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Implications of Sea Level Rise on Liquefaction Vulnerability in Christchurch

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ABSTRACT

A preliminary study was conducted to investigate the effects of sea level rise on liquefaction vulnerability in five selected locations in eastern Christchurch and Kaiapoi, New Zealand. Projected values of sea level rise in the next 25 years, 50 years, and 100 years corresponded to elevated ground water level and reduced thicknesses of non-liquefiable crust and larger estimates of near-surface reconsolidation settlement (S). Larger settlements and thinning non-liquefiable crust is expected to cause increased damage to surface structures in future earthquake events. A semi-empirical, depth-weighted index parameter called the Liquefaction Severity Number (LSN) was used to compare current liquefaction vulnerability to projected liquefaction vulnerability due to sea level rise. Significant increases in vulnerability were determined given sea level rise projections for 2065 and 2115. These findings suggest that a more detailed study would provide engineers and city planners with useful information concerning the distribution of liquefaction vulnerability in the future. The increasing liquefaction vulnerability also strengthens the case to use engineering solutions that mitigate liquefaction (e.g. avoidance and ground improvement) rather than solutions that can accommodate liquefaction-induced ground surface deformations estimated using the current groundwater level.

Introduction

Global Sea Level Rise and Expected Sea Levels in Christchurch

Sea level rise (SLR) poses significant challenges to coastal communities. Low-lying coastal areas (< 10 m above sea level) that encompass approximately 10 % of the world's inhabitants will likely become more vulnerable to hazards such as complete inundation, storm surges, tsunamis, flooding, subsidence, and changes to upstream groundwater levels (McGranahan et al. 2007). Projections of global SLR vary due to uncertainty in factors affecting SLR such as natural climate cycles, human activity, ice sheet melt rates, and ocean temperature (e.g., Mimura 2013). The SLR measured at the Port of Lyttelton near Christchurch mimicked global SLR from 1925 to 2010 and it is assumed that future global SLR is roughly equivalent to expected SLR for Christchurch (Tonkin and Taylor 2013c). Projections of global SLR and local SLR adopted in this study are presented in Table 1.

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Table 1. Projections of global SLR.

Reference	Sea level rise	Time (years AD)
RSNZ (2010)	0.3 m to 2.0 m	by 2100
IPCC (2013) Table 13.5	~0.15 m to ~0.4 m	by 2046 – 2065
IPCC (2013) Table 13.5	0.3 to 1.0 m	by 2100
Tonkin and Taylor (2013c)	1.0 m	by 2100
Adopted in this study:	0.15, 0.3, 1.0 m	by 2040, 2065, 2115

The SLR values adopted in this study are within a broad range of SLR projections, but are expected to be slightly conservative (high), based on the levels reported by the fifth IPCC deemed likely to occur. The fifth IPCC report, IPCC (2013), uses the period from 1986 – 2005 as a baseline for measuring future SLR. The discrepancy between 1986 sea level and sea level measured at the time of the subsurface investigations amounts to approximately 0.05 m, based on 1.9 mm / year SLR measured at the Port of Lyttelton, which has been ignored for this study (Hannah and Bell 2012). Other forms of uncertainty over the next 100 years include the contribution to SLR from melting of the Greenland and Antarctic ice sheets, which may contribute significantly more to the SLR.

Factors Affecting Liquefaction-induced Damage in Christchurch

The possibility of increased liquefaction risk due to SLR has received relatively little attention. Several studies have identified that SLR will likely increase liquefaction vulnerability in coastal zones and near tidal reaches (e.g., Tonkin and Taylor 2013b, 2013c) but very little quantitative information is available to assess these hypotheses. Tonkin and Taylor (2013a) also identified that 20 % fluctuations of the mean depth to groundwater had significant effects on LSN. A study of the effects of larger groundwater level increases on LSN (e.g., associated with SLR) has not been made available.

Geological and Geomorphological Factors

Christchurch is located approximately 100 km south and east of the Pacific-Australian tectonic plate boundary. High rates of tectonic deformation occur near the plate boundary giving rise to the Southern Alps and relief in North Canterbury and Marlborough. The seismic hazard in Christchurch comes from nearby hidden faults, faults in the foothills and faults forming the plate boundary. All of these fault systems are capable of generating significant earthquakes such as the 2010-2011 Canterbury Earthquake Sequence (CES) which caused widespread damage to the greater Christchurch area and was located on nearby hidden faults.

Earthquakes may be associated with large-scale tectonic uplift or subsidence which can locally cause relative sea level fall or rise respectively. More than 80 % of Christchurch subsided from the CES, with 10 % of areas subsiding more than 0.5 m (Hughes, 2015). Total subsidence is a function of both tectonic deformation of the ground surface and liquefaction reconsolidation settlement. For this study, global SLR was assumed to be the only cause of relative SLR.

Christchurch is situated on the interface between alluvial fan sediments from the Southern Alps to the west and coastal deposits to the east. The geology beneath the city reflects coastal and headwater responses to fluctuating climate and sea level over geological time. East of Hagley Park, near-surface soils were deposited within approximately the last 5000 years during a period of relatively stable sea level in beach, back-beach, estuarine and wetland environments. These environments are associated with fine-grained sedimentation including organics, in addition to sands and silts that are susceptible to liquefaction during significant ground shaking (Brown and Weeber 1992). Recurring liquefaction in the Christchurch area was observed by Quigley et al. (2013) at PGA values of as little as 0.05 g.

Hydrogeological Factors

Saturation, or near-saturation (e.g., Yoshimi et al. (1989); Ishihara and Tsukamoto (2004)), is a prerequisite to triggering liquefaction in a given soil. Soils above the groundwater table are typically assumed to be unsaturated and not susceptible to liquefaction-induced reconsolidation settlement. Increases in the elevation of the groundwater surface may result in an increase in the amount of potentially liquefiable soils depending on soil type and relative density.

Although tidal fluctuations rarely travel more than 1km inland, the effects of a change in mean sea level could reach much further inland, with a higher mean sea level requiring a gradual adjustment of the water table to find a new equilibrium (Fordyce 2014). The extent to which this would occur will depend on local geology and topography. Kocurek et al. (2001) modeled different scenarios incorporating a range of hydraulic parameters and periods of sea-level cycle, and found that scenarios could range from ones in which the continental water table is essentially unaffected by sea level, to ones showing that the water table exactly mimics the sea-level curve. Using realistic parameters, the model produced water-table curves that evolved from the coast to inland with decreasing amplitude, loss of more minor cycles, and a time lag.

Similar modelling has not yet been carried out for Christchurch. The groundwater response to SLR will be complex due to the presence of many spring-fed streams, artesian water pressure, groundwater extraction, short-term and long-term tidal fluctuations and spatially non-uniform soil type and permeability. Increases in the elevation of the groundwater table are expected to mimic the increase in sea level in the near-shore environment and areas near stream tidal reaches, with decreasing influence further inland. A detailed numerical groundwater model would be necessary to determine the change in median groundwater levels due to SLR, and other factors, over time. For the purposes of this study we have assumed that increases in the groundwater elevation (or decreases in depth to groundwater) are equal to the magnitude of SLR for the near-shore and near-tidal reach sites selected for this study.

Liquefaction Severity Number

The Liquefaction Severity Number (LSN) was developed specifically to assess vulnerability to land damage caused by liquefaction (Tonkin and Taylor 2013a). LSN is a depth-weighted strain parameter that accounts for the influence of depth of liquefiable soil layers on the overall liquefaction vulnerability of a particular site. LSN is determined using Equation (1):

$$\text{LSN} = 1000\int \frac{\varepsilon_v}{z}\,dz \tag{1}$$

Where ε_v is incremental volumetric strain (%), z is depth (m), and dz is incremental depth. Incremental volumetric strain may be calculated from the combined analyses of liquefaction triggering (e.g., Boulanger and Idriss (2014)) and reconsolidation settlement (e.g., Zhang et al. (2002)), using the equivalent clean sand normalized penetration resistance, $(q_{c1N})_{cs}$, from cone penetration test (CPT) data.

Tonkin and Taylor (2013) demonstrated a correlation between LSN and observed liquefaction damage following the 2010 – 2011 Canterbury earthquake sequence, based on an investigation comprising approximately 7000 CPTs, 1000 boreholes, and 800 groundwater monitoring wells. LSN is a suitable indicator of future liquefaction vulnerability in Christchurch (and possibly worldwide, given similar geological and geomorphological environments) and has been adopted for this analysis. Ranges of LSN and observed land performance are presented in Table 2.

Table 2. LSN ranges and observed land performance, adapted from Tonkin and Taylor (2013a).

LSN range	Estimated performance
0 – 10	Little to no expression of liquefaction, minor effects
10 – 20	Minor expression of liquefaction, some sand boils
20 – 30	Moderate expression of liquefaction, with sand boils and some structural damage
30 – 40	Moderate to severe expression of liquefaction, settlement can cause structural damage
40 – 50	Major expression of liquefaction, undulations and damage to ground surface, severe total and differential settlement of structures
>50	Severe damage, extensive evidence of liquefaction, severe total and differential settlements affecting structures, damage to services

The LSN integral may be evaluated over the entire depth of the investigation or truncated at a depth of interest. For purposes of this analysis, LSN was calculated over the entire depth of CPT investigation. Pre-drill was not performed for the CPTs used in the test program and all CPTs penetrated to a depth of at least 10 m, so the slice method as described by Tonkin and Taylor (2013a) was not necessary.

Procedure

An analysis was performed to assess changes in liquefaction vulnerability due to SLR for five sites in eastern Christchurch and Kaiapoi. An average LSN was calculated for each of the sites for each liquefaction scenario using CLiq (Geologismiki, 2006).

Site Selection

The five sites were selected to be representative of eastern Christchurch in terms of seismic performance. Data for the site selection were taken from the publicly available Canterbury Geotechnical Database (CGD). Sites were chosen only where mapped by the EQC as Technical Category 3 (TC3): "Liquefaction damage is possible in future large earthquakes". Within TC3 zones, sites within close proximity to oceans or river tidal reach areas were preferred in order to assume that SLR translated to an equal increase in groundwater surface elevation. The sites were screened to include data only from cone penetration tests (CPTs) where the depth of exploration was greater than 10 m to maintain a relative degree of similarity in LSN among the sites. A general description for each site is presented in Table 3.

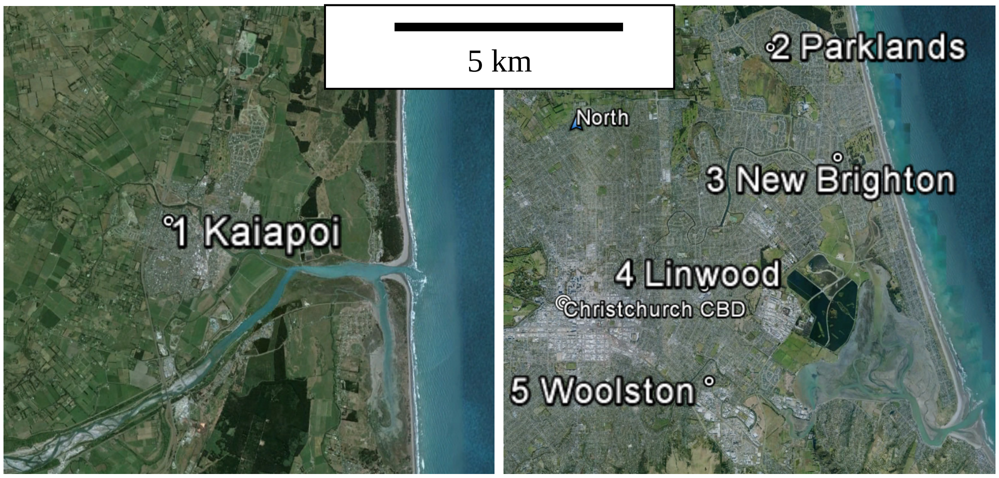

Figure 1. Site locations

Table 3. General soil description of sites.

Site name	Dominant soil type	Depth to groundwater[1] (m)
Kaiapoi	-Loose to medium dense silty sands / sandy silts or firm to stiff silt to 6.5 m below ground level (bgl) -Medium dense to dense sand / sandy gravel from 6.5 m bgl to 9.0 m bgl -Dense gravel below 9.5 m bgl	1.0
Parklands	-Loose to medium dense silty sand / sandy silt to 20 m bgl	2.0
New Brighton	-Loose to medium dense sand / silty sand to 20 m bgl	1.5
Linwood	-Dense sand / silty sand to 25 m bgl	1.5
Woolston	-Loose to medium dense silty sand / sandy silt or firm silt to 3.5 m bgl -Medium dense sand / silty sand from 3.5 m bgl to 18.5 m bgl -Firm to very stiff silt from 18.5 m bgl to 25 m bgl	2.5

[1]Median surface with surrogate means, obtained from the Canterbury Geotechnical Database (CGD) (van Ballegooy et. al. 2014).

Liquefaction Vulnerability Model Inputs

Reconsolidation settlement and LSN were calculated using the CLiq program (Geologismiki, 2006). Seismic loading parameters were adopted from Christchurch-specific government guidelines (MBIE 2012), for the Serviceability Limit State (SLS) and Ultimate Limit State (ULS) ground motions and are summarised in Table 4. The SLS and ULS ground motions have an annual probability of exceedance of 1/25 and 1/500, respectively for ordinary (Importance Level 2) structures (AS/NZS 1170.0). Liquefaction triggering was performed using the Boulanger and Idriss (2014) method. Fines content was estimated using the Roberston and Wride (1998) method, as no soil samples were retrieved during the subsurface investigations. Post-liquefaction reconsolidation settlements were calculated according to Zhang et al. (2002). A threshold probability of liquefaction, P_L, of 15 % was adopted according to MBIE (2014).

Groundwater depths for future scenarios were established by adding the depths given in Table 4 to the baseline groundwater depths given in Table 3 (i.e., current groundwater level taken from the CGD). When the resulting groundwater depth was determined to be at or above the existing ground level a depth to groundwater of 0.1 m bgl was adopted for purposes of calculating LSN.

Table 4. Test matrix used for parametric assessment of liquefaction vulnerability.

	Design Earthquake	
Analysis Timeframe	**SLS (a = 0.13 g, Mw = 7.5)**	**ULS (a = 0.35 g, Mw = 7.5)**
25 Years	0.15 m SLR	0.15 m SLR
50 Years	0.3 m SLR	0.3 m SLR
100 Years	1.0 m SLR	1.0 m SLR

Results and Discussion

LSN was calculated for each of the scenarios from the test matrix, averaged for each site for clarity, and is presented in Figure 2 a) and b). The minimum and maximum calculated values of LSN among the CPTs are presented as tick marks for each site.

For the assessment of land damage as a result of the CES a property is identified as vulnerable when it has a ULS LSN greater than 20. To assess if the change in the depth to groundwater for a particular property caused a significant change in liquefaction vulnerability we assumed that a change of ULS LSN of 3 or more was considered significant. Based on these criteria: (1) all of these sites are currently vulnerable to liquefaction except the Linwood site, (2) most of the sites will experience a significant change in vulnerability in the next 50 years, and (3) in 100 years all of the sites will be considerably more vulnerable to liquefaction than they are now. Given that LSN and similar indices are used to select foundations for new buildings and the building are designed to last at least 50 years, it would be prudent to consider the impact of SLR on foundation selection.

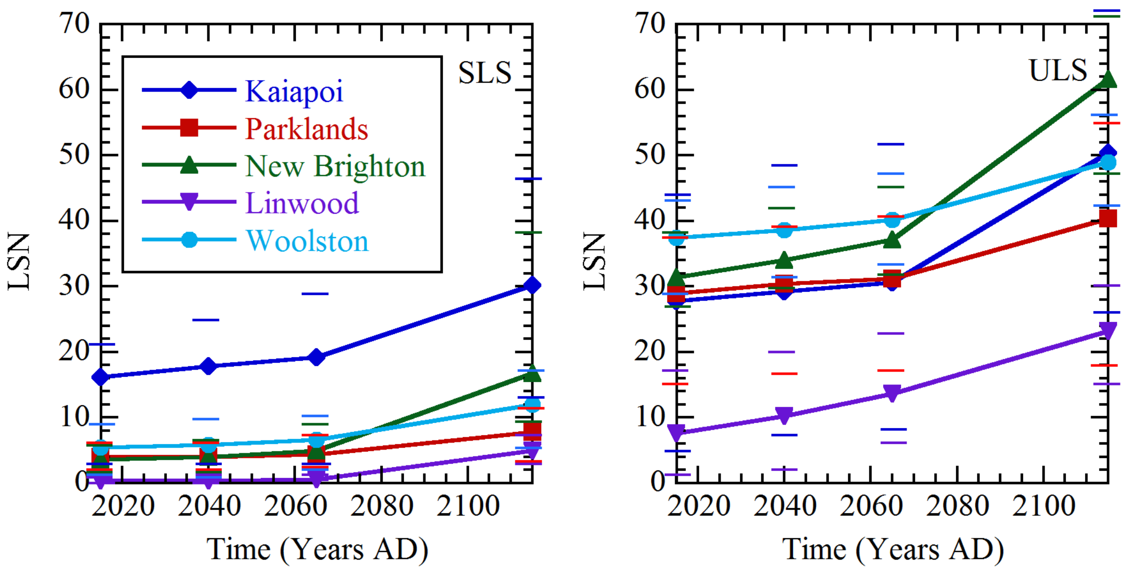

Figure 2 a) to b). Change in LSN with time due to SLR.

The uncertainty in LSN due to SLR may be attributed to uncertainty in the liquefaction triggering procedure and SLR model. The uncertainty in LSN within a single CPT dataset may be obtained by varying the P_L parameter in CLiq, based on Boulanger and Idriss (2014) then combined with the uncertainty from the IPCC (2013) SLR model. This preliminary approach would allow for low-budget, case-by-case assessments of potential increases in liquefaction vulnerability for coastal sites over a wide study area. The results could then be refined with a detailed model of the groundwater response to SLR.

Conclusions

A preliminary assessment was performed to determine the effects of climate-driven sea level rise (SLR) and earthquake ground motion on liquefaction vulnerability for five sites in eastern Christchurch. The analysis was performed with future SLR corresponding with 25 years, 50 years, and 100 years given the current state of knowledge of sea level projection models. The results indicate significant negative changes in vulnerability to liquefaction in the next 50 years. Further investigation should be undertaken to identify the extent and magnitude of increased vulnerability to liquefaction in Christchurch, Kaiapoi and other coastal cities in New Zealand and abroad. Engineering design and long-term city planning could benefit from considering the changes in liquefaction vulnerability due to climate change.

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