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Scrutiny of CPT-based liquefaction assessment procedures using case histories from the 2016 Kaikoura earthquake, New Zealand

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ABSTRACT: This paper explores the most recent set of liquefaction observations in New Zealand which resulted from the 2016 $M_W7.8$ Kaikoura earthquake, in which widespread manifestations of liquefaction occurred in the north of the South Island of New Zealand. Groundwater and ground motion models were developed for the affected region, which are implemented in the simplified CPT-based liquefaction assessment procedure using geotechnical data located in areas with and without surface manifestation. Combining the outcomes from these assessments with observational datasets provides a greater understanding of the predictive efficacy of these simplified frameworks and their applicability in engineering design and other applications. Areas where predictions are inconsistent with the observations are readily identified, highlighting some of the root causes for false-predictions. The case studies support the idea that hydraulic continuity between layers is fundamental to the system response of the soil profile, with inhibition of vertical dissipation of pore water pressures greatly reducing the likelihood of surface manifestations.

1 INTRODUCTION

Liquefaction of fine-grained, cohesionless soils has been observed in a number of developed areas throughout New Zealand due to the numerous earthquakes which have caused significant ground motions (van Ballegooy 2018). These observations have spanned the last 150 years with one of the most devastating examples being the 2010 – 2011 Canterbury Earthquake Sequence (CES) which produced widespread liquefaction-induced land damage. The vast economic, social, and environmental impacts of liquefaction and the damage imposed to 51,000 of the 140,000 residential properties in Christchurch (Wallace et al. 2012, Rogers et al. 2015) has left a lasting impact on New Zealand and the way this natural hazard is assessed and mitigated.

This paper explores the most recent set of liquefaction observations over the Lower Wairau Plains, in the north-eastern region of the South Island of New Zealand which were caused by the 2016 $M_W7.8$ Kaikoura earthquake. The observations included liquefaction in the form of sand boils, subsidence, and lateral-spreading and were accurately mapped through ground-based reconnaissance and remote sensing techniques. These observations are used to assess the predictive efficacy of the simplified Cone Penetration Test (CPT) frameworks. Regional depth to groundwater (GWD) and peak ground acceleration (PGA) surfaces are coupled in order to conduct a rigorous back-assessment of the manifestations. The sensitivity of the predicted consequence to GWD and PGA, in the form of the Liquefaction Severity Number (LSN), is then analysed to ascertain whether discrepancies between observed manifestations and estimated consequence can be explained by model uncertainty or if there are shortcomings to the simplified methods which need to be addressed going forward.

2 MANIFESTATIONS OF LIQUEFACTION OVER THE LOWER WAIRAU PLAINS

The study area comprises the Lower Wairau Plains which is bound by the north-east trending mountain ranges to the north and south and is presented in Figure 1. The main town in the area is Blenheim, a relatively small rural town having a population of approximately 30,000.

The depositional setting of soils in seismically prone areas is fundamental to the realisation of liquefaction and understanding this should be the first step in any liquefaction analysis. The depositional setting governs many of the soil properties such as density, plasticity, and grain structure which are fundamental to firstly, whether the soils are susceptible to liquefaction and secondly, the seismic demand required to trigger liquefaction. It is then the characteristics of the soil profile which can be explained by the depositional environment that governs the consequence at the ground surface of any liquefaction triggered.

The Lower Wairau Plains comprise the alluvial outwash plain of the Wairau River and are predominately underlain by re-worked glacial outwash gravels, sands, and silts originating from the surrounding mountains. The soils are a combination of Holocene age marine and estuarine silts and sands of the Dillons Point Formation and alluvial gravels and sands of the Rapaura Formation. The alluvial sediments are inter-fingered with lagonal muds and coastal sands, silts, and gravels of varying density and clay composition which reflects coastal progradation and marine regression following the mid-Holocene high stand some 6,000 years ago (Basher 1995). The nature of the soils and the presence of many fluvial features indicates that the soils present in the Lower Wairau Plains are likely to be susceptible to liquefaction.

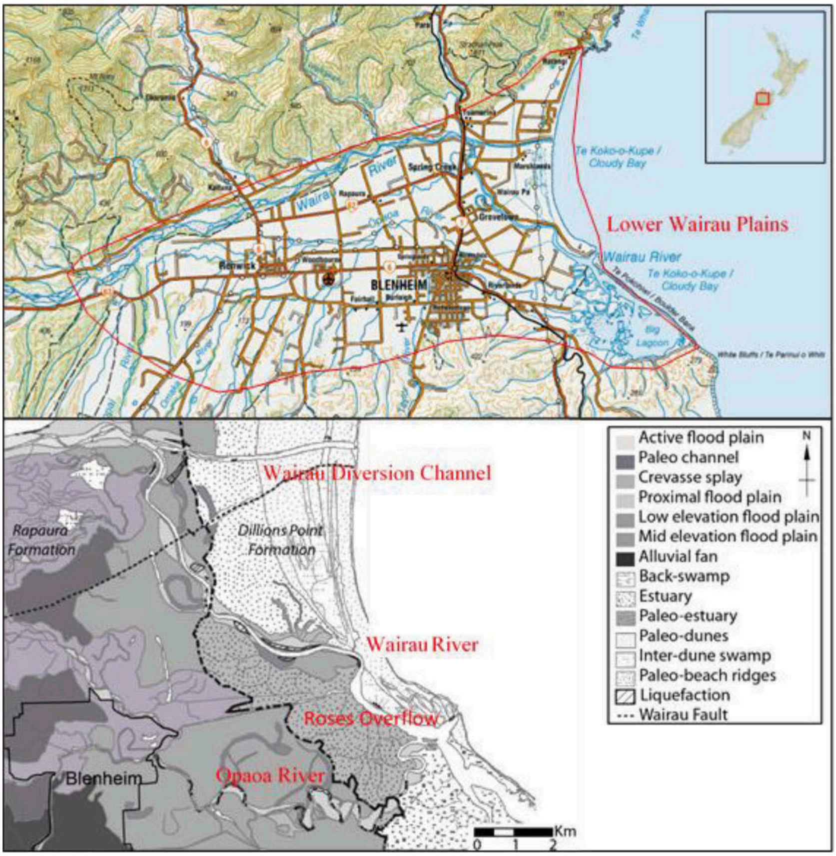


Figure 1. Study area; Lower Wairau Plains and associated geomorphology and underlying geological formations (Bastin 2018).

An important consideration for the Lower Wairau Plains is the significant anthropogenic modifications that have been carried out in an attempt by locals to mitigate the flooding hazard stemming from low-lying topography and proximity to the coast. These modifications have included construction of a network of stopbanks around the Taylor, Omaka, and Opaoa Rivers along with various river diversion channels as shown in Figure 1. The areas contained within the stopbank network are highly susceptible to flooding with over-bank floods regularly depositing low density fine-grained sands and silts.

2.1 *Historic manifestations*

The nature of the soils in the Lower Wairau Plains combined with the high local seismicity has meant that liquefaction has manifested on the plains following a number of historic earthquakes. These have included the M_W7.4–7.7 1848 Marlborough earthquake, M_W8.2–8.3 1855 Wairarapa earthquake, and the M_W6.5 2013 Lake Grassmere earthquake. The recorded observations are sparse but suggest liquefaction occurred proximal to the Grovetown oxbow lake and to the east of the township at various points along the Opaoa River, again emphasising the importance of geomorphological setting. The most historical observations have limited accuracy given the available technology and lack of knowledge concerning liquefaction at the time. Additionally the township was much less developed and the impact of liquefaction was not as consequential as if it were to happen today. However, at a high level, manifestations were generally located close to active or paleo-rivers. An unsurprising correlation give that fine-grained, low density deposits are most commonly associated with inner bends of meandering rivers as highlighted in Beyzaei (2017).

2.2 *2016 Kaikoura earthquake manifestations*

A significant degree of liquefaction was triggered during the 2016 M_W7.8 Kaikoura earthquake with moderate to severe levels of liquefaction and associated lateral-spreading observed

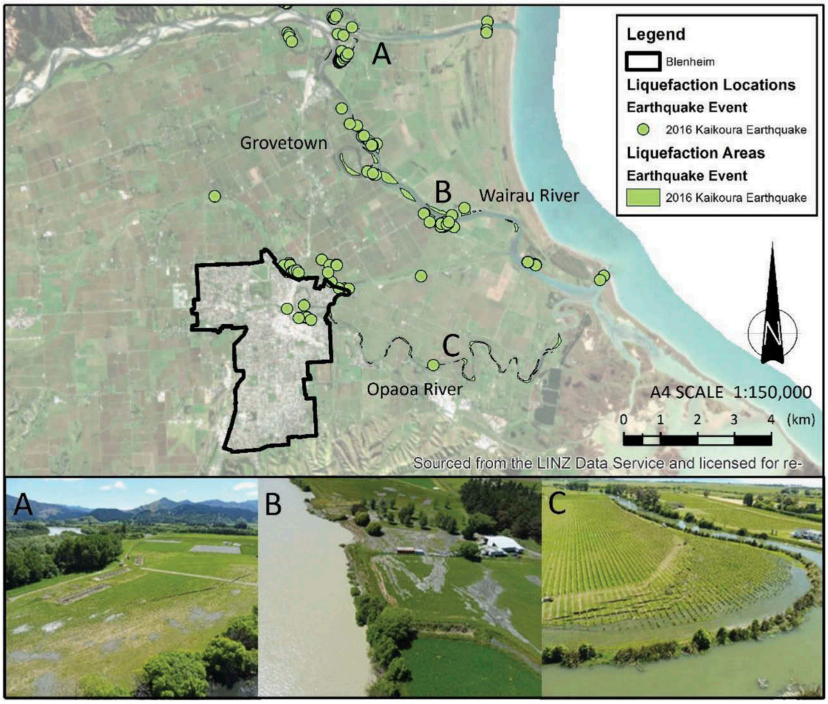


Figure 2. Liquefaction manifestations observed on the Lower Wairau Plains caused by the 2016 Kaikoura earthquake.

at a number of locations on the Lower Wairau plains. Mapping and subsequent refinement of the observational dataset has been carried out by a number of parties involved in the reconnaissance and post-earthquake assessments. Figure 2 presents the comprehensive collection of liquefaction manifestations which encompasses both ground-based and remote sensing derived observations.

3 SIMPLIFIED CPT-BASED LIQUEFATION ASSESSMENT FRAMEWORK

3.1 *General procedure*

For this study the semi-empirical Boulanger and Idriss (2014) triggering framework was used to assess the liquefaction potential of the soils. This framework is a stress-based methodology which has roots in work performed by Seed & Idriss (1971) and Whitman (1971). There have been subsequent revisions made to the original framework by various academics with New Zealand industry standards converging on the Boulanger and Idriss (2014) framework after this was found to provide the greatest correlation between predicted and observed levels of triggering based off land damage observations during the CES (Tonkin + Taylor 2015).

Liquefaction vulnerability parameters are commonly used to estimate the severity of liquefaction manifestation by combining the cumulative effects of strata predicted to liquefy based on the computed factor of safety against liquefaction triggering (FS). The FS is calculated as the ratio of the cyclic resistance to liquefaction to the cyclic demand imposed by the earthquake loading. For this study the Liquefaction Severity Number (LSN) as presented in van Ballegooy et al. (2013) is used for estimating the consequence and predicting liquefaction manifestation at the ground surface.

The input parameters adopted and which are carried through the Boulanger and Idriss (2014) framework are summarised in Table 1. They generally correspond to the default values as there was insufficient laboratory data across the CPT dataset to warrant modifying these values. In order to minimise conservatism in the back-assessment a 50th percentile probability of liquefaction (P_L) triggering curve is applied. This is to ensure that there is the best balance between manifestation and no manifestation in the case history dataset from which the CRR curved is derived in the Boulanger and Idriss (2014) framework. A soil behaviour type index (I_C) cutoff of 2.6 has been applied for screening of soils layers which are too plastic to liquefy.

4 BACK-ANALYSIS OF LIQUEFACTION MANIFESTATIONS FROM THE 2016 KAIKOURA EARTHQUAKE

4.1 *Inputs to the regional back-analysis*

The back-assessment of the manifestations of liquefaction presented in Figure 2 required collation of all available CPTs over the Lower Wairau Plains along with development of GWD and PGA surfaces. The CPT dataset was extended through the course of the research with funding from Marlborough District Council (MDC) and support from QuakeCoRE to produce the dataset given in Figure 3. The CPTs were then classified depending on whether the point locations where the CPTs were pushed exhibited surface manifestations of liquefaction.

Table 1. Input parameters for the CPT-based liquefaction assessment procedure utilising Boulanger and Idriss (2014) framework.

Parameter	Value adopted in this study
Soil density	18 kN/m^3
I_C cutoff	2.6
FC – I_C correlation	$C_{FC} = 0.0$
CRR triggering curve	P_L =50 %

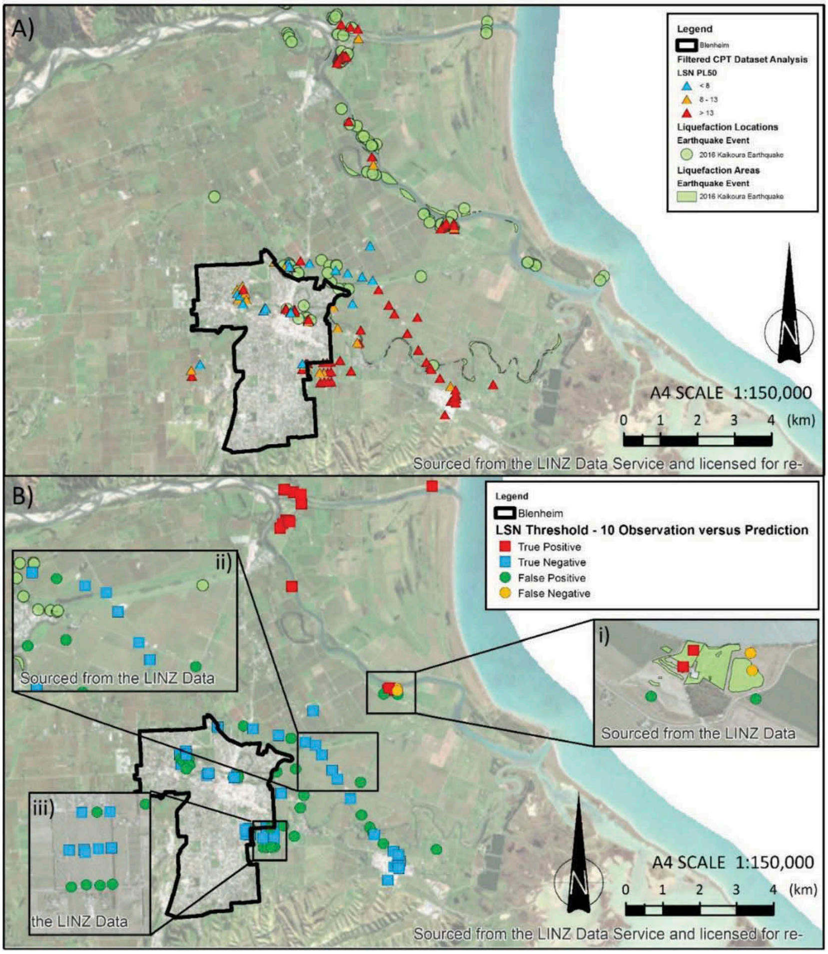


Figure 3. A) Computed LSNs for CPTs available over the Lower Wairau Plains overlaid on liquefaction observations for the 2016 Kaikoura earthquake B) Nature of the liquefaction prediction for each CPT sounding, note significant over-prediction in the south-west shown in inset iii).

A median GWD model was computed over the Lower Wairau Plains by first developing a groundwater level surface and then subtracting this from the elevation model for the area. The groundwater level surface was generated by interpolating a set of points corresponding to the coastline, major tributaries, and in-land groundwater measurements made in intrusive investigations. A number of draw down points were also included in the pre-interpolation dataset in order to ensure that areas of negative GWD were removed. As a reference, a study by Davidson & Wilson (2011) provides a thorough description of the groundwater regime of the Lower Wairau Plains. Their analyses indicate that GWD is approximately 2 m below ground level for much of the eastern parts of the plains and flows from west to east.

For the estimation of PGA over the Lower Wairau Plains during the 2016 Kaikoura earthquake this study has had access to the recently developed physics-based simulation produced by parallel QuakeCoRE flagship projects. By comparing the model with the strong motion station records in the region it would suggest that the physics-based simulation overestimates PGA by some 10–20%. Opposed to correcting the model this over-prediction was assessed through sensitivity analyses which are discussed below.

3.4 *Analysis results*

The computed LSNs at each CPT location using the procedure and inputs discussed above is given in Figure 3A. The results for each CPT are then classified in into one of four prediction outcomes as presented in Maurer et al. (2015). The outcomes for a prediction such as whether liquefaction manifests or not are one of positive or negative depending on whether liquefaction is predicted to manifest or not and true or false depending on whether the prediction is correct.

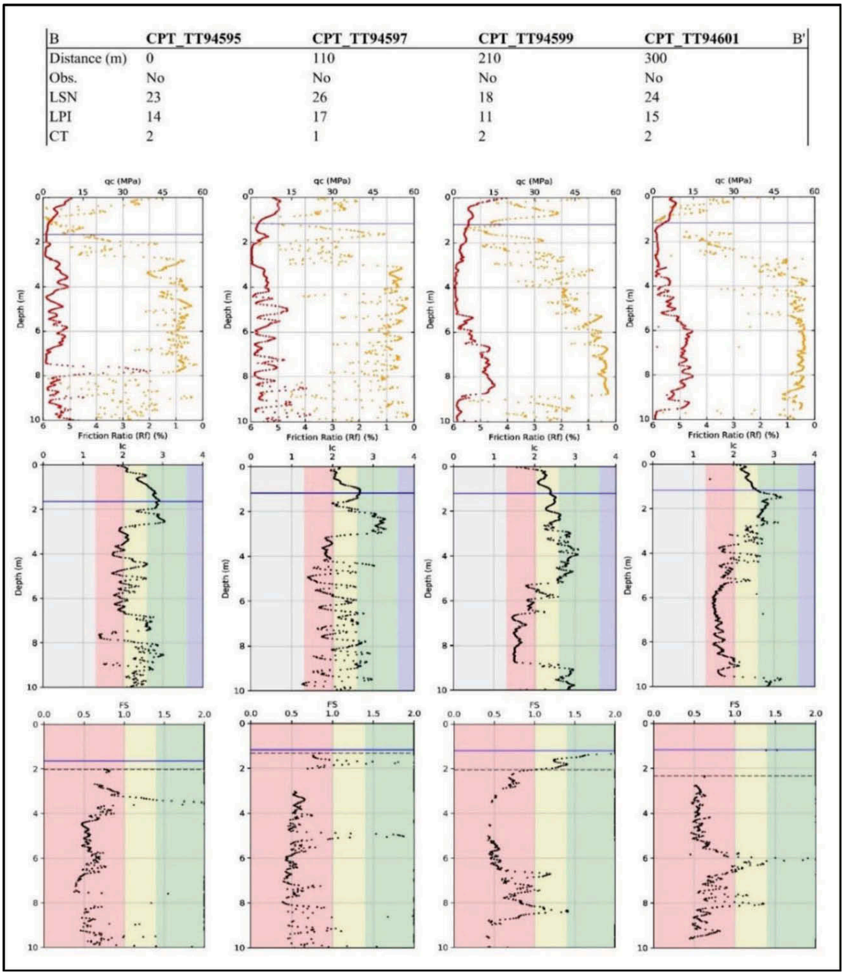
The results, when grouped according to these classifications, demonstrate the significant over-prediction in the simplified methods when applied to the CPT dataset over the Lower Wairau Plains with a large number of false positive predictions calculated as shown in Figure 3B. In general, where liquefaction occurred the simplified methods were able to accurately predict the manifestation of liquefaction with only two false negatives calculated. Sensitivity of the prediction efficacy to GWD and PGA estimates was inspected and it was found that some of the over-prediction could be attributed to this, however there is still significant over-prediction.

5 DISCUSSION

The study has demonstrated the significant degree of misprediction that can arise in certain soil conditions when the simplified methods are used to estimate liquefaction manifestation. This was shown by the large number of false positives that were calculated when the observations and predictions were compared for the 2016 Kaikoura earthquake. Sensitivity analyses concerning GWD and PGA estimates only improved the prediction at a small number of locations which is discussed in greater detail in Ogden (2018). The sensitivity of calculated LSNs to shallow GWD estimates and the potential contribution of this to over-prediction was highlighted, where seasonal variations and partial saturation effects could increase the true in-situ GWD. A reasonable alignment between observation and prediction was demonstrated when GWD was increased at locations characterised by relatively uniform, non-interlayered profiles. On a regional level, when GWD was increased to an upper bound for the region (deepest groundwater levels) the number of false positives decreased. However, as this happened, new false negatives were introduced. Therefore GWD could be a contributing factor to misprediction, but it was unlikely to be the primary source for over-prediction for the Lower Wairau Plains.

The major discrepancies between the observations and the predictions from the simplified methods largely arises from complexities in the subsurface stratigraphy. This was most clearly demonstrated in two areas. For the CPT traces available in these areas it was inferred that a 3 m silt capping layer is underlain by interlayered silts and sands of various densities as shown for a particular transect of CPTs in Figure 4. The same trend was present at sites which had manifestations of liquefaction, however, these generally coincided with zones of lateral-spreading which creates complexities in terms of vertical dissipation of pore pressures. As the deeper layers liquefied, the overlying soils could move laterally creating cracks, which in-turn would provide preferential pathways through which the liquefied material could surface under the developed excess pore pressures. Cubrinovski et al. (2017) demonstrated the importance of the system response of liquefiable dissipation with the inhibition of vertical pore-pressures greatly reducing the likelihood of liquefaction manifestation at the ground surface. This study has provided further case studies which supports this theory and that accurate predictions of liquefaction using the current simplified methods and therefore land damage is unlikely in highly stratified soil profiles.

The false positive predictions have significant implications for many stakeholders including engineers with liquefaction prone land, risk analysts involved with loss estimation, and insurance providers and regulators. Therefore, it is imperative to understand the conditions under which inaccurate predictions are likely in order to refine assessment procedures and offer less conservative solutions such to minimise overstating of the liquefaction hazard and prohibitive remediation solutions.



B	CPT_TT94595	CPT_TT94597	CPT_TT94599	CPT_TT94601 B'
Distance (m)	0	110	210	300
Obs.	No	No	No	No
LSN	23	26	18	24
LPI	14	17	11	15
CT	2	1	2	2

Figure 4. Transect of CPTs in Area iii) in Figure 3 comparing unprocessed CPT data, I_C, and FS against liquefaction triggering for input conditions. Shallow groundwater estimates and interlayered soils likely reasons for false positive predictions for these CPTs.

6 CONCLUSIONS

The findings from this study have highlighted the significant degree of over-prediction that can be computed when using the simplified CPT-based procedures. Shortcomings in the simplified methods ultimately related to the inability of the methods in their current form to account for system effects when soil stratigraphy is heterogeneous. The importance of accurate GWD and PGA estimates in achieving correct predictions of liquefaction manifestation was also highlighted as this accounted for some part of the over-prediction.

However, interlayered soils profiles in which there is significant discontinuity between liquefiable layers can provide a significant resistance to liquefied sediments reaching the ground surface. The case histories provided by the 2016 Kaikoura earthquake reinforce that the inconsistences found in liquefaction assessments during the CES are applicable in other regions of New Zealand and therefore caution should be warranted when these methods are applied in similar ground conditions.

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REFERENCES

Basher, L. R., 1995. Geomorphology of the Wairau Plains: implications for floodplain management planning, Manaaki Whenua Press

Bastin, S. H., Ogden, M. L., Wotherspoon, L. M., van Ballegooy, S., Green, R. A., & Stringer, M. (2018).Geomorphological influences on the distribution of liquefaction in the Wairau plains, New Zealand, following the 2016 Kaikōura earthquake. Bulletin of the Seismological Society of America.

Beyzaei, C. Z., Bray, J. D., van Ballegooy, S., Cubrinovski, M., & Bastin, S. (2018). Depositional environment effects on observed liquefaction performance in silt swamps during the Canterbury earthquake sequence. Soil Dynamics and Earthquake Engineering, 107, 303–321.

Boulanger, R. W. & Idriss, I. M., 2014. CPT and SPT based liquefaction triggering procedures. Centre for Geotechnical Modelling.

Bray, J. D. & Sancio, R. B., 2006. Assessment of the Liquefaction Susceptibility of Fine-Grained Soils. Journal of Geotechnical and Geoenvironmental Engineering, 132(9),pp.1165–1177.

Cubrinovski, M., Rhodes, A., et al., 2017. System Response of Liquefiable Deposits. 3rd International Conference on Performance-based Design in Earthquake Geotechnical Engineering, p.18.

Davidson, P. & Wilson, S., 2011. Groundwaters of Marlborough, Marlborough District Council.

Ogden, M. L., 2018. Assessment of Liquefaction Manifestations from New Zealand Case Histories. Master of Engineering Thesis, University of Auckland, New Zealand.

Maurer, B. W., Green, R. A. & Taylor, O. D., 2015. Moving towards an improved index for assessing liquefaction hazard: Lessons from historical data. Soils and Foundations, 55(4),pp.778–787.

Rogers, N. et al., 2015. Considering Post-Disaster Damage to Residential Building Construction - Is Our Modern Building Construction Resilient? 6th International Conference on Earthquake Geotechnical Engineering, Christchurch, (November).

Seed, H. B. & Idriss, I. M., 1971. Simplified procedure for evaluating soil liquefaction potential. Journal of Geotechnical Engineering Division, 97(9),pp.1249–1273.

Tonkin + Taylor, 2015. Canterbury Earthquake Sequence: Increased liquefaction vulnerability assessment methodology, Auckland.

van Ballegooy, S. et al., 2013. LSN – a new methodology for characterising the effects of liquefaction in terms of relative land damage severity. In 19th NZGS Geotechnical Symposium. Queenstown.

van Ballegooy, S, 2018. Use of geotechnical and liquefaction observation GIS databases for liquefaction hazard mapping. In International Conference on GIS and Geoinformation Zoning for Disaster Mitigation.

Wallace, S. C., Macdonald, A. J. & Murahidy, K. M., 2012. Observation and characterisation of land damage due to liquefaction and lateral spreading. In ANZ 2012 Conference Proceedings. pp. 1485–1490.

Whitman, R. V., 1971. Resistance of soil to liquefaction and settlement. Soils and Foundations, 11(4), pp.59–68.