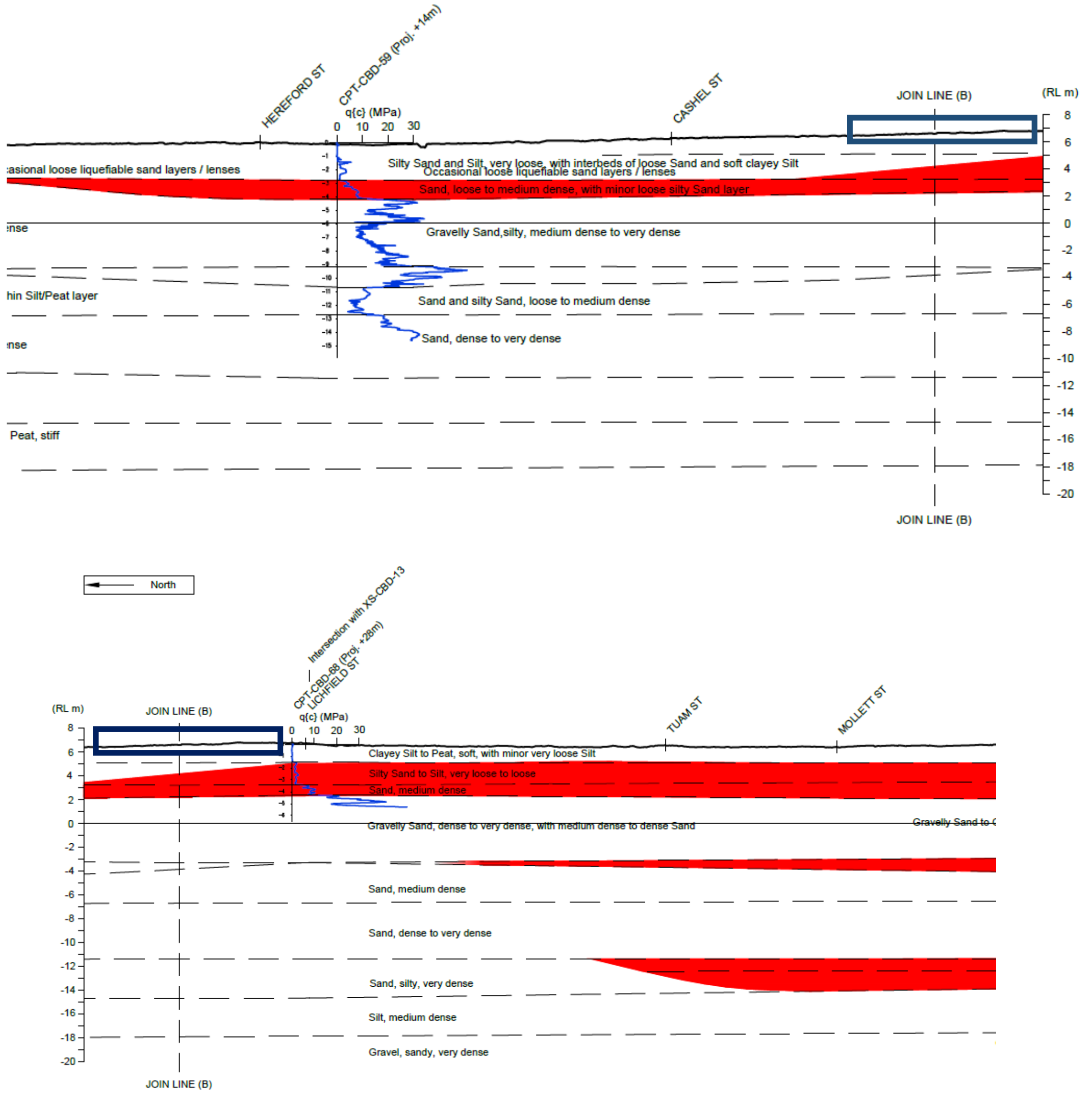

Figure 15: Cross-section showing zones susceptible to liquefaction (RED) from T&T Ref # 51845. *Blue box shows projected position of Litchfield Carpark and Bus Exchange on to liquefaction hazard map. Note southward thickening and increasing abundance of liquefiable sediment.*

4. CONCLUSIONS

- SE-directed cumulative horizontal land surface displacements in the study area were driven by liquefaction-induced gravitational displacements associated with (i) increasing thicknesses of liquefiable sediments at depths of ~2-5 m below surface towards the South and East associated with sedimentary facies changes, and (ii) South and East sloping sedimentary layers in liquefiable sediments ate depths of ~2-5 m below surface. Sediments with highest liquefaction vulnerability tend to have highest lateral displacements.

- Areas with most abundant identified surface manifestations of liquefaction (e.g., sand blows and fissures) generally coincide with areas with largest cumulative vertical subsidence, largest differential horizontal displacements (i.e. horizontal stretching strains), increased abundance of highly susceptible sediments, and possibly the proximal presence of shallow historical channels. Localized patterns of liquefaction surface manifestation at the small scale (e.g., individual sand blows) are frequently influenced by anthropogenic structures (e.g., piles, lamp posts) that provide efficient conduits for upward transport of liquefiable material from depth.
- The patterns of land and building damage in the Litchfield St Carpark, Old Bus Exchange, and Old Civic Building area are well-explained by the area-wide seismic induction of cyclic strains in liquefiable sediments which subsequently fail by downslope by gravitational flow within liquefiable sediments. Modern surface topography does not exert a first-order influence on the azimuth or magnitude of surface displacements. The patterns are not consistent with contributions from static loading in the absence of earthquake-induced strong ground motions and associated liquefaction.

5. REFERENCES

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Quigley, M., Bastin, S., and Bradley, B., (2013) Recurrent liquefaction in Christchurch, New Zealand during the Canterbury earthquake sequence, Geology 41 (4) p. 419-422.

6. BRIEF GLOSSARY

"Historical channels" – former, historical stream channels in Christchurch that were infilled during urban development

"LiDAR" – Light Detection And Ranging; in this report used to refer to laser scanning data obtained through airborne laser scanning

"Tectonic displacements" – permanent land movements attributed to deep faulting movement of crustal rock and overlying sediments and surface during earthquakes. Distinct from liquefaction-induced displacements, which relate to near-surface liquefaction phenomena.

"Sedimentary facies" – in this report used to refer to lateral changes in the physical / lithologic characteristics of sedimentary units (e.g. grain size, fines content) that may influence the dynamic behaviour of the sediment.

7. APPLICABILITY

This report has been prepared for the benefit of Christchurch City Council with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.

Canterbury Geotechnical Database: Important notice

The aerial photography and other figures presented in this report were created from maps and/or data extracted from the Canterbury Geotechnical Database (https://canterburygeotechnicaldatabase.projectorbit.com), which were prepared and/or compiled for the Earthquake Commission (EQC) to assist in assessing insurance claims made under the Earthquake Commission Act 1993 and/or for the Canterbury Geotechnical Database on behalf of the Canterbury Recovery Authority (CERA). The source maps and data were not intended for any other purpose. EQC, CERA, their data suppliers and their engineers, Tonkin & Taylor, have no liability for any use of the maps and data or for the consequences of any person relying on them in any way. This "Important notice" must be reproduced wherever these maps or any derivatives are reproduced.

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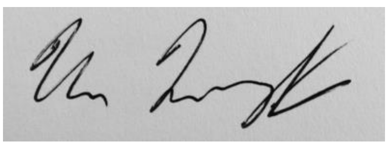

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Mark Quigley

University of Canterbury

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

LANCASTER PARK STUDY

Dr. Mark Quigley
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Department of Geological Sciences, University of Canterbury

With assistance in map production from

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Tonkin & Taylor Ltd – Canterbury Earthquake Recovery Project Office
15 Barry Hogan Place, Addington, Christchurch 8011, New Zealand

University of Canterbury Consultancy Report CN4600001360

25 November 2015

EXECUTIVE SUMMARY

The 2010-2011 Canterbury earthquake sequence (CES) in New Zealand's South Island caused extensive and recurrent damage to land and infrastructure within the Central Business District (CBD) of Christchurch. In this report we consider the effects of the CES on ground deformations and building deformations at Lancaster Park in southeast Christchurch. We present geologic, geotechnical, geophysical and geomorphic data in the form of series of interpreted maps. We show cumulative vertical and horizontal land and building displacements at this site. We interpret Cone penetration tests (CPT), multichannel analysis of surface wave surveys (MASW), and geologic cross-sections. From our analyses we conclude that the severe land and building damage, including surface manifestations of liquefaction and horizontal and vertical land and building displacements, resulted from severe earthquake-induced strong ground motions superimposed on a geologically complex site with spatial variations in the location, geometry, and liquefaction susceptibility of Holocene sediments. More specifically, we draw the following conclusions from the data presented herein:

- sediments underlying the study site exhibit apparent southward sloping liquefiable layers and apparent southward decreases in penetration resistance and increases in liquefaction vulnerability beneath the central and southern parts of the eastern Deans Stand relative to the northern part,
- a higher velocity sedimentary body interpreted as a dense sand paleochannel is located beneath northern part of the Deans stand and is not present beneath central and southern part of Deans stand
- there is an increased thickness of low velocity layer(s) beneath the central Deans stand, and apparent southward dip of low velocity sediments,
- repeat land surveys and differential lidar analysis indicates that total and differential settlement of the central part of the Deans Stand is > southern part is > northern part,
- The horizontal land displacement field derived from measurements of cumulative horizontal displacements with tectonic displacements subtracted shows S to SE-directed displacements towards areas of higher liquefaction potential, increased thickness of liquefiable material, and downslope within liquefiable sediments; in many cases displacement vectors do not correlate with surface slope, topography, geomorphology, or historic waterway features.
- Areas with most abundant identified surface manifestations of liquefaction (e.g., sand blows and fissures) generally coincide with areas with largest cumulative vertical subsidence, largest differential horizontal displacements (i.e. horizontal stretching strains), increased abundance of highly susceptible sediments, and possibly the proximal presence of shallow historical channels. Localized patterns of liquefaction surface manifestation are influenced by the stadium and related structures; liquefaction ejecta is most prominent around the edges of the stands.
- We conclude that total and differential land and building deformation is largely attributable to strong earthquake shaking in the Mw 6.2 Feb 22, 2011 and Mw 6.0 June 13 earthquakes and associated liquefaction at depths from 1-10 m and deeper, superimposed on variations in sediment type relating to lateral facies changes and geologic evolution of the sedimentary system. This implies a cause-and-effect between seismic loading during the largest Canterbury earthquakes and observed building deformation. We do not explicitly consider

possible post-construction loading effects in this report; this is the focus of related studies conducted by different authors.

1. SCOPE

The University of Canterbury (Dr. Mark Quigley) was commissioned by Christchurch City Council to (1) Produce detailed geologic, geomorphic, and geotechnical site maps for Council key assets, and (2) Produce earthquake-induced horizontal and vertical displacement maps for ground surface surrounding CCC key assets.

The seven key asset sites to be considered in this suite of reports are listed in **Error! Reference source not found.**, 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

This work required the attainment and reproduction of a suite of previously produced maps (Geology Maps, Black Maps, DEMs), reinterpretation of a variety of datasets (CPT data, boreholes, auger data, differential LiDAR data, survey data), and production of a new suite of annotated maps and cross-sections for the CCC key assets.

The purpose of these studies was to (1) document geologic setting of council assets, document heterogeneity of surface and near-surface materials with variable engineering properties, and (2) document 2010-2011 earthquake-induced land elevation and position changes at CCC asset sites to document severity of ground deformation and document geologic/geotechnical controls on ground deformation. The primary purpose of these reports is to synthesize geologic, geomorphic, geotechnical, and geophysical data into a unified model that best explains the patterns and origin of land and building deformation in the 2010-2011 Canterbury earthquake sequence.

The focus of this report is LANCASTER PARK (AMI STADIUM).

2. LOCATION AND PRIOR WORK

Lancaster Park (aka AMI Stadium) is located in Waltham, Christchurch (Fig. 1). The central lat-long of the site is -43.542031, 172.654145. Details of the geotechnical ground conditions and performance of the different stands during the Canterbury earthquake sequence are provided in "AMI Geotechnical Report" T&T Ref # 51845.

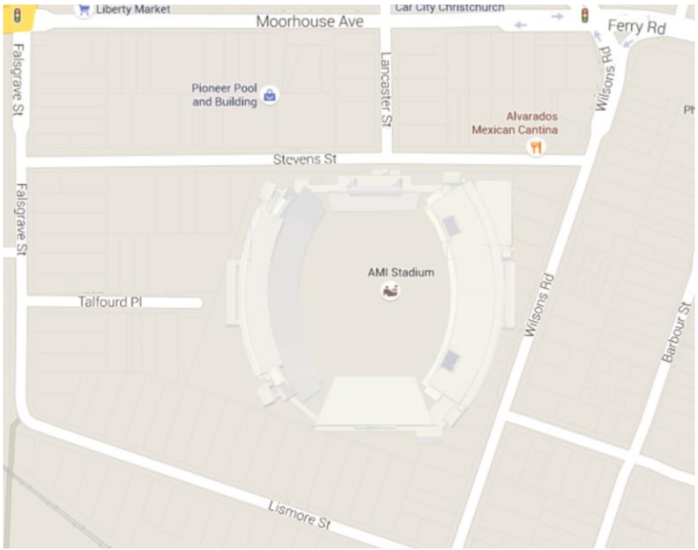

Figure 1. Location of Lancaster Park (AMI Stadium) shown on Google Maps.

Following the 22 February 2011 Mw 6.2 Christchurch earthquake, VBase engaged Tonkin & Taylor (T&T) to undertake a geotechnical assessment of foundation performance for each of the 4 stands (Deans, Paul Kelly, Tui, and Hadlee). T&T conducted mapping (Fig. 2), CPT investigations (Fig. 3), and surveying (Fig. 4) as part of this analysis. We turn readers to the report entitled "AMI Geotechnical Report" T&T Ref # 51845 (see References) for further detail.

Horizontal and vertical displacement data were derived using differential lidar and airphoto interpretations throughout the Canterbury earthquake sequence (Fig. 5,6) and plotted on digital elevation model underlays. From these data, the tectonic component of displacement was removed (using tectonic displacements inferred geodetic seismic source models presented in Beavan et al., 2012), with the residual displacements interpreted to reflect shaking-induced permanent ground displacements relating to liquefaction and ground failure. See "Evaluation of Building Settlements during the Canterbury Earthquake Sequence using LiDAR" (T&T Ref # 53841) (see References) for further detail on how horizontal and vertical land displacements were obtained from differential LiDAR. The source of horizontal displacement data shown here is the Canterbury Geotechnical Database.

Individual horizontal displacement measurements reported in the displacement maps have an error range of ± 200 mm that corresponds to the lidar pixel resolution. The relatively large error compared to individual displacements requires that displacements be used only to provide a general picture of progressive land deformation through the Canterbury earthquake sequence and that individual measurements are not over-interpreted. However, added confidence to the cited displacements is found in the general agreement between cumulative displacements inferred from differential lidar and (i) cumulative displacements of LINZ benchmarks (Deam, 2015), and (ii) cumulative displacements from field measurements (Hughes et al., 2015). For these reasons, we use our horizontal displacement maps to make general conclusions regarding cumulative land deformation throughout the Canterbury earthquake sequence with an emphasis on relative horizontal land deformation variability on the m to 10s of metres scale, rather than emphasizing any individual measurement on the pixel scale. We do not use them to characterise strain on the scale of an individual building in this study; this could perhaps serve as a focus for further investigation however, particularly where individual measurements show large (e.g., >200-300 mm) variations in displacement across a building site.

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Ecological maps (pre-development vegetation and waterways) were produced by T&T for Christchurch area (Fig. 7) from historic "Black Maps".

A series of MASW surveys were conducted by T&T in the vicinity of the stadium (Fig. 8,9). By combining topographic data, borehole data, CPT data, and MASW data, T&T constructed a suite of geologic cross-sections in this area (Fig. 10). Please see Christchurch Central City Geologic Interpretative Report" (T&T Ref REP-CCC-INT) for details including location of geotechnical sampling sites, raw and interpreted data, complete cross-sections, and preliminary geologic interpretations.

The richness of data obtained from these prior investigations provides the basis for our integrated geologic and geomorphic models for the Lancaster Park site, and our interpretations of how seismic loading and geology influenced the patterns of deformation.

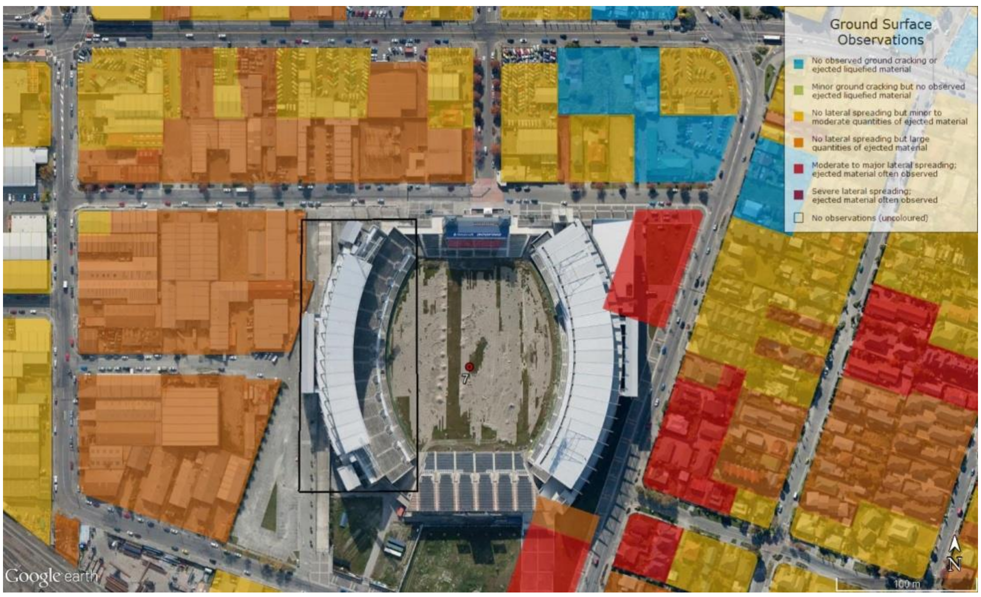


Figure 2: Area reconnaissance mapping of liquefaction and lateral spreading in the vicinity of Lancaster Park following the 22 Feb 2011 Christchurch Mw 6.2 earthquake (mapping by Tonkin and Taylor Ltd). More detailed mapping (this report) is presented in Fig. 11

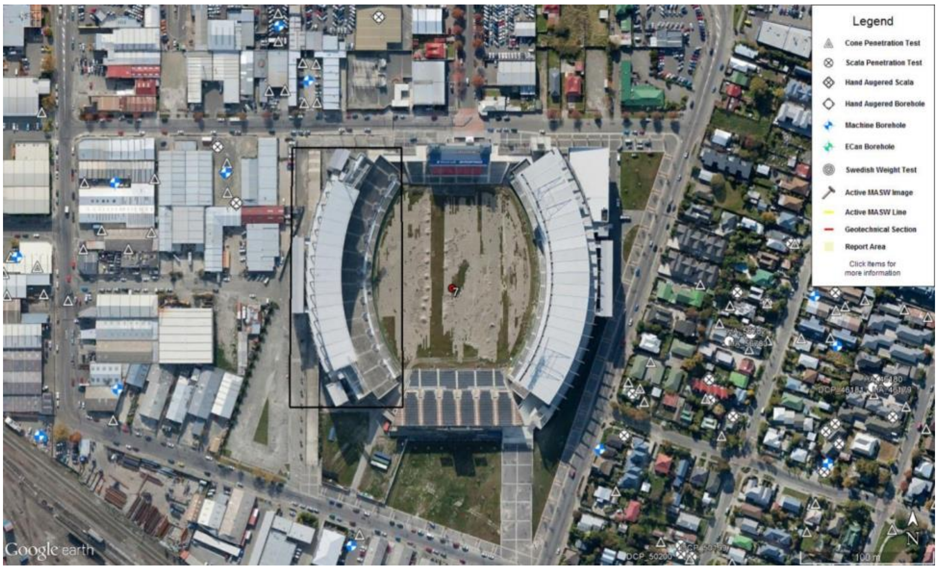


Figure 3: Location of CPT, borehole, and other geotechnical sampling sites in the vicinity of Lancaster Park. These data were variably used to construct geologic cross-sections (e.g., Fig. 10).

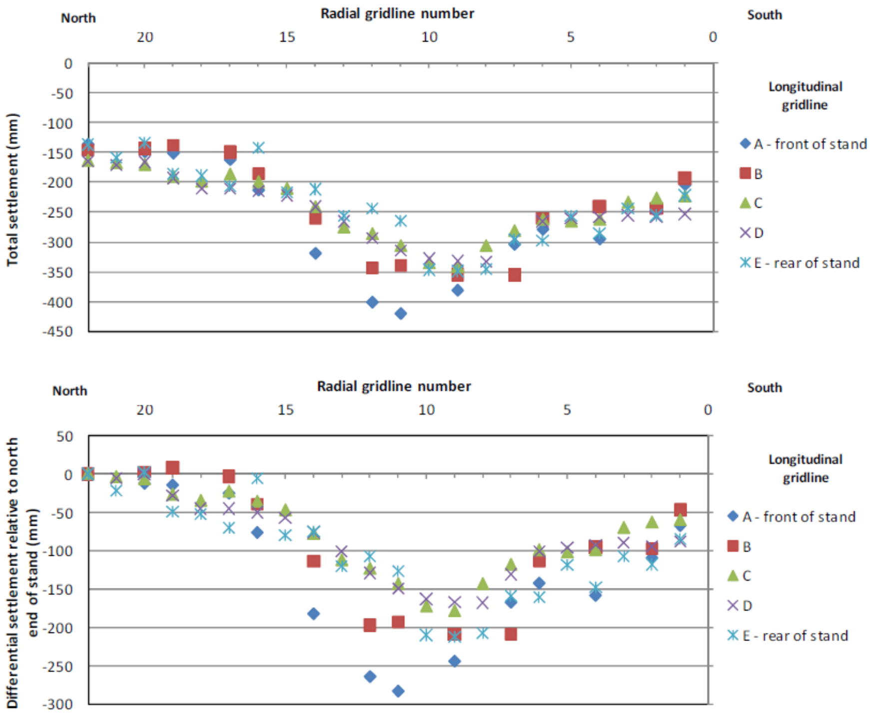


*Figure 4: An example of preliminary survey results, showing total and differential vertical movements of the roof of the Deans Stand following the 22 February 2011 Mw 6.2 Christchurch earthquake (*T&T Ref # 51845*). Readers are turned to* T&T Ref # 51845 *for additional survey results for other stands.*

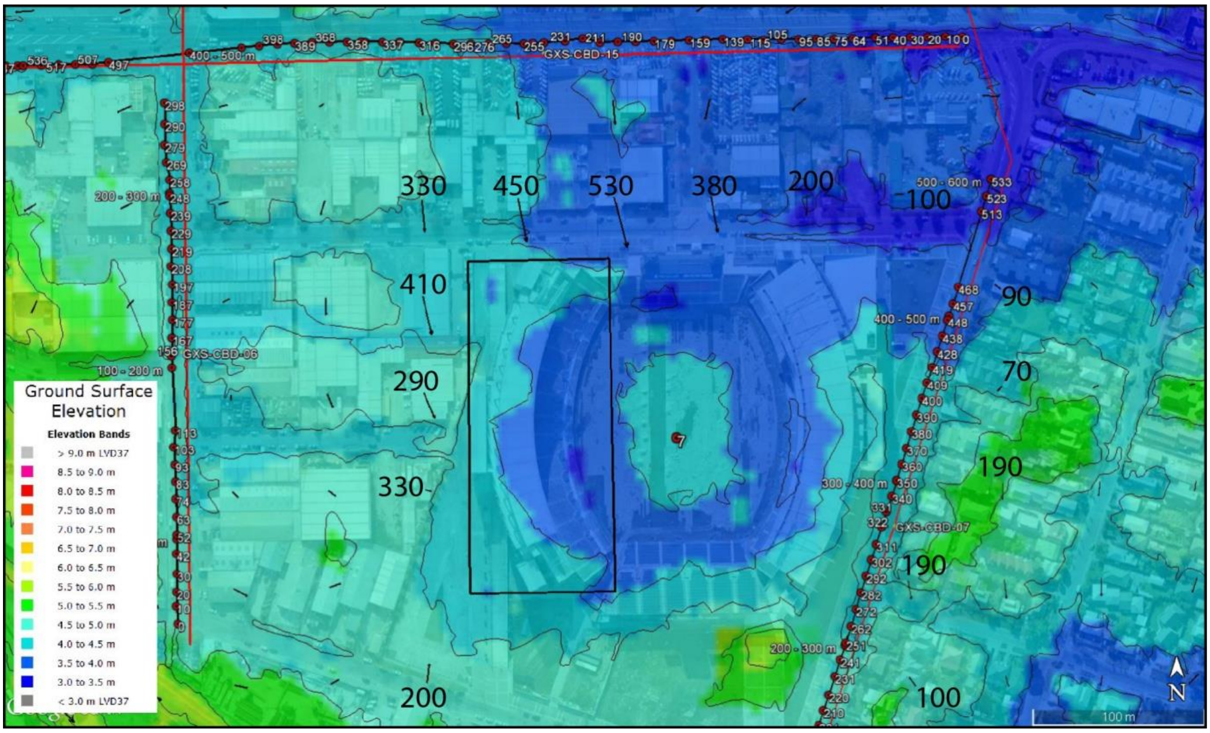


Figure 5: Horizontal permanent land displacements in mm with tectonic component removed for the Lancaster Park area, superimposed on DEM underlay. Location of MASW surveys and geologic cross-sections shown. Data source: Canterbury Geotechnical Database. Ground displacements are largest in areas that subsided the most and that are underlain by

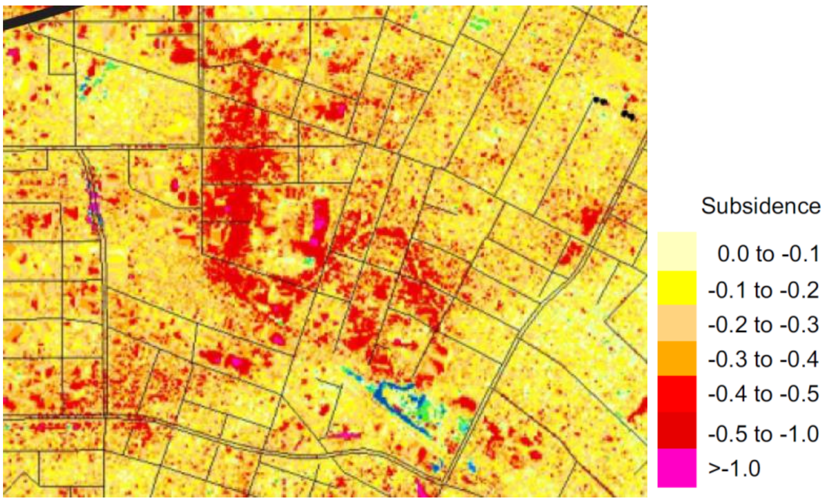


Figure 6: Permanent 'bare-earth' vertical land displacements from 2003 to December 2011 in metres for the Lancaster Park area. Image from Hughes et al. (2015). Note differential subsidence beneath Dean's Stand (largest vertical displacements beneath middle of stand) and largest vertical ground displacements in the area associated with

Figure X: Locations of LINZ/CCC benchmarks ETDM & ETDJ referenced further in text.

Figure 7: Paleo-ecology of the Lancaster Park site, showing position of former waterway (historic stream channel), Raupo (aka T. Orientalis, a wetland plant that grows on the edges of ponds, lakes and slow flowing rivers and streams), and grassland.

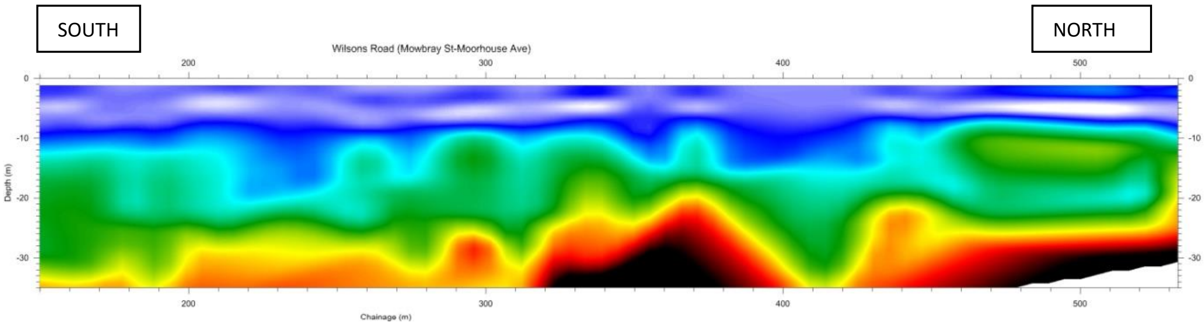


Figure 8: MASW survey for Wilsons Road, immediately east of Lancaster Park. See Fig. 5 for corresponding chainage.

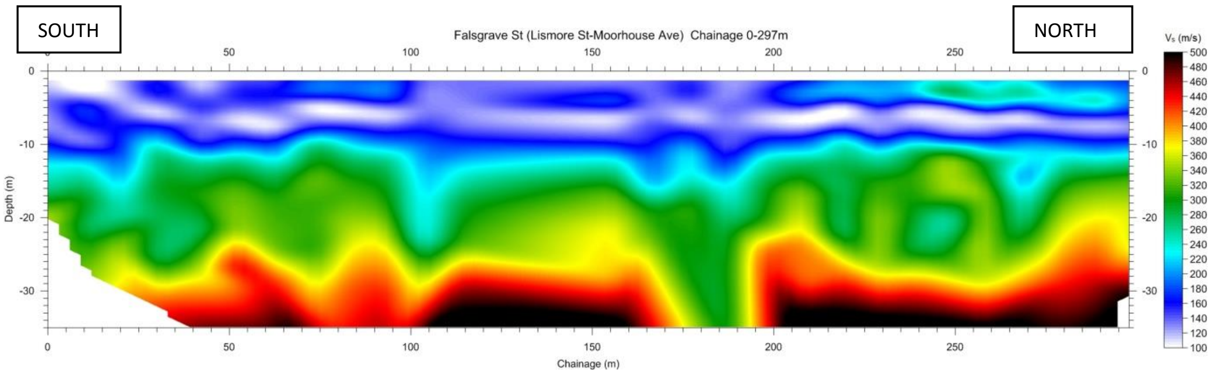


Figure 9: MASW survey for Falsgrave Street, immediately west of Lancaster Park. See Fig. 5 for corresponding chainage.

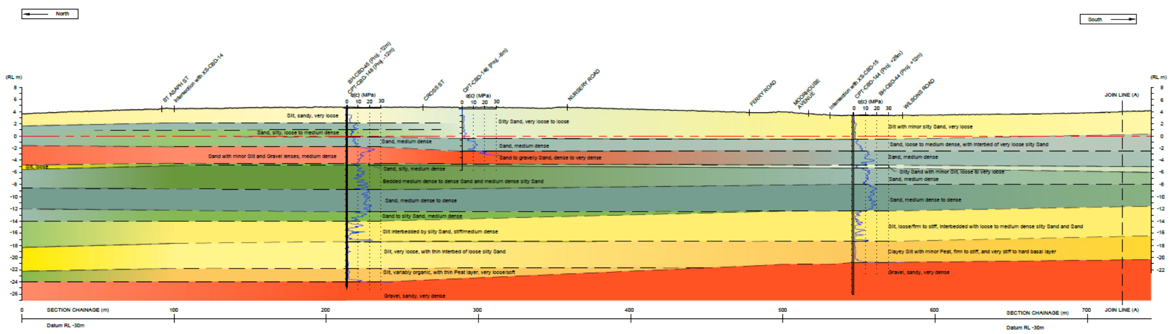


Figure 10: Example of geologic cross-section prepared for the Christchurch City by Tonkin and Taylor Ltd. All cross-sections are available in Appendix X.

3. THIS WORK

3.1. MAPPING OF LIQUEFACTION EJECTA

The first part of our analysis was to produce detailed maps of liquefaction surface ejecta (Fig. 11) using airphotos obtained immediately following the 22 February earthquake in order to better quantify the extent of liquefaction surface ejecta. Distributions of liquefaction were characterised as definite or inferred. Former (historic) stream channels were added to maps where present.

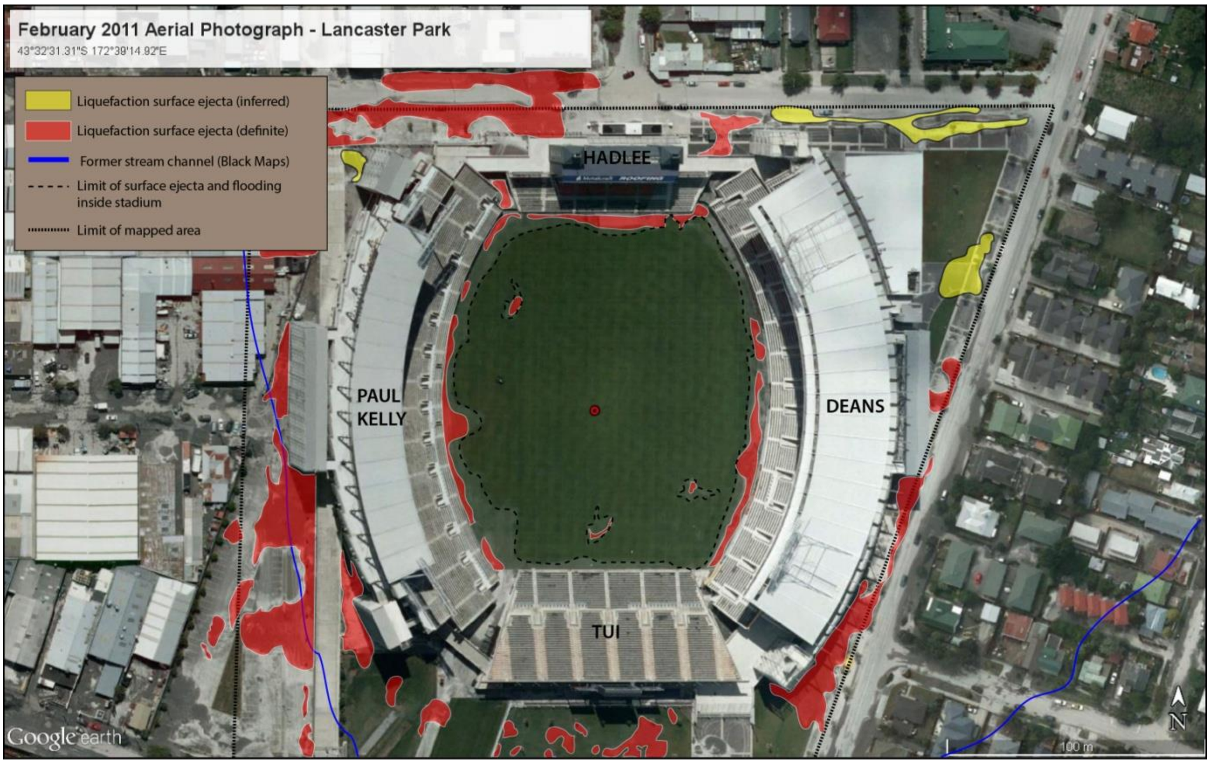


Figure 11: Map of liquefaction surface ejecta following the 22 February 2011 Mw 6.2 Christchurch earthquake. Note boundaries of detailed mapping; ejecta maps were limited to within 10s of metres of the stadium.

The map presented in Fig. 11 provides higher resolution and improved accuracy compared to previously published maps (Fig. 2), which were undertaken at the suburb-scale for general land-damage and liquefaction severity purposes. The following conclusions can be drawn from the mapping.

1. Surface manifestation of liquefaction is heavily concentrated around the edges of the stands, particularly on the interior of the stadium (ejecta primarily limited to within 10-20 m of edge of stand). In the Dean's Stand, the largest density of surface ejecta appears to concentrate in the central and southern portions of the stand. Surface ejecta volumes do not appear to systematically vary from north to south along the Kelly Stand.
2. In general, surface liquefaction features cover a larger area on the western side of the stadium and in the southeast corner of the stadium compared to the northeastern side of the stadium. This pattern of liquefaction is distinct from that presented in earlier maps (Fig. 2).

A comparison of liquefaction ejecta distributions with land and building damage is presented in Section 3.3.

3.2. COMPARISON OF VERTICAL DISPLACEMENTS WITH TOPOGRAPHY, GEOMORPHOLOGY, GEOLOGY, AND GEOTECHNICAL DATA

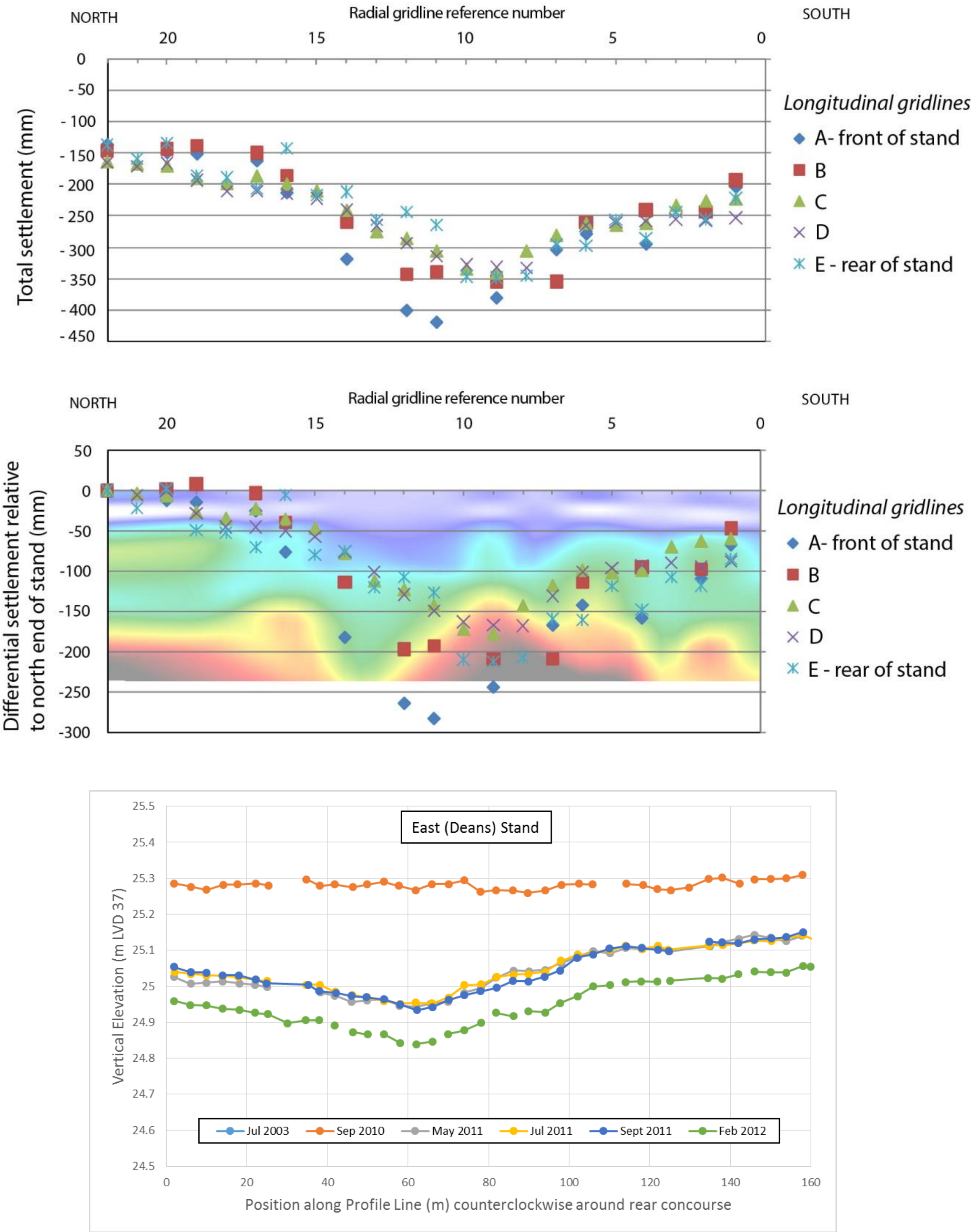


Figure 12: Summary of survey data obtained by T&T and comparison with LiDAR survey data

Movement	Time Period	East	North	Uplift
At ETDK	Entire CES	0.29	0.05	-0.27
At ETDJ	Entire CES	0.33	0.13	-0.58
At ETDM	Entire CES	0.15	0.10	-0.32
At AF36	Entire CES	0.19	-0.04	N/A

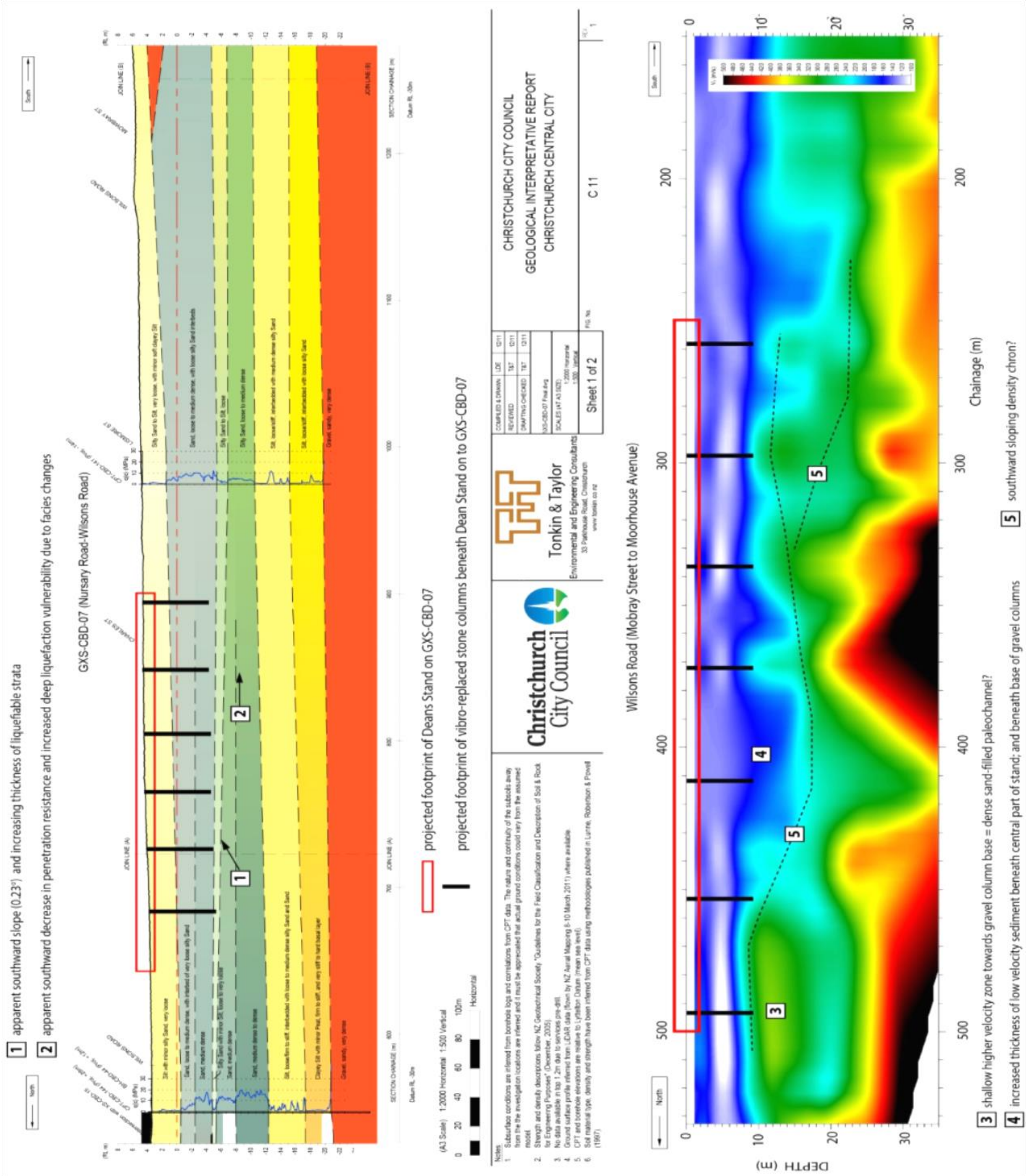
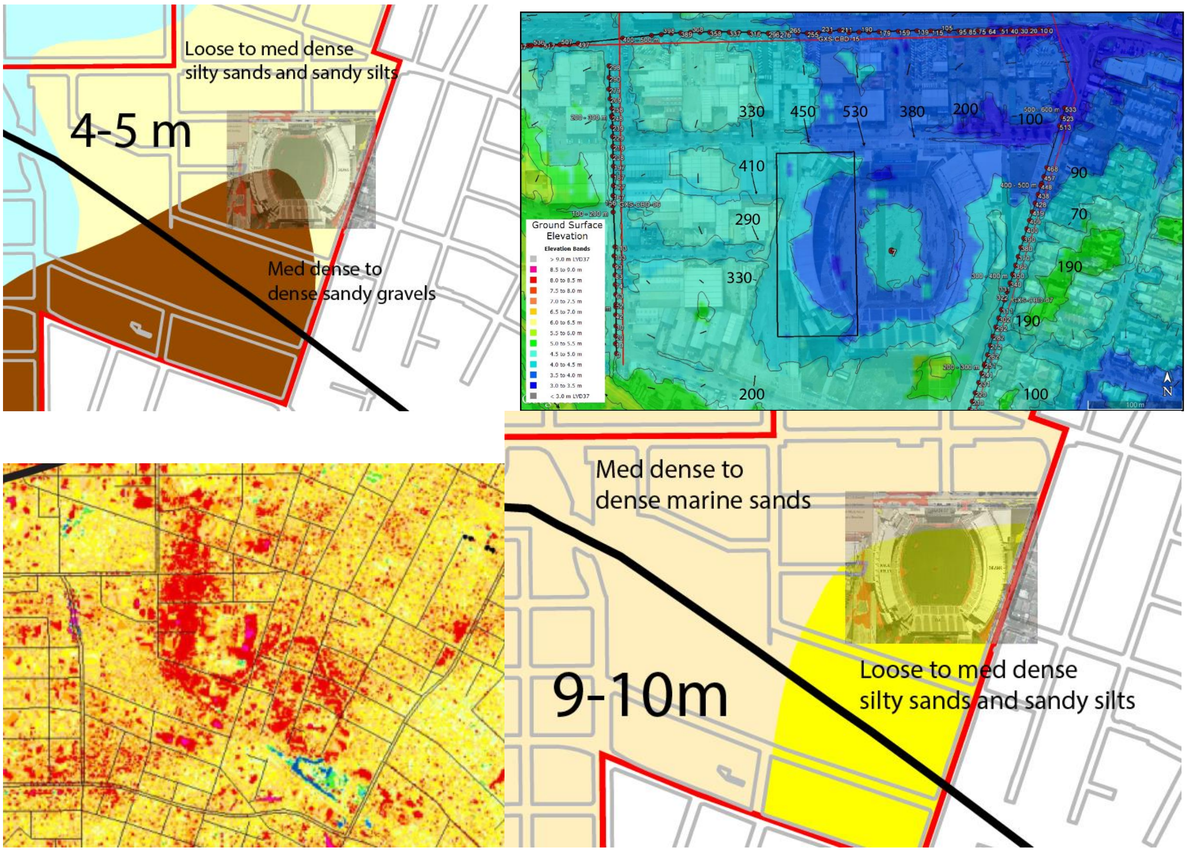


Figure 13: Geologic cross-section, CPT data, and MASW cross-section showing subsurface geology projected from survey lines to beneath the Deans Stand. See text for discussion of survey results and geologic interpretations.



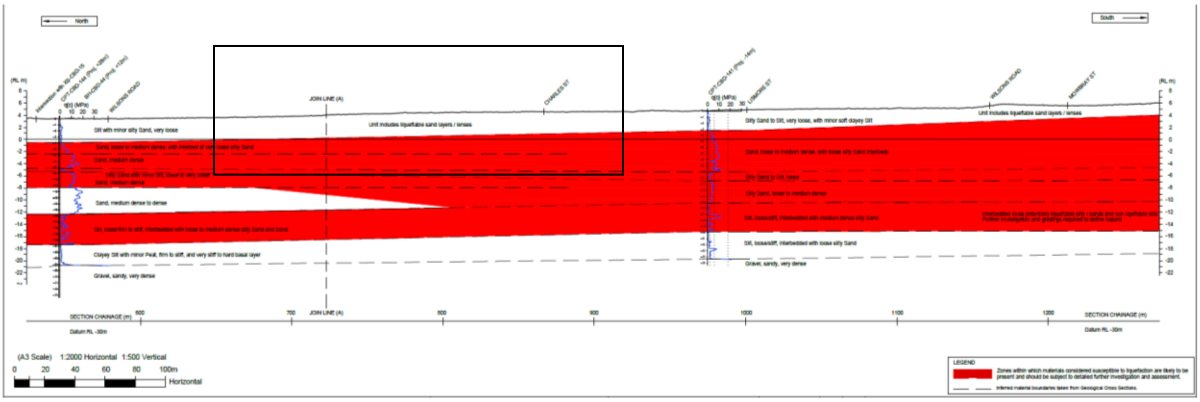


Figure 14: Projected footprint of Deans Stand on to LHXS-CBD-07. Cross-section showing zones susceptible to liquefaction (RED) from T&T Ref # 51845. *Note southward thickening of liquefaction-susceptible zones and southward slope of top-of-dense-sand layer beneath northern part of Dean's Stand; corresponding with southward increasing surface manifestations of liquefaction and increased differential subsidence.*

3.3. UNIFIED SYNTHESIS OF LANCASTER PARK DATA AND MODEL FOR GEOLOGIC CONTROLS ON BUILDING PERFORMANCE IN THE 2010-2011 CANTERBURY EARTHQUAKES

Horizontal ground displacements and density of observed liquefaction ejecta during the Canterbury earthquake sequence in the area surrounding Lancaster Park are largest in areas underlain by shallow (i.e., 0-8 m) sediments with higher susceptibility to liquefaction.

Largest horizontal ground displacements tend to occur in areas with largest cumulative vertical subsidence. General (area-wide) lateral displacements trend towards the South. We attribute this to general southward increases in liquefaction susceptibility and decreases in sediment shear wave velocity integrated over depths to 10-20 m due to sedimentary facies changes, and gently south-sloping liquefiable sediments that facilitate southward ground displacement.

There is evidence that the local surface displacement field around the western part of Lancaster Park is affected by the Paul Kelly Stand. Lateral displacements trend towards the stand on the northern, western, and southern flanks. Variations in lateral displacements on the 10s of m scale are thus likely to reflect variations in surface loading due to the stadium weight above liquefiable strata superimposed on an overall displacement field driven by sediment facies changes and subsurface sedimentary geometries.

I consider the relative vertical displacements observed for the Deans Stand following the 22 February Mw 6.2 Christchurch earthquake to relate primarily to lateral changes in the liquefaction susceptibility and shear wave velocity of sediments beneath the penetration depth (~10 m) of supporting engineered gravel columns beneath the stand. Projection of the stand and columns onto a proximal MASW profile shows this relationship. The northern part of the stand is supported by a body of dense sand at depths of ~9-16 m with comparably high shear wave velocity. Lower velocity sediments are found at the equivalent depths beneath the central (and to a lesser extent the southern) parts of the stand. Further evidence for the increase in vertical displacement towards the central and southern parts of the stand is found in the planar geologic maps, which show an increase in liquefaction susceptibility for sediments beneath the central and southern parts of the Dean's Stand at depths of ~9 to 15 m. This is also portrayed in the liquefaction hazard cross-section. Absolute vertical elevation changes are the focus of an additional report.

5. REFERENCES

Beavan, J., Motagh, M., Fielding, E. J., Donnelly, N., & Collett, D. (2012a) Fault slip models of the 2010–2011 Canterbury, New Zealand, earthquakes from geodetic data and observations of postseismic ground deformation. New Zealand Journal of Geology and Geophysics. Accessed 19 Feb 2015 at http://www.tandfonline.com/doi/suppl/10.1080/00288306.2012.697472

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6. BRIEF GLOSSARY

"Historical channels" – former, historical stream channels in Christchurch that were infilled during urban development

"LiDAR" – Light Detection And Ranging; in this report used to refer to laser scanning data obtained through airborne laser scanning

"Tectonic displacements" – permanent land movements attributed to deep faulting movement of crustal rock and overlying sediments and surface during earthquakes. Distinct from liquefaction-induced displacements, which relate to near-surface liquefaction phenomena.

"Sedimentary facies" – in this report used to refer to lateral changes in the physical / lithologic characteristics of sedimentary units (e.g. grain size, fines content) that may influence the dynamic behaviour of the sediment.

7. APPLICABILITY

This report has been prepared for the benefit of Christchurch City Council with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.

Important Notice

Some of the maps and data presented herein were prepared and/or compiled for the Earthquake Commission (EQC) to assist in assessing insurance claims made under the Earthquake Commission Act 1993 and/or for the Canterbury Geotechnical Database on behalf of the Canterbury Earthquake Recovery Authority (CERA). It was not intended for any other purpose. EQC, CERA, their data suppliers and their engineers, Tonkin & Taylor, have no liability to any user of this map and data or for the consequences of any person relying on them in any way. Each Canterbury Geotechnical Database (https://canterburygeotechnicaldatabase.projectorbit.com/) map and data is made available solely on the basis that:

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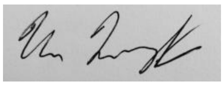

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GEOLOGIC, GEOMORPHIC, GEOTECHNICAL, AND DISPLACEMENT MAPS OF LAND AND BUILDINGS AT SELECTED SITES OF CHRISTCHURCH CITY COUNCIL OWNED REINFORCED CONCRETE STRUCTURES DAMAGED DURING THE 2010-2011 CANTERBURY EARTHQUAKES

CHRISTCHURCH SOUTH LIBRARY STUDY

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Associate Professor of Active Tectonics and Geomorphology
School of Earth Sciences at the University of Melbourne, and
Department of Geological Sciences, University of Canterbury

With assistance in map production from

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University of Canterbury Consultancy Report CN4600001360

25 November 2015

EXECUTIVE SUMMARY

The 2010-2011 Canterbury earthquake sequence (CES) in New Zealand’s South Island caused extensive and recurrent damage to land and infrastructure within the Central Business District (CBD) of Christchurch. In this report we consider the effects of the CES on ground deformations and building deformations at the Christchurch South Library in southern Christchurch. We present geologic, geotechnical, geophysical and geomorphic data in the form of series of interpreted maps. We draw the following conclusions from the data presented herein: (1) the surface manifestation of liquefaction ejecta during the 22 February Mw 6.2 Christchurch earthquake occurred < 10 metres northwest of the northwest corner of the Christchurch South Library and was associated with lateral-spreading induced extensional failure of the cap sediments overlying the liquefiable layer and transport of the cap layer towards the Heathcote River, and (2) the distribution of surface ejecta correlates well with the vertical land displacements in the vicinity of the Christchurch South Library, implying cause and effect between earthquake-induced loading and observed ground failure.

1. SCOPE

The University of Canterbury (Dr. Mark Quigley) was commissioned by Christchurch City Council to (1) Produce detailed geologic, geomorphic, and geotechnical site maps for Council key assets, and (2) Produce earthquake-induced horizontal and vertical displacement maps for ground surface surrounding CCC key assets. The purpose of this project was to develop a geologic and geotechnical model for explaining the observed deformation field of land and buildings throughout the Canterbury earthquake sequence.

The seven key asset sites to be considered in this suite of reports 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

This study required the attainment and reproduction of a suite of previously produced maps (Geology Maps, Black Maps, DEMs), reinterpretation of a variety of datasets (CPT data, boreholes, auger data, differential LiDAR data, survey data), and production of a new suite of annotated maps and cross-sections for the CCC key assets.

The purpose of these studies was to (1) document geologic setting of council assets, document heterogeneity of surface and near-surface materials with variable engineering properties, and (2) document 2010-2011 earthquake-induced land elevation and position changes at CCC asset sites to document severity of ground deformation and document geologic/geotechnical controls on ground deformation. The primary purpose of these reports is to synthesize geologic, geomorphic, geotechnical, and geophysical data into a unified model that best explains the patterns and origin of land and building deformation in the 2010-2011 Canterbury earthquake sequence.

The focus of this report is CHRISTCHURCH SOUTH LIBRARY.

2. LOCATION AND PRIOR WORK

Christchurch South Library is located in Cashmere, Christchurch (Fig. 1). The central lat-long of the site is -43.561394, 172.63805.

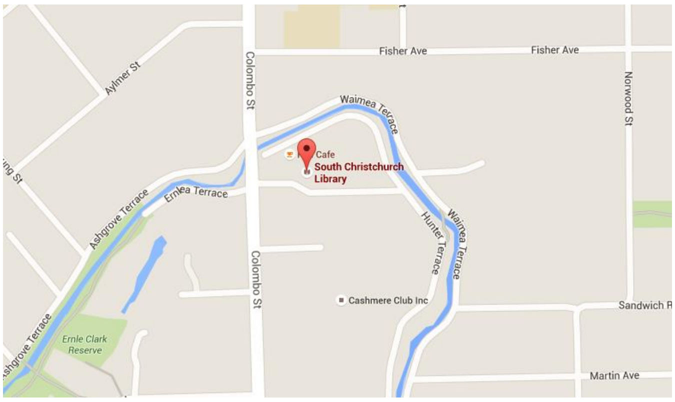

Figure 1. Location of Christchurch South Library shown on Google Maps.

T&T conducted mapping (Fig. 2), and CPT investigations (Fig. 3) in close proximity to these sites.

Horizontal and vertical displacement data was derived using differential lidar and airphoto interpretations throughout the Canterbury earthquake sequence (Fig. 4,5) and plotted on digital elevation model underlays. From these data, the tectonic component of displacement was removed (using tectonic displacements inferred geodetic seismic source models presented in Beavan et al., 2012), with the residual displacements interpreted to reflect shaking-induced permanent ground displacements relating to liquefaction and ground failure. See "Evaluation of Building Settlements during the Canterbury Earthquake Sequence using LiDAR" (T&T Ref # 53841) (see References) for further detail on how horizontal and vertical land displacements were obtained from differential LiDAR.

Individual horizontal displacement measurements reported in the displacement maps have an error range of ± 200 mm that corresponds to the lidar pixel resolution. The relatively large error compared to individual displacements requires that displacements be used only to provide a general picture of progressive land deformation through the Canterbury earthquake sequence and that individual measurements are not over-interpreted. However, added confidence to the cited displacements is found in the general agreement between cumulative displacements inferred from differential lidar and (i) cumulative displacements of LINZ benchmarks (Deam, 2015), and (ii) cumulative displacements from field measurements (Hughes et al., 2015). For these reasons, we use our horizontal displacement maps to make general conclusions regarding cumulative land deformation throughout the Canterbury earthquake sequence with an emphasis on relative horizontal land deformation variability on the m to 10s of metres scale, rather than emphasizing any individual measurement on the pixel scale. We do not use them to characterise strain on the scale of an individual building in this study; this could perhaps serve as a focus for further investigation however, particularly where individual measurements show large (e.g., >200-300 mm) variations in displacement across a building site.

The vertical displacement measurements reported in cumulative differential lidar displacement maps likely have an error of ± 300 mm. Errors accumulate due to varying quality of lidar data acquired (2003 vs 2011) and apparent 'tilt effects' corresponding to swath edges in the data. The reliability of these data for many individual locations (Hughes et al., 2015) is confirmed by field observations (Quigley et al., 2013; Hughes et al., 2015) and LINZ benchmarks (Deam, 2015). We thus use the differential lidar vertical displacement maps to make general conclusions regarding cumulative vertical land deformation throughout the Canterbury earthquake sequence with an emphasis on relative vertical land deformation variability on the m to 10s of metres scale, rather than emphasizing any individual measurement on the pixel scale.

Ecological maps (pre-development vegetation and waterways) were reproduced by T&T for Christchurch area (Fig. 6) from historic "Black Maps".

Initial mapped liquefaction distributions (Fig. 2) do not cover the site of interest in detail. However, in general, liquefaction severity appears highest in this map in areas most proximal to (i.e. within 50 m) the Heathcote River. The Christchurch South Library is proximal to the river.

Mapped horizontal displacements (Fig. 4) tend to show west to northwest directed movement. Displacements tend to be highest in low elevation areas close to the Heathcote River, consistent with increased density of liquefaction ejecta. The correlation with topography in the southern part of the map area suggests that the lateral displacement field is driven by a shallow mechanism; liquefaction-induced lateral spreading is the most feasible mechanism for this. The absence of 3-d cross-sectional data for this area precludes interpretation of spreading data in the context of subsurface variations in the distribution of liquefiable strata. Horizontal displacements in the Christchurch South Library are ~160-170 mm north towards the Heathcote River. This is consistent with predicted lateral spreading towards the nearest free-face.

The permanent vertical land displacement field (Fig. 5) is challenging to interpret in the vicinity of the Christchurch South Library. We expect that a component of the vertical displacements (uplift > 1m on eastern end and >0.1m on southern end) probably relates to pre-earthquake construction activities in 2003 during building completion around the periphery of the building. We attribute the subsidence to the northwest corner of the building to liquefaction-induced land subsidence and lateral spreading because it overlaps well with the location of mapped surface ejecta (Fig. 7). Other areas of maximum subsidence in the southwest corner of the map area overlap with the edges of paleochannels (terrace risers) and areas where we consider extensional strains to be largest, providing further evidence for the relationship between ground subsidence and liquefaction during the CES in this location.

The paleo-ecology map simply shows the Heathcote River was proximal to the Christchurch South Library site in the past, as it is currently.

Figure 2: Area reconnaissance mapping of liquefaction and lateral spreading in the vicinity of Christchurch South Library following the 22 Feb 2011 Christchurch Mw 6.2 earthquake (mapping by Tonkin and Taylor Ltd). More detailed mapping (this report) is presented in Fig. 11

Figure 3: Location of CPT, borehole, and other geotechnical sampling sites in the vicinity of Christchurch South Library.

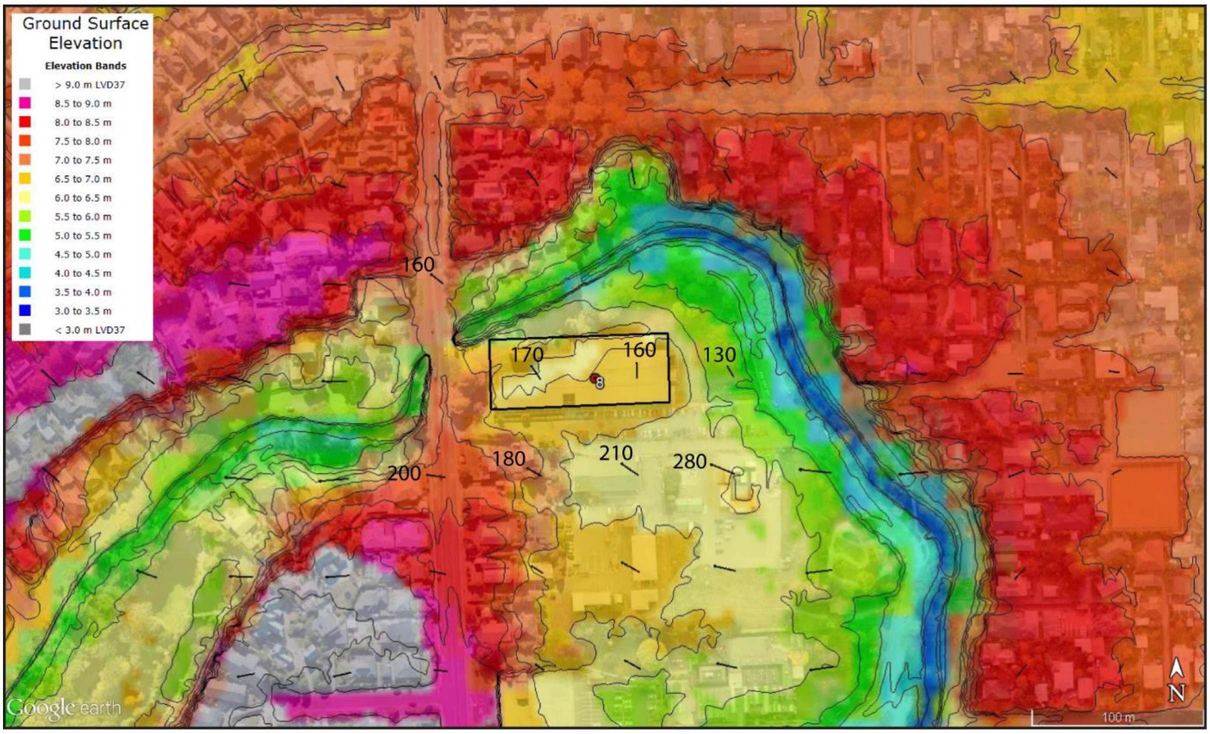

Figure 4: Cumulative horizontal permanent land displacements in mm with tectonic component removed for the South City Library area, superimposed on DEM underlay. Location of MASW surveys and geologic cross-sections shown

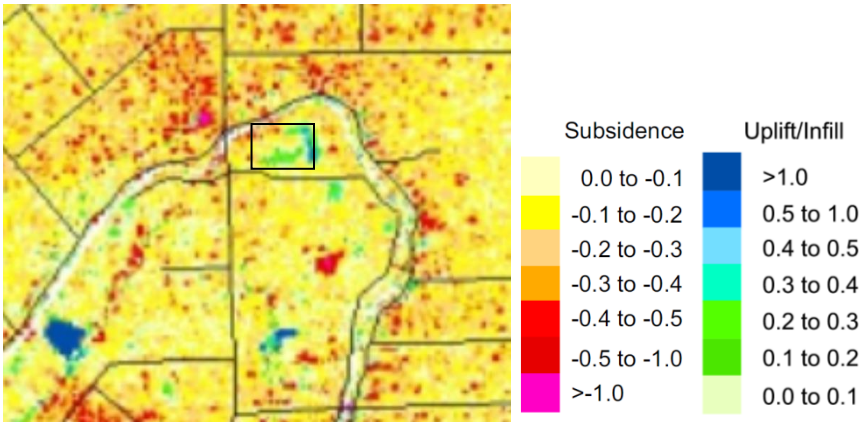

Figure 5: Permanent vertical land displacements from 2003 to December 2011 in metres for the Christchurch South Library area. Image from Hughes et al. (2015)

Figure 6: Paleo-ecology of the Christchurch South Library site.

3. THIS WORK

3.1. MAPPING OF LIQUEFACTION EJECTA

The new map of liquefaction surface ejecta using airphotos obtained immediately following the 22 February earthquake is presented in Fig. 7 in order to better quantify the extent of liquefaction surface ejecta. Distributions of liquefaction were characterised as definite or inferred.

Figure 7: Map of liquefaction surface ejecta in the Christchurch South Library area following the 22 February 2011 Mw 6.2 Christchurch earthquake.

The map presented in Fig. 7 provides higher resolution and improved accuracy compared to previously published maps (Fig. 2), which were undertaken at the suburb-scale for general land-damage and liquefaction severity purposes. The following conclusions can be drawn from the mapping.

1. Surface manifestation of liquefaction is heavily concentrated around southern bank of the Heathcote River with a linear array that is parallel to the river channel. This implies liquefied material was ejected through the surface via lateral spreading cracks resulting from extensional land failure towards the river channel. Isolated small pockets of surface ejecta are also inferred from mapping to have formed to the southeast of the library. This implies that liquefaction at the study site was controlled by local topography and geomorphology.
2. The liquefaction ejecta distributions to the northwest side of the library similarly correspond with increased vertical subsidence (~0.3-0.5 m) at that location.

We note also that cumulative lateral spreading vectors (Fig. 4) show local variations in orientation and displacement superimposed on an overall north to northeast trend of displacement. We argue that this regional displacement results from liquefaction-induced lateral displacements towards a Holocene embayment north of the study site (Fig. 8). Observed ground displacements at the study site thus show regional and site-specific components, consistent with widespread ground failure induced by the 2010-2011 Canterbury earthquakes.

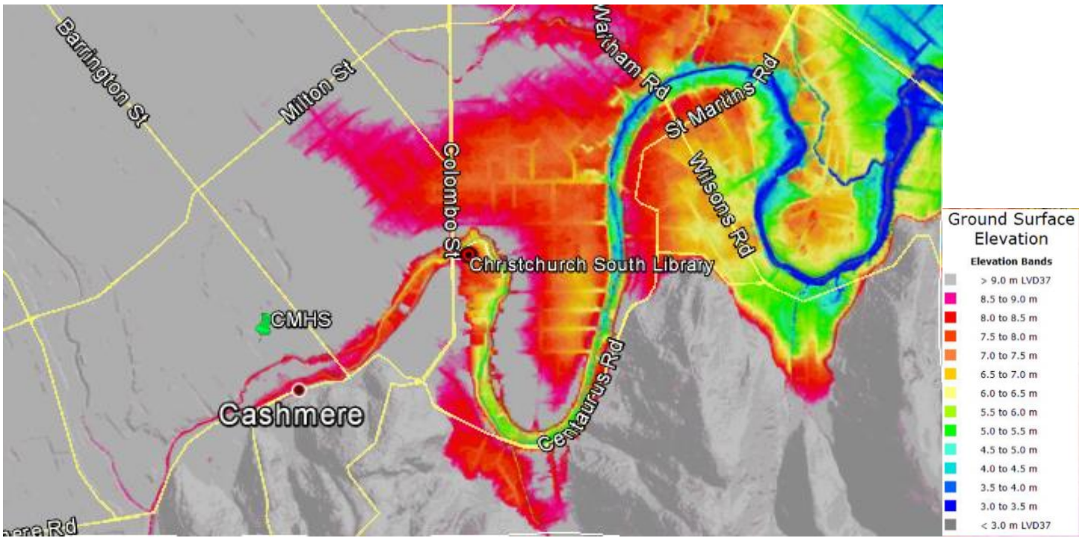

Figure 8: Regional DEM for the study site.

4. CONCLUSIONS

Differential lidar analysis (Deam, 2015) shows negligible vertical deformation of the roof of the Christchurch South Library through the CES. However, the vertical and horizontal displacements of the land surrounding the Christchurch South Library are consistent with liquefaction-induced lateral spreading. The surface manifestation of liquefaction ejecta during the 22 February Mw 6.2 Christchurch earthquake occurred < 10 metres northwest of the northwest corner of the Christchurch South Library and was associated with lateral-spreading induced extensional failure of the cap sediments overlying the liquefiable layer and transport of the cap layer towards the Heathcote River. The distribution of surface ejecta correlates well with the vertical land displacements in the vicinity of the Christchurch South Library, implying cause and effect between earthquake-induced loading and ground failure.

5. REFERENCES

Beavan, J., Motagh, M., Fielding, E. J., Donnelly, N., & Collett, D. (2012a) Fault slip models of the 2010–2011 Canterbury, New Zealand, earthquakes from geodetic data and observations of postseismic ground deformation. New Zealand Journal of Geology and Geophysics. Accessed 19 Feb 2015 at http://www.tandfonline.com/doi/suppl/10.1080/00288306.2012.697472

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This report has been prepared for the benefit of Christchurch City Council with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.

Important Notice

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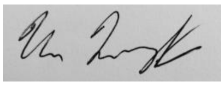

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