Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 49, No. 4, December 2016

TECHNICAL NOTE

LIQUEFACTION VULNERABILITY INCREASE AT NORTH NEW BRIGHTON DUE TO SUBSIDENCE, SEA LEVEL RISE AND REDUCTION IN THICKNESS OF THE NON-LIQUEFYING LAYER

Christopher B. Monk[1], Sjoerd van Ballegooy[2], Matthew Hughes[3] and Marlene Villeneuve[4]

(Submitted *December 2015*; Reviewed *April 2016*; Accepted *September 2016*)

ABSTRACT

The Canterbury Earthquake Sequence (CES) of 2010 – 2011 caused widespread liquefaction related land damage to the city of Christchurch. This paper addresses the impact the CES had on the eastern Christchurch suburb of North New Brighton with emphasis on the ground condition at the time of the initial 4 September 2010 earthquake, as well as subsidence caused by the CES, and the future potential for increased liquefaction vulnerability due to Sea Level Rise (SLR).

Subsidence at North New Brighton accumulated throughout the CES due to a reduction in volume of the soil profile through liquefaction; and overall settlement due to regional tectonic subsidence. The total amount of subsidence caused by the CES at North New Brighton was as much as 1 m in some places and this has changed the relationship between the position of the ground surface and the top of the groundwater table. A reduction in thickness of the non-liquefying layer has been shown to increase the vulnerability of the soil profile to liquefaction related land damage during earthquake events. As a coastal suburb, North New Brighton is vulnerable to the impact of SLR and this paper considers the response of the groundwater table to rising sea level and the influence this will have on the thickness of the non-liquefying layer and liquefaction vulnerability.

INTRODUCTION

From 4 September 2010 until early 2012 the Canterbury region of New Zealand including the City of Christchurch was affected by a sequence of earthquakes and aftershocks. The most significant earthquakes during this period were: 4 September 2010 (M_w 7.1), 22 February 2011 (M_w 6.2), 13 June 2011 (M_w 6.0), and 23 December 2011 (M_w 5.9) [1]. Detail about the ground motions experienced during the Canterbury Earthquake Sequence (CES) can be found in Bradley & Hughes (2012) [2]. The CES caused widespread liquefaction related land damage as well as building and foundation damage. Liquefaction related damage affected 51,000 of the 140,000 residential properties in Christchurch and caused approximately 15,000 residential houses to be damaged beyond economic repair [3]. The severity of the damage was primarily influenced by the levels of earthquake shaking, soil grain size, and depth to the groundwater surface.

The CES caused regional tectonic subsidence as well as widespread liquefaction related subsidence. In Christchurch 85% of urban residential flat land properties have subsided (both tectonic and liquefaction related) and this has left a legacy of a city with suburbs that are now more flood prone [4] and more vulnerable to liquefaction damage in future earthquake events because the ground surface is now closer to the groundwater level [1].

This paper is focused on the eastern Christchurch suburb of North New Brighton which was affected by liquefaction related land damage during the CES and as a result has subsided by as much as 1m. The impact of subsidence at North New Brighton provides insight into the potential impacts of Sea Level Rise (SLR) in the future as the experienced changes in relative groundwater levels are equivalent to a century of SLR (0.5 to 1 m) [3]. This paper investigates the impact the 4 September 2010 earthquake had on North New Brighton and pays particular attention to the position of the groundwater table and thickness of the non-liquefying layer pre-CES. Using the September 2010 earthquake as a base case scenario, modelling has been completed to estimate liquefaction vulnerability of the suburb post-CES. Liquefaction vulnerability modelling takes into account reduction in thickness of the non-liquefying layer due to the effects of subsidence caused by the CES. Comparisons have been drawn between liquefaction vulnerability before the September 2010 earthquake and liquefaction vulnerability post-CES. Using forward analysis of design level earthquake events, changing liquefaction vulnerability is investigated through modelling the impact SLR will have on the groundwater table position at North New Brighton.

LOCAL GEOLOGY

Present day surface deposits at North New Brighton are similar to other parts of coastal Christchurch and include fixed sand dunes, drained swamps, and lagoon and estuary deposits formed during the coastal progradation of the last 6,500 years [5]. Travis Swamp is situated west of the North New Brighton area, while beach sand dunes occupy the coastal margin on the eastern side of the suburb.

---

[1] *Corresponding Author, Engineering Geologist, Tonkin and Taylor, Auckland, (cmonk@tonkintaylor.co.nz)*

[2] *Senior Geotechnical Engineer, Tonkin and Taylor, Auckland*

[3] *Lecturer in Geohazards, Risk and Resilience, University of Canterbury, Christchurch*

[4] *Senior Lecturer, University of Canterbury, Christchurch*

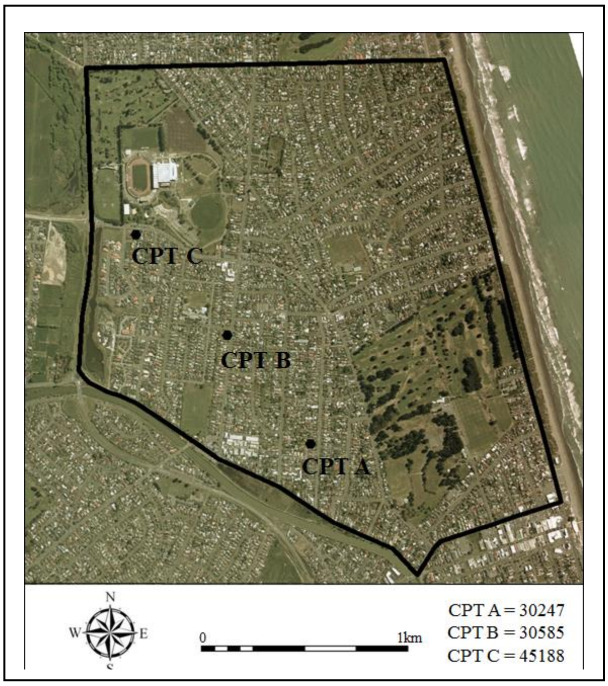

Figure 1: Location of North New Brighton study area and focus of this paper. The three Cone Penetration Test (CPT) locations have been used to compare liquefaction vulnerability against Peak Ground Acceleration (PGA) for a range of depth to groundwater scenarios.

In the shallow subsurface of North New Brighton, Christchurch Formation dune and beach deposits are common and consist of loose to dense, fine to coarse sand and gravel (Unified Soil Classification SP-SM-GP) [5]. These soil types are known to have high liquefaction potential when loosely consolidated and saturated. In addition to the dune and beach sand deposits, Christchurch Formation estuarine, lagoonal, and interdune swamp deposits also occur beneath North New Brighton. These deposits consist of a wide range of soil types, mainly clayey silt, fine to coarse shelly sand, and peat (Unified Soil Classification ML-CL-OL-PT) [5].

The ground at North New Brighton has been re-graded close to flat, with a slight suburb wide grade southwards towards the Avon River. The soil deposits in this area are generally consistent in material type (sand with some silt layers), with variable density over short distances. This rapid change in density (referred to as geologic variability) is as a result of the change in topography of sand dunes or change in grade from sand banks to natural channels in marginal marine estuarine environments [6].

LSN LIQUEFACTION VULNERABILITY AND THE NON-LIQUEFYING LAYER

To estimate the potential for liquefaction and the impact it will have in a given earthquake scenario a number of conditions need to be quantified first. Saturated, loosely consolidated fine sands and silts represent the primary soil type candidate for liquefaction. If this material is within the top 10m of the soil profile, there is a high probability it will liquefy and cause liquefaction related land damage in an earthquake of sufficient Magnitude (M_w) and Peak Ground Acceleration (PGA). To calculate whether the soil profile is prone to liquefaction, a liquefaction triggering analysis method is required. The variable nature of the soil profile makes it impossible to accurately predict vulnerability to liquefaction in all locations; however a number of liquefaction triggering analyses have been developed to estimate liquefaction triggering. van Ballegooy and others [7] reviewed four simplified liquefaction triggering methods for the CES and came to the conclusion that while each method showed reasonable correlation between land damage observations and the selected liquefaction vulnerability parameter, the Boulanger and Idriss 2014 (BI-2014) [8] method provided the greatest consistency.

The liquefaction triggering analysis methodology is used to determine whether liquefaction of the soil profile can occur given a specified magnitude of shaking and ground acceleration. To determine if the liquefied soil is likely to manifest as liquefaction related land damage, another parameter needs to be calculated. Liquefaction vulnerability parameters (or indices) use the liquefaction triggering methodology as well as other factors to determine if the soil profile is susceptible to liquefaction and whether land damage will result. Liquefaction vulnerability evaluations in the Christchurch area have made extensive use of four Cone Penetration Test (CPT)-based liquefaction vulnerability parameters including; one-dimensional (1D) post-liquefaction reconsolidation settlement (SV1D), liquefaction potential index (LPI), modified liquefaction potential index (LPI_{ISH}) and liquefaction severity number (LSN) [3]. van Ballegooy and others [7] reviewed the listed liquefaction vulnerability parameters and found that the LSN liquefaction vulnerability index consistently provided a closer correlation between observed liquefaction related land damage and the index number generated when compared with the other indices. For the LSN liquefaction vulnerability parameter, LSN ranges between: 0 to 15 generally correlate with none-to-minor liquefaction related land damage, 16 to 25 generally correlates with minor-to-moderate liquefaction related land damage and more than 26 generally correlates with moderate-to-severe liquefaction related land damage [3].

Ishihara [9] published observations on the protective effect of an upper layer of non-liquefied material against the effects of liquefaction at the ground surface. Ishihara plotted observations of the expression of liquefied material at the ground surface using the thickness of the overlying non-liquefying surface layer (H_1) or “crust” and the thickness of the underlying liquefied material (H_2), and defined boundary curves that separated those sites where liquefied material was expressed at the ground surface and sites that did not [1]. The simple ground model that the Ishihara curves were developed from is an over simplification of the complex, highly stratified soil profiles typically encountered in the Canterbury region. However, it is a useful model for understanding liquefaction vulnerability and the phenomenon of increasing vulnerability to liquefaction-induced land damage due to a reduction in the thickness of the non-liquefying crust as a result of ground subsidence [1].

Recent work [10] shows there is a good correlation between the LSN index parameter and the Ishihara [9] boundary curves. This correlation shows that a LSN greater than 20 occurs for soil profiles to the left of the Ishihara boundary curve and LSN values less than 15 occur for soil profiles to the right of the Ishihara boundary curve [1]. This work makes it possible to plot LSN versus PGA for a range of earthquake scenarios and is a powerful tool for observing how liquefaction vulnerability changes as the thickness of the non-liquefying layer is reduced. Three CPT’s from the North New Brighton area were selected to compare LSN versus PGA for a range of non-liquefying layer thickness scenarios.

Figures 2, 3, and 4 illustrate changing liquefaction vulnerability as the seismic demand is increased for an M_w 7.5 earthquake event at larger ranges of PGA. The PGA threshold of 0.3g has been highlighted in each of the figures as this corresponds to the boundary curve generated by Ishihara [9] after his observations of liquefaction at the surface. While each LSN versus PGA curve responds uniquely, it is clear that

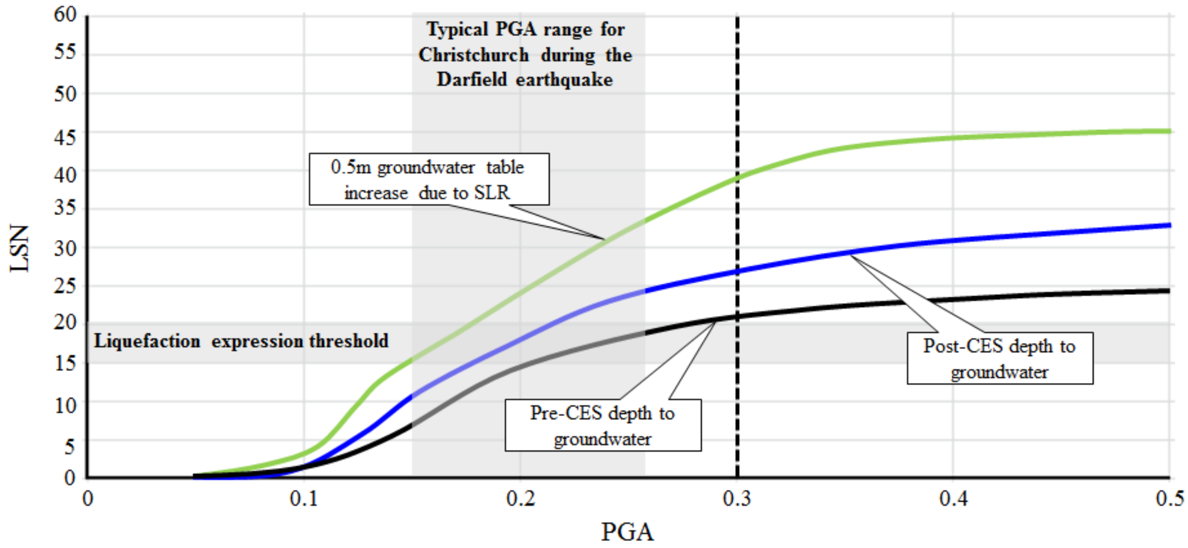

Figure 2: LSN vs. PGA for a M_w 7.5 earthquake event for CPT 30247 with pre- and post-CES median depth to groundwater of 1.7m to 1.1m as well as a 0.5m decrease to depth of groundwater due to SLR.

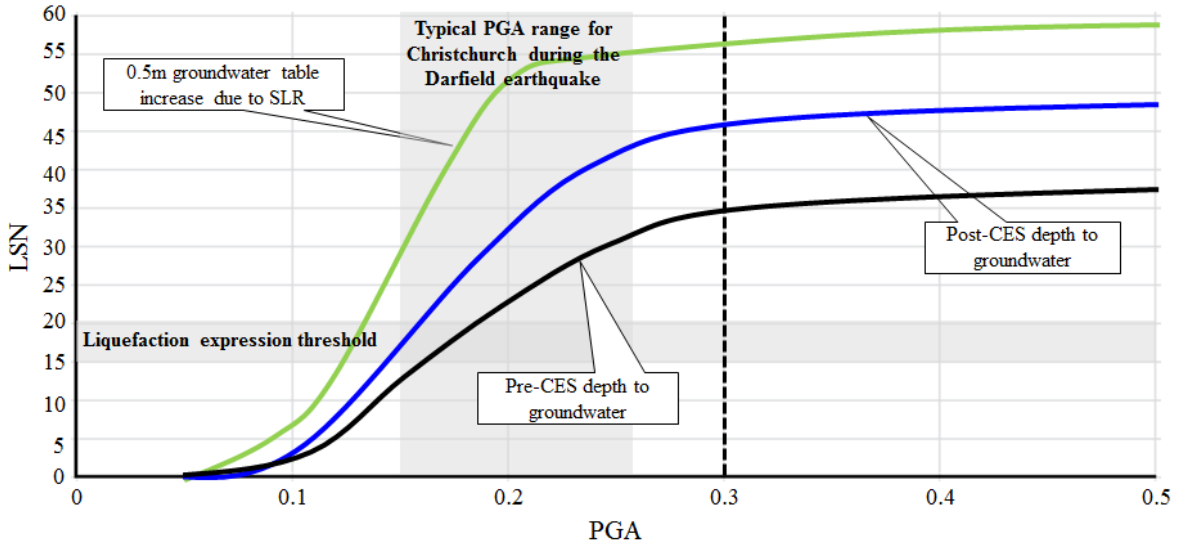

Figure 3: LSN vs. PGA for a M_w 7.5 earthquake event for CPT 30585 with pre- and post-CES median depth to groundwater of 1.7m to 1.0m as well as a 0.5m decrease to depth of groundwater due to SLR.

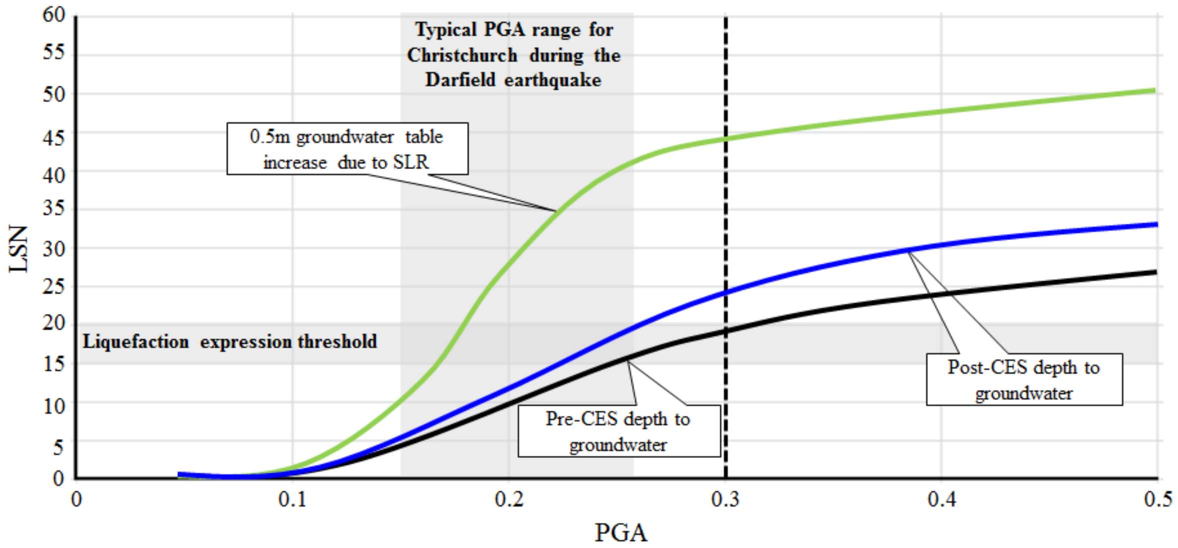

Figure 4: LSN vs. PGA for a M_w 7.5 earthquake event for CPT 45188 with pre- and post-CES median depth to groundwater of 1.5m to 1.0m as well as a 0.5m decrease to depth of groundwater due to SLR.

the depth to the median groundwater surface plays a significant role in the scale of the LSN number generated.

Both pre- and post-CES depth to groundwater conditions have been investigated for each CPT and an attempt has been made to model the impact a 0.5 m rise in sea level will have on the groundwater position and on the LSN versus PGA curves. SLR and the response of the groundwater table as well as liquefaction vulnerability are investigated in further detail later in the paper.

4 SEPTEMBER 2010 EARTHQUAKE

Like many areas around Christchurch, North New Brighton was affected by liquefaction related land damage throughout the CES. In the immediate aftermath of the 4 September 2010 earthquake the regions of North New Brighton which exhibited liquefaction ejecta at the surface, water ponding, lateral spreading cracks and subsidence were mostly along the Avon River corridor and adjacent to the Travis Wetland area. Figure 5c presents land damage observations for the September 2010 earthquake and categorises those areas by the severity of the damage observed. Liquefaction related land damage impacted North New Brighton in later earthquake events of the CES and that detail is covered elsewhere [11].

This paper has focused on the September 2010 earthquake event so comparisons can be drawn between pre-CES depth to groundwater and post-CES depth to groundwater and the resulting change to liquefaction vulnerability investigated.

The 4 September 2010 'Darfield Earthquake' was a M_w 7.1 earthquake which occurred near the town of Darfield, approximately 50km west of North New Brighton. Modelling of PGA contours [2] has provided data for estimating the ground shaking intensity at North New Brighton. Figures 5a, 5b and 5c illustrate the PGA = 0.18g contour which is oriented approximately north-south through North New Brighton.

For the September 2010 earthquake LSN modelling and for all other LSN maps presented in this paper the LSN parameter was computed for each CPT location using the respective groundwater surfaces based only on the top 10 m of any CPT sounding as discussed by van Ballegooy and others [11]. In order to apply the LSN parameter to the North New Brighton study area of 800 CPT's (available from the Canterbury Geotechnical Database https://canterburygeotechnicaldatabase.projectorbit.com), assumptions have been made including:

- The probability of liquefaction triggering curves adopted are the 15 percentile curves;
- No liquefaction occurs where the soil behaviour type index, $I_c > 2.6$; and
- The soil Fines Content (FC) was estimated in accordance with the BI-2014 method-specific FC-I_c correlation assuming a default C_{FC} fitting parameter zero.

Depth to the median groundwater table for the 4 September 2010 earthquake was modelled by van Ballegooy and others [11] and their work generated event specific groundwater maps for each major earthquake of the CES as well as modelling for post-CES groundwater conditions. The liquefaction vulnerability LSN map illustrated in Figure 5b presents a good correlation with the land damage observations for North New Brighton shown in Figure 5c. This correlation along with work completed by van Ballegooy and others [7] provides compelling evidence for the predictive capacity of the LSN liquefaction vulnerability parameter as well as the BI-2014 [8] liquefaction triggering analysis method.

POST CES LIQUEFACTION VULNERABILITY AT NORTH NEW BRIGHTON

Subsidence caused by the CES has resulted in most of Christchurch now being at a lower elevation relative to the position it was in before the earthquakes began in 2010. Regional tectonic subsidence affected most of the city and for those areas impacted by liquefaction related land damage; the effect of regional tectonic subsidence was exacerbated. In the case of North New Brighton the suburb average subsidence rate was approximately 0.4 m and the total amount of subsidence was as much as 1 m in some areas.

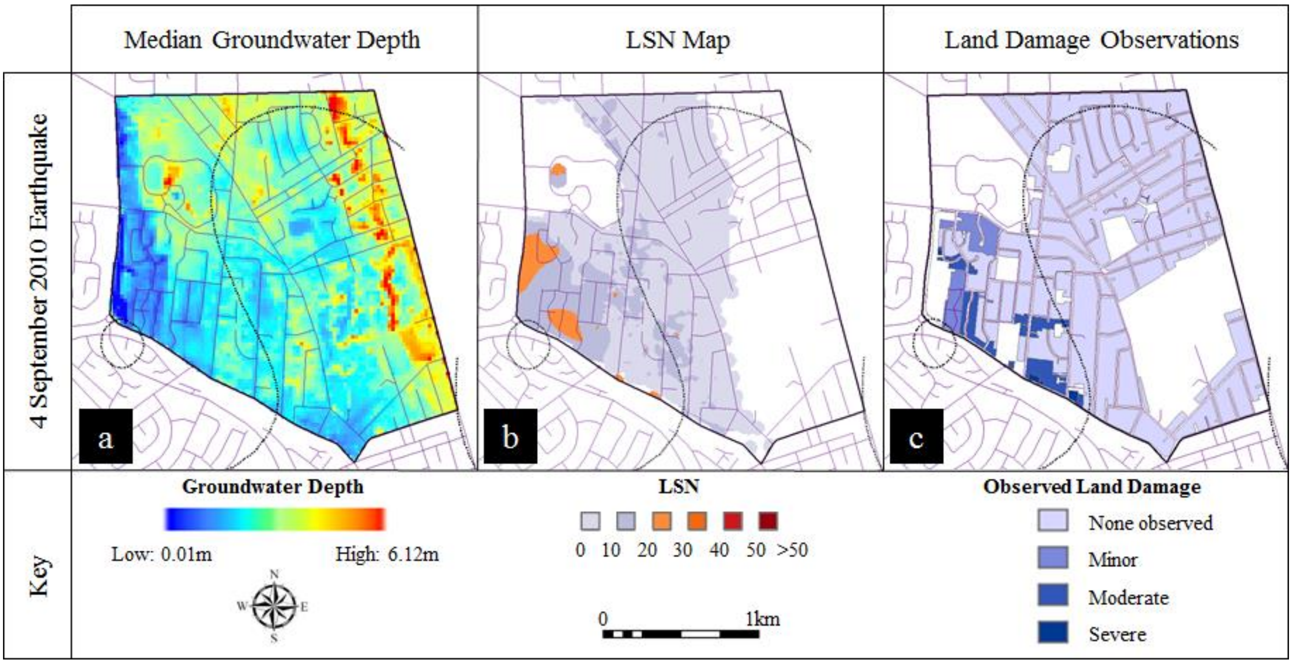

Figure 5: (a) North New Brighton median depth to the groundwater table for the 4 September 2010 earthquake [12], including the PGA = 0.18g contour. (b) LSN liquefaction vulnerability modelling for North New Brighton for the 4 September 2010 earthquake including the PGA = 0.18g contour. (c) Land damage observations for North New Brighton for the 4 September 2010 earthquake, including the PGA = 0.18g contour.

Ground subsidence has resulted in a reduction in depth to the groundwater table and correspondingly the thickness of the non-liquefying layer has decreased. The LSN versus PGA plots illustrated in Figures 2, 3, and 4 were generated from CPT's located throughout North New Brighton and provide an indication as to how liquefaction vulnerability has changed as a result of the CES in this area.

LSN maps produced by Tonkin and Taylor [3] were generated using design level earthquake events established by the Ministry of Business, Innovation and Employment (MBIE) guidelines [13-14]. The three scenarios established by the guidance documents represent the 25, 100 and 500 year return period levels of earthquake shaking for Christchurch. Each scenario is identified uniquely as: 25 year = Serviceability Limit State (SLS), 100 year = Intermediate Limit State (ILS) and 500 year = Ultimate Limit State (ULS). The magnitude and PGA values for SLS and ILS cases are the design PGA values of 0.19g and 0.30g for a M_w 6.0 earthquake, and for ULS the PGA is 0.35g for a M_w 7.5 earthquake.

Studies undertaken [15] show that the ULS M_w 7.5, 0.35g ground motions result in virtually the same LSN values in Christchurch compared to the equivalent M_w 6.0, 0.52g ground motions when using the BI-2014 [8] liquefaction triggering assessment methodology. Therefore, for simplicity, the ULS case has been modelled using the M_w 6.0, 0.52g ground motions.

The LSN maps illustrated in Figure 6 provide a useful indication of how liquefaction vulnerability has changed at North New Brighton as a result of the CES. The September 2010 earthquake (Figure 5b) had comparable levels of ground shaking with the 25 year (SLS) design event modelled at North New Brighton in Figure 6a. Comparing the two LSN maps it is evident that the LSN index has increased and correspondingly North New Brighton is more vulnerable to liquefaction than it was prior to the CES. If an earthquake of the same magnitude and PGA of the 4 September 2010 event were to occur in the future, this modelling indicates that greater levels of land damage can be expected for North New Brighton, particularly for the western and southern sides of the suburb.

SEA LEVEL RISE AND LIQUEFACTION VULNERABILITY

Analysing the impact of climate change is a complex science and this paper has not been written for the purpose of predicting how sea level will respond to climate change, except to investigate how liquefaction vulnerability in earthquake prone coastal suburbs can alter if the groundwater table were to rise in response to SLR. Rather than propose an idea of when sea level will rise by 0.5 m or more, this paper uses that scenario and investigates how the groundwater table is likely to respond and what impact that will have on liquefaction vulnerability at North New Brighton. Work by Chang and others [16] has shown that given enough time, aquifers and as a corollary, the groundwater table position will respond to match the changed position of sea level, assuming they are connected and the aquifer is not artesian. The large gravel aquifer system of the Canterbury plains which passes beneath Christchurch and empties into Pegasus Bay appears to represent the ideal conditions for rapid groundwater table response to changing sea level conditions; though this is an area requiring further study.

Tonkin and Taylor completed one-dimensional steady state backwater profile modelling of the Waimakariri, Styx, Heathcote and Avon rivers based on the median river flow rates using the software HEC RAS, US Army Corps of Engineers [3], to better understand how SLR could affect river backwater profiles.Their modelling elevated the position of sea level by 0.5 m and 1.0 m simulating two SLR scenarios. Due to the close proximity of North New Brighton to the coast and the relatively shallow position of the groundwater table post-CES, the 1.0 m SLR scenario generated erroneous LSN results for North New Brighton so this paper only takes into account the 0.5 m SLR scenario. For the 0.5 m SLR increase modelling the groundwater table was predicted to rise uniformly by 0.5 m as far west as Burwood and therfore the groundwater table at North New Brighton was increased evenly across the suburb.

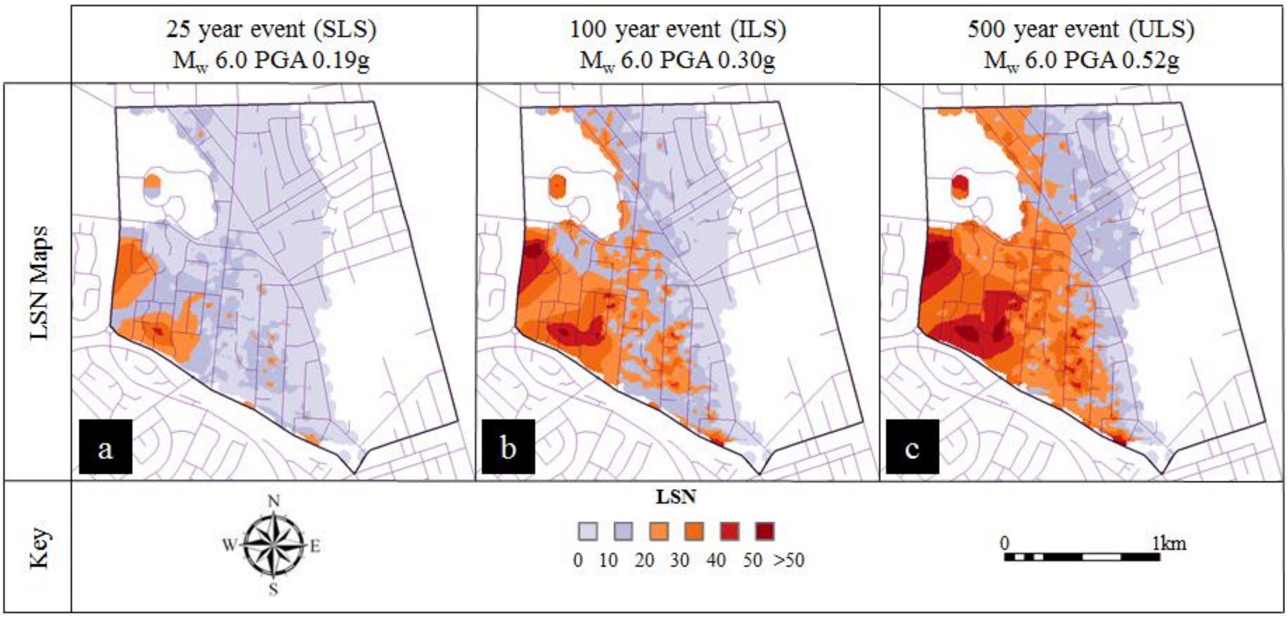

Figure 6: Liquefaction vulnerability modelling using the LSN parameter for North New Brighton. The three earthquake intensity scenarios represent the design level shaking specified by the MBIE [13-14] guidance documents, and post-CES depth to groundwater has been used.

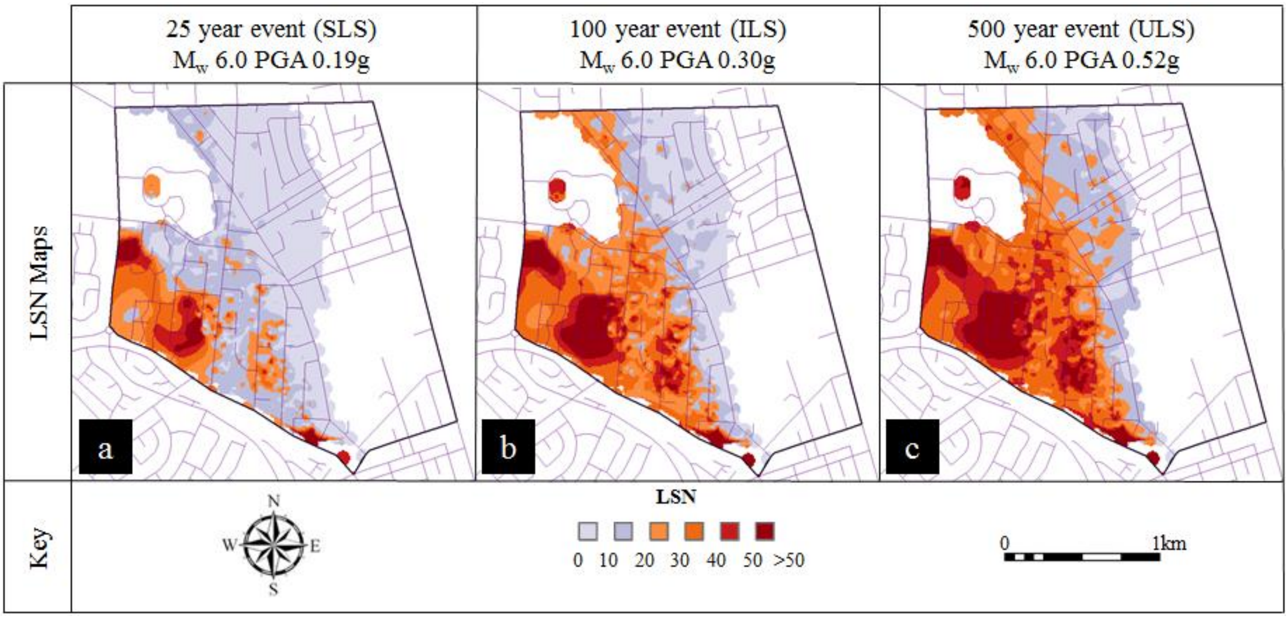

Figure 7: Liquefaction vulnerability modelling using the LSN parameter for North New Brighton. Depth to the groundwater table has been reduced by 0.5m from post-CES conditions to simulate an increase in SLR by 0.5m. The three earthquake intensity scenarios represent the design level shaking specified by the MBIE [13-14] guidance documents.

The LSN maps illustrated in Figures 7a, 7b and 7c reveal that a 0.5 m SLR increase will have a dramatic impact on liquefaction vulnerability at North New Brighton and correspondingly the amount of liquefaction related land damge that would result. The most important feature of the LSN maps is not the dark brown areas but rather the significant increase in area corresponding to the orange colour which represents the threshold at which liquefaction is beginning to manifest in a given earthquake event.

DISCUSSION

The events of the CES and the site investigation data collected since have provided an unparalleled dataset for completing earthquake research. The science of liquefaction vulnerability prediction is evolving and analysis methods are becoming increasingly accurate which is making vulnerability assessments from CPT data a powerful tool for city planners and policy makers.

The LSN maps presented in this paper provide compelling evidence that North New Brighton is becoming increasingly vulnerable to liquefaction related land damage from a future earthquake event as the depth to the groundwater table is reduced. Subsidence caused by the CES means that if North New Brighton is affected by a future earthquake on the scale of any from the CES, the expected liquefaction related land damage would be greater

Evidence is mounting in climate change science that sea level is rising and this will certainly have an impact on North New Brighton as well as other coastal suburbs throughout Christchurch and New Zealand. As liquefaction vulnerability is likely to increase, ground improvement and residential house design needs to be considered in those areas prone to earthquakes. The practice of building heavy concrete-slab-on-grade houses which has become the dominant house type in New Zealand since 1970 onwards [17] is unlikely to be the most suitable option in areas where liquefaction triggering during an earthquake is likely.

Data collected by CPT investigations and the numerical modelling that can be analysed provide a tool for liquefaction vulnerability assessment. However completely accurate prediction of liquefaction is impossible due to the variable nature of the sub-surface and the way in which earthquake energy is transferred through the ground. The methods discussed in this paper are useful for predicting trends in liquefaction vulnerability but are not a guaranteed predictor of how the ground will perform in a future earthquake event.

ACKNOWLEDGEMENTS

This work was made possible by the site investigation data available in the Canterbury Geotechnical Database courtesy of the NZ Earthquake Commission and the Canterbury Earthquake Recovery Authority. The author would also like to acknowledge the support and data provided by Sjoerd van Ballegooy and Tonkin and Taylor as well as the time spent developing GIS skills with Matthew Hughes of the University of Canterbury.

REFERENCES

1. Russell J, van Ballegooy S, Rogers N and Jacka M (2015). “The effect of subsidence on liquefaction vulnerability following the 2010 – 2011 Canterbury earthquake sequence”. *Twelfth Australia-New Zealand Geomechanics Conference*, Wellington, Paper 81.
2. Bradley BA and Hughes M (2012). “*Conditional Peak Ground Accelerations in the Canterbury Earthquakes for Conventional Liquefaction Assessment”*. Technical Report Prepared for the Department of Building and Housing.
3. Quilter PW, van Ballegooy S and Russ M (2015). “The effect of sea level rise on liquefaction vulnerability”. *Proc. 6th International Conference on Earthquake Geotechnical Engineering*, November 1-4, Christchurch, New Zealand.
4. Hughes MW, Quigley MC, van Ballegooy S, Deam BL, Bradley BA, Hart DE and Measures R (2015). “The sinking city: Earthquakes increase flood hazard in Christchurch, New Zealand”. *GSA Today*, **25**(3-4): doi: 10.1130/GSATG221A.1.
5. Brown LJ, Beetham RD, Paterson BR and Weeber JH (1995). “Geology of Christchurch, New Zealand”. *Environment & Engineering Geoscience*, **I**(4): 427-488.
6. Russell J, van Ballegooy S, Torvelainen E and Gulley R (2015). “Consideration of ground variability over an Area of geological similarity as part of liquefaction assessment

for foundation design". *Proc. 6th International Conference on Earthquake Geotechnical Engineering,* November 1-4, Christchurch, New Zealand.

7. van Ballegooy S, Lacrosse V, Russell J, Simpson J and Malan P (2015). "Comparison of CPT–based simplified liquefaction assessment methodologies based on Canterbury geotechnical dataset". *Proc. Of the 12th Australia New Zealand Conference on Geomechanics* (pp. 618-625). Wellington, New Zealand: NZGS & AGS.
8. Boulanger RW and Idriss IM (2014). "*CPT and SPT Based Liquefaction Triggering Procedures*". Report UCD/CGM-14/01, Department of Civil and Environmental Engineering, University of California, Davis CA, 134 pp.
9. Ishihara K (1985). "Stability of natural deposits during earthquakes". *Proc. of the 11th International Conference on Soil Mechanics and Foundation Engineering,* San Francisco, CA, 321-376.
10. van Ballegooy S, Green R, Lees J, Wentz F and Maurer B (2015). "Assessment of various CPT based liquefaction severity index frameworks relative to the Ishihara (1985) H1–H2 boundary curves". *Soil Dynamics and Earthquake Engineering, Special Issue: Liquefaction in New Zealand and Japan*, 79: 347-364.
11. van Ballegooy S, Malan P, Lacrosse V, Jacka M, Cubrinovski M, Bray JD and Cowan H (2014). "Assessment of liquefaction-induced land damage for residential Christchurch". *Earthquake Spectra*, **30**(I): 31-55. Doi: 10.1193/031813EQS070M.
12. van Ballegooy S, Cox SC, Thurlow C, Rutter HK, Reynolds T, Harrington G and Smith T (2014). "*Median Water Elevation in Christchurch and Surrounding Area after the 4 September 2010 Darfield Earthquake, Version 2*". GNS Science Report 2014/18.
13. MBIE (2012). "*Repairing and Rebuilding Houses Affected by the Canterbury Earthquakes*". Ministry of Business, Innovation and Employment. December 2012
14. MBIE (2014). "*Clarifications and Updates to the Guidance 'Repairing and Rebuilding Houses Affected by the Canterbury Earthquakes': Issue 7".* Christchurch, New Zealand: Ministry of Business, Innovation and Employment. October 2014.
15. van Ballegooy S, Wentz F and Boulanger RW (2015). "Evaluation of a CPT –based liquefaction procedure at a regional scale". *Soil Dynamics and Earthquake Engineering, Special Issue: Liquefaction in New Zealand and Japan*, 79: 315-334.
16. Chang SW, Clement TP, Simpson MJ and Lee KK (2011). "Does sea-level rise have an impact on saltwater intrusion?". *Journal of Advances in Water Resources.* **34**: 1283-1291, doi: 10.1016/j.advwaters.2011.06.006.
17. Rogers N, van Ballegooy S, Williams K and Johnson L (2015). "Considering post-disaster damage to residential building construction – Is our modern building construction resilient?". *Proc. 6th International Conference on Earthquake Geotechnical Engineering,* November 1-4, Christchurch, New Zealand.