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Geotechnical reconnaissance of the damage triggered by liquefaction of the Christchurch Formation following the February 2011 earthquake

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ABSTRACT

Following the 22 February 2011 earthquake (Christchurch earthquake), large scales of liquefaction-induced damage occurred to the foundations of residential dwellings and lightweight structures in east Christchurch where the foundations were founded on loose to medium dense sands of Christchurch Formation. In these areas, major foundation repair or complete replacements were deemed necessary where the sand was not dense (Dr ≤ 65%). The authors reviewed the geological history of the area, the available site investigation information, as well as the information available on Canterbury Geotechnical Database (CGD). Further, they reviewed the patterns of the foundation failures for several houses founded on this geologic formation. It was found that the human activity applied to the upper layers of the native sand formation coupled with the depositional environmental factors contributed to the liquefaction-induced damage across east Christchurch. Using the available data, the authors also analysed the liquefaction-induced damage which may occur in a future event whether or not a dense non-liquefiable crust above the liquefiable soil was placed so as to prevent foundation failure.

Keywords: Christchurch Formation, liquefaction, lateral spreading

1 INTRODUCTION

The Christchurch earthquake (Mw 6.3) was the strongest seismic event in a series of damaging aftershocks in and around Christchurch after the Darfield earthquake on 4th of September in 2010. The Christchurch earthquake was generated on a fault in close proximity to the city, causing widespread damage, in the form of shaking and liquefaction-induced damage, as well as rockfall and cliff collapse on the Port Hills, Banks Peninsula. The earthquake occurred due to a reverse thrusting to the Port Hills fault. GNS Science data indicates that Christchurch and its greater area are still within a period of heightened seismic activity.

Following the Christchurch earthquake, much geotechnical earthquake engineering research has been undertaken, with a particular focus on the damage mechanisms which occurred to the Christchurch Central Business District (CBD). This paper simply aims to *'fit the pieces of the puzzle together'* as it focusses on the damage caused by the Christchurch earthquake to the area of east Christchurch. More specifically, the suburbs north of the estuary and east of the Travis Wetland (i.e. New Brighton and North New Brighton) are the focus of this paper, as shown in Figure 1.

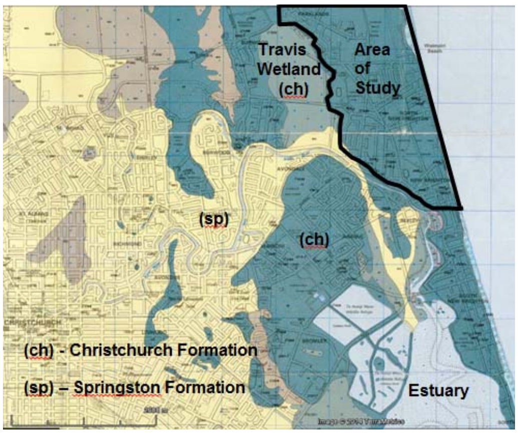

Figure 1. Geology of east Christchurch (Brown & Weeber, 1992)

2 GEOLOGY AND GROUND CONDITIONS

2.1 Soil profile and properties

As per Brown & Weeber's (1992) geological model of the Christchurch urban area, the Christchurch Formation comprises *"beach, estuarine, lagoonal, dune, and coastal swamp deposits of gravel, sand, silt, clay, shell and peat"*. The map indicates the surficial geology of the study area mostly consists of *"Sand of fixed and semi-fixed dunes and beaches"* of the Christchurch Formation. Several site investigations available on the CGD, and undertaken by New Zealand's Earthquake Commission (EQC), Canterbury Earthquake Recovery Authority (CERA) and various consultancies, show that the sands of the Christchurch Formation are fine to medium grained. The geology of the Travis Wetland consists of *"sand, silt, and peat of drained lagoons and estuaries"*.

The surficial sediments of the Christchurch Formation have an average thickness of about 25m (Tasiopoulou et al, 2011). Although a single geological unit, it varies in density and strength. Following the earthquakes, Coffey have undertaken numerous piezocone penetration tests (CPTu) in the area of study. Figure 2 provides the range of the corrected cone resistance (15th percentile, median and 85th percentile), sleeve friction and pore pressure recorded across several (over fifty) of these CPTu tests down to 25m below ground level (bgl).

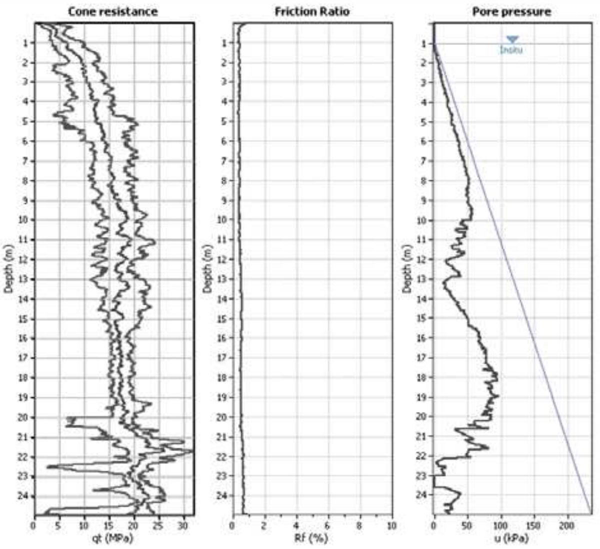

Figure 2. Mean normalised plots across area of study

It is important to highlight that, firstly, these plots are *averaged values.* The profile of an individual CPTu may vary with the pattern/s shown in these plots. Secondly, these plots are representative of the current in-situ conditions *after the earthquakes* and not prior.

2.2 Human factors influencing surface conditions

It is important to understand the history and the nature of man-made activity in the area, since loose, poorly compacted fill deposits most likely will experience greater deformations under seismic (cyclic) loading than native loose sands.

To get a better understanding of the historical timeline of the study area from the time of European settlement, the authors interviewed local Christchurch historian Laurence Eagle. We learned that although there are multiple records regarding the development of the CBD, the existing records (if any) relating to the development of east Christchurch are scarce. Even the oldest photos of schools, churches and streets (which were in neighbouring areas) do not reveal much information regarding the underlying geology or landform. The study area simply wasn't considered newsworthy at the time of early settlement. Most the remaining information regarding how that area developed is merely common knowledge among the elderly local residents who also acknowledge that inland dunes were once noticeable features, but have since been depleted. In accordance with Mr Eagle's comments, J.P. Morrison records the following; *"Where there were sand-dune ridges in Wainoni, Burwood, Linwood and Bromley, these areas were sparsely, if at all settled, even by 1903. Those on the way to New Brighton and smaller ridges now close to the central city area, for instance one at the north end* *of Linwood Avenue, can still be distinguished. The lagoon hollows behind the sand-dune ridges and between the shingle lobes have steadily filled with swamp vegetation and wind-blown sand, but when Captain Thomas first saw the site of Christchurch many of these depressions were still peat swamps".*

According to Brown & Weeber (1992);

- *"The exact location of the oldest and furthest inland dunes is difficult to define. This is because levelling of the terrain since European settlement has largely obliterated the original topographical features."* (pp.16)
- *"Surface deposits of the Christchurch Formation include fixed sand dune and young interdune swamp deposits (now largely reclaimed with fill)".* (pp.34)
- *"Early fills in particular were poorly supervised (if at all), and in many cases contain unsuitable foundation material because of the inhomogeneity and resulting in low strength".* (pp.62)

A survey of the Christchurch aerial maps from as early as 1941 suggests that when east Christchurch was eventually settled, it was initially an agricultural and sand dune area. Aeolian ripples in the sand dunes are noticeable features in the earlier aerial photographs, but as the area evolved to become a more residential area, the dunes more inland were no longer noticeable. This is shown in Figure 3.

Figure 3. 1941 and present day aerial photographs of area of study (images available from Canterbury Maps and Google Earth)

Landfill sites recorded by the Christchurch City Council (CCC) landfill map record *"Shallow Fill"* within New Brighton across Baker Street.

From these multiple sources, we can assume that the elevated dune landform was levelled out and used as fill material throughout Christchurch during its development. Therefore, plenty of the sandy shallow fills underlying the foundations of many buildings in east Christchurch are likely to have been derived from the sand dunes. Considering also that modern technology wasn't available (i.e. vibrating rollers), it is logical to infer that this material was poorly compacted (if at all) when it was placed. Admittedly, a key limitation in this study is that we do not know how much volume of the original sand dunes were levelled and used for backfill purposes. However, from Figure 2, the cone resistance for the 15 Percentile plot (unlike the other two plots) does not show a steady improvement for the upper 5m. It is *unlikely* that the depth of the fill extended to 5.0mbgl, as this would be below groundwater; however this profile may suggest the combined effect of shallow poorly compacted fill overlying naturally weaker Christchurch Formation deposits.

2.3 Groundwater conditions

Seasonal rainfall, coastal tides and the recent earthquakes have all had an effect on the groundwater levels across east Christchurch.

The shallow groundwater table, particularly in the areas more inland, experiences fluctuations due to the seasonal rainfall. Generally, in a wet season, the hydrostatic groundwater level follows the pattern of the surface topography. The tides of the Pacific Coastline also influence the groundwater levels across east Christchurch and recent studies prepared for the CCC indicate the possibility of greater sea level rise than previously estimated.

Environment Canterbury (ECan) has records of several borehole wells that were drilled throughout east Christchurch prior to the earthquakes. The drilling dates of these wells go back to as early as

1911 and as deep as 433.0mbgl. However, the water levels recorded in these can be misleading because they could either to be perched water (for the shallow boreholes) or artesian flow coming from the deep gravel aquifers.

In addition, the recent Canterbury Earthquake Sequence has altered the ground elevation across Christchurch. As a result, in places where the land elevation has settled, the groundwater level is now higher (closer) to the ground surface level. The GNS Science Median Groundwater Surface Elevations map indicates that the median groundwater level from long term monitoring across the focus area is generally between 1.0m to 2.0mbgl, but ranging from 0.0m to 1.0mbgl in the areas close to the Pacific Coastline and the Travis Wetland.

The depth to groundwater is a key parameter in assessing liquefaction potential for any given soil profile, especially those that comprise sand-like particle layers. The shallower the groundwater, the higher the potential of the saturated-loose sand layers liquefying. As the shallow groundwater is now closer to the surface, there may be potentially a more inherent risk of liquefaction-induced damage occurring in a future large magnitude seismic event.

2.4 Liquefaction potential

Much literature has been published with regards to understanding the phenomenon of liquefaction. Liquefaction is a soil failure mechanism triggered by earthquake-induced pore water pressures (in mostly non-cohesive) and the subsequent reduction in effective stress (i.e. reducing the confining stress between particles). When this occurs, the particles rearrange in an attempt to compact the soil matrix by filling the pore water spaces. But as the water pressure continues to build up, it rejects the particle rearrangement causing the particles to ‘float’, therefore causing the soil to lose strength and stiffness and behave more like a fluid. The ejected liquefied material is that which punctures through the less permeable and/ or weaker ground crust.

The resistance of sands to cyclic loading depends on environmental factors such as mode of deposition, cementation, age, relative density, and the number of cycles experienced during a seismic event.

As discussed by Youd (1972), the cyclic loading of free draining - saturated sands can make the sands more dense. When cyclic loading is triggered, a shear displacement is induced on the sand particles, causing them to contract (decreasing void ratio) and dilate (increasing void ratio). As cyclic loading continues, the void ratio and the degree of change in void ratio progressively decrease and the soil matrix progressively increases in density. At the particulate level, the loose or honeycombed soil structures, when subjected to cyclic loading, are collapsing to have a more dense arrangement and decreasing their porosity (i.e. *rhombohedral packing*).

Prior to the Canterbury Earthquake Sequence, a risk assessment study undertaken by the University of Canterbury (1997) stated that Christchurch is potentially at risk from widespread liquefaction. More specifically, it was known that east Christchurch had a *“high liquefaction potential”*, as shown in Figure 4.

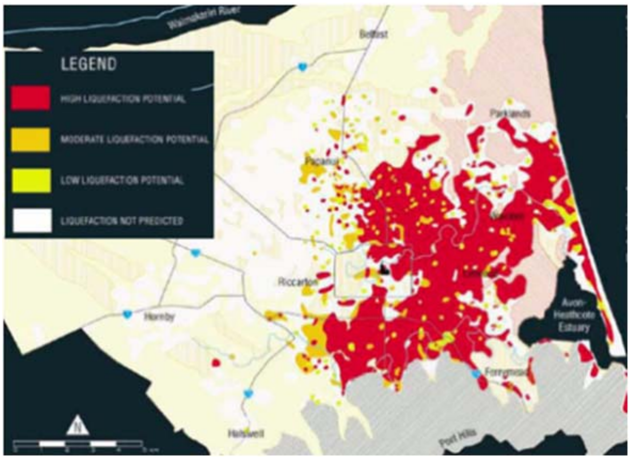

Figure 4. Liquefaction hazard map for Christchurch, provided to the public by Environment Canterbury (Available at: http://ecan.govt.nz/publications/general/solid-facts-christchurch-liquefaction.pdf)

3 EARTHQUAKE DAMAGE

3.1 Ground motion

The “Port Hills fault”, as it came to be known, is an underground fault which formed when the Lyttelton Volcano emerged through the base greywacke rocks. It’s a relatively small fault, laterally extending approximately 10km. Names of faults are usually assigned to those that are observable at the ground surface, but the Port Hills fault was noticed due to the pattern of aftershocks in the region and the seismic sounding investigations.

The Christchurch earthquake (Mw 6.3) occurred due to a reverse thrusting to the Port Hills fault. Its action during the Christchurch earthquake did not surface but ceased approximately 1 km below the ground.

The 22 February 2011 Christchurch earthquake was the strongest seismic event in a series of aftershocks around the Canterbury region. It only took about four seconds for the energy of the rupture to surface, and as the waves travelled throughout Christchurch, large peak ground accelerations (PGA’s) were recorded. The vertical accelerations recorded at one particular Primary School in Christchurch were the strongest recorded in New Zealand, being more than twice that of gravity (2.2g). The strong ground motion of the February earthquake was likely to be around the Ultimate Limit State (ULS) design level for the dwellings and structures in east Christchurch. The highest median conditional PGA recorded in our area of study was recorded to be 0.66g.

3.2 Damage and failure mechanisms

From the time between the establishment of European settlement in Christchurch (in 1850) to the Darfield earthquake in 2010, only two earthquake events were recorded to have caused failure to structures (particularly chimneys). These earthquake events occurred on the 5 June 1869 and 31 August 1870. However, no liquefaction or ground damage was recorded across the Christchurch area as a result of these earthquakes.

Considering the human and environmental factors that influenced the liquefaction-resistance of the sand deposits in east Christchurch, large quantities of liquefaction ejecta and liquefaction-induced lateral spreading ground deformations were experienced near the free faces (Travis Wetland, Avon River and possible “hidden” abandoned maiandrus) following the 2011 Christchurch earthquake. This was not only because of the sloping ground towards the free-face, but also because of the loose surficial layers of the drained estuary and poorly compacted fill deposits due to human influence. Infrastructure buried beneath the groundwater level (e.g. pipes, tanks, manholes, etc.) that were sealed and empty experienced significant uplift pressures. Due to the large lateral ground displacements which occurred to the suburb of North New Brighton, as inferred by the LiDAR survey data, the suburb was categorised in the Ministry of Business, Innovation and Employment (MBIE) Guidance as an area that would experience *“Major”* global lateral movement in a future large earthquake.

Many residential dwellings in east Christchurch are founded on either short internal piles underneath the floor board and a concrete beam underneath the perimeter of the dwelling footprint, or a concrete slab-on-grade foundation. The Christchurch earthquake caused footings and floor levels to experience bearing capacity failures and/ or differential settlements resulting in distress to the structural members. This was observed in the form of: step-cracking in the wall cladding, foundation hogging and sagging, etc. Prior the recent earthquakes, creep settlements from applied static (monotonic) loads over time – albeit minor - may have caused foundations to be out-of-level. However, during and following the earthquakes, foundation deformations in terms of differential settlements could be attributed (in varying degrees) to some of these factors:

- Cyclic mobility which causes the ground to settle, as the sand particles rearrange to become more dense.
- Loss of ground mass underneath a foundation. This could be a result of liquefaction ejecta and/ or lateral spreading.
- Strength and stiffness degradation / shear deformation caused by the inertial loads of the oscillating superstructure and cyclic softening - liquefaction. This was particularly noticeable with buildings that had unevenly distributed loads on the ground – such as those with asymmetrical footprints and/ or heavy brick chimneys attached.

Such large quantities of ground and structural deformations were not however recorded near the Pacific Coastline, where structures are situated on native sand dunes. This could be attributed to the action of the coastal tides which deposit the sands also acting to make the dunes denser and maintain their density.

4 PREDICTING FUTURE EARTHQUAKE GROUND RESPONSE

Fatalities occur in an earthquake when structural members fail, causing collapse. Practitioners aim to better predict the ground response and design foundation systems that prevent the structural failure by allowing the ground to perform uniformly, thereby allowing the structure to perform uniformly.
In doing so, both the vertical and lateral displacements of the site need to be predicted and accounted for.

To predict the ground response of a future large earthquake in east Christchurch, ULS cyclic loading conditions were modelled using Mw = 7.5, PGA of 0.35g, and a groundwater table at 1.0mbgl. Vertical and lateral displacements were predicted for the corrected cone resistance (15th percentile, median and 85th percentile), recorded over fifty CPTu tests down to 25.0mbgl (shown in Figure 2). Adopting a crude assumption that the 85 percentile profile is indicative of the stronger dune deposits (such as those near the coastline) and that the 15 percentile profile is indicative of the shallow poorly compacted fills overlying the weaker sand dune deposits, a ground improvement crust (of 2m and 3m deep) was applied for the 15 percentile values having an improvement of 1.5 (factor of safety against liquefaction). The ground improvement non-liquefiable crust in this analysis does not take into account the type or properties of the engineered fill used (its grading, density, particle shape) or the use of geogrid reinforcement placed between the layers of the engineered fill.

4.1 Vertical displacements

With regards to predicting vertical settlements, the Zhang et al (2002) method has been a commonly adopted method in estimating the liquefaction-induced ground settlements, as per the MBIE Guidance. Since this method was based on laboratory testing of clean sands, it is a useful method to adopt in east Christchurch. The key limitation with this method, however is that it is a one dimensional approach and doesn't account for volumetric strains (e.g. shear strains, ground loss due to lateral spread and ejecta, strength and stiffness reduction, inertial loads of foundations and bearing capacity failure).

An assessment of the earthquake-induced free field vertical settlement was carried out using the Idriss & Boulanger method (2008) and Zhang et al (2002) method. Results are shown in Table 1.

Table 1: Estimated free field settlement for east Christchurch surficial deposits (25.0mbgl)

CPTu Profile	Total ground surface settlements (mm) to 25.0mbgl	MBIE "Index Value" (settlement in upper 10m) mm
15 Percentile	170	130
Median	50	30
85 Percentile	3	0
15 Percentile (2m Crust)	150	115
15 Percentile (3m Crust)	130	95

In the event of a future earthquake, these results would indicate that the ground response of the stronger dune deposits would be much more favourable than having a ground improved crust applied over weaker strata.

4.2 Lateral displacements

Liquefaction-induced lateral spreading as defined by Rauch (1997) is the *"finite, lateral displacement of gently sloping ground as a result of pore pressure build up or liquefaction in a shallow underlying deposit during an earthquake".* Either during earthquake shaking or afterwards as liquefaction ejecta flow continues, the soil profile above the groundwater moves laterally over the liquefied soils, towards an area with a lower elevation. Predicting lateral displacements caused by lateral spreading is a complex nonlinear phenomenon to analyse. Simplified methods (such as Newmark's sliding block model [1965]) and/ or empirical methods (such as Bartlett & Youd's model [2002]) may be adopted, but these have their limitations, such as those outlined in Rauch's dissertation.

Derived from laboratory testing of clean sands, the Zhang et al (2004) semi-empirical method of using CPT and SPT data to estimate liquefaction-induced lateral displacements is a useful tool to adopt for level-ground or gently sloped sites in east Christchurch. It's particularly suitable for low-medium risk projects. However, when this method is examined (using available case histories), the difference between the predicted lateral displacements and the empirical data shows variations in the order of 50% to 200%. Given the complexity of analysing liquefaction-induced lateral spreading, large magnitude variations of lateral displacements should be expected following an earthquake.

An assessment of the earthquake-induced lateral displacement was carried out using the Robertson & Wride (1998) method and Zhang et al (2004) semi empirical method. An assumed height of 3m above the free-face was adopted for the analysis. An additional analysis where the depth of the ground improvement crust is twice the height to the free face (i.e. 6m) was also undertaken. Results are shown in Table 2.

Table 2: Estimated lateral displacement in relation to distance from free face

CPTu Profile	Distance to free face (m)					
	5	10	15	30	60	100
	Total lateral displacement settlements (mm)					
15 Percentile	3350	1900	1400	800	450	300
Median	300	200	150	100	50	30
85 Percentile	3	2	1	0.5	0.4	0.3
15 Percentile (2m Crust)	2800	1600	1200	650	400	250
15 Percentile (3m Crust)	2050	1200	850	500	300	200
15 Percentile (6m Crust)	1.5	0.8	0.6	0.3	0.2	0.1

As with the results of the vertical settlements, these results indicate that the ground response of the stronger dune deposits would be much more favourable than having a ground improved crust applied over weaker strata. The MBIE Guidance recommends a 2m ground improved crust; these results indicate that deeper ground improvement treatment would be needed to have similar results to that of the stronger dune deposits, however, the parameters used in this analysis are not representative of all sites in the area.

5 CONCLUSIONS

Based on our geological study of east Christchurch, the site investigation data, the observed earthquake-induced failure mechanisms and our analysis, the following can be summarised:

1. *The noticeable inland sand dunes were obliterated by human construction activity and used as shallow backfill material as east Christchurch was levelled out and developed.*
2. *As this backfill material was poorly compacted, it allowed for greater deformations in the form of liquefaction ejecta and liquefaction-induced lateral spreading in the area.*
3. *The native sand dunes near the Pacific Coastline, being a more dense material, allowed for it to have a better ground response during the Christchurch earthquake.*
4. *Ground improvement works may be needed below the foundations of properties founded on loose poorly compacted sandy backfill. The depth of the treatment will depend on the site-specific predicted vertical and lateral displacements.*
5. *As stated in Section 2, the key limitations in this study that the volume of shallow backfill material derived from the sand dunes is unknown and that the assumptions used are based on averaged values of CPTu data obtained after the earthquakes. More CPTu correlations with borehole data would better clarify the depth of the fill at individual sites.*

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