6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch, New Zealand

Correlation of Differential Building Settlement with Predicted CPT-based Liquefaction Vulnerability Parameters

L. Chapman[1], S. van Ballegooy[2], G. Ashby[3], V. Lacrosse[4] and S. Burgess[5]

ABSTRACT

Many buildings within the Canterbury region which were located in areas which experienced liquefaction related land damage as a result of the 2010 - 2011 Canterbury Earthquake Sequence (CES), suffered damaging differential settlement to their foundations. Housing New Zealand Corporation (HNZC) and the Ministry of Education (MOE) undertook a large number of surveys of the internal differential floor levels of their buildings to inform damage assessments and repair strategies after the CES. This paper uses the HNZC and MOE internal floor survey data together with the liquefaction analysis from Cone Penetration Test (CPT) investigations to examine the correlation between various predicted liquefaction vulnerability parameters (LVP) and measured Building Differential Settlement (BDS). The results of the CPT-based liquefaction analyses show that when low LVP values are predicted the distribution of measured BDS is predominantly within construction tolerances (i.e. < 25 mm). Conversely, at higher calculated LVP values the distribution of measured BDS reflects a greater likelihood of more severe BDS. This type of correlation can be useful for loss modelling purposes as well as informing the design requirements of foundation systems for new buildings on potentially liquefiable soils.

Introduction

The 2010 – 2011 Canterbury Earthquake Sequence (CES) affected the Canterbury region of New Zealand resulting in widespread ground surface deformation, mainly due to liquefaction ejecta, liquefaction related ground volumetric densification, topographic relevelling and lateral spreading. The main events in the CES occurred on 4 September 2010 (M_w 7.1), 22 February 2011 (M_w 6.2), 13 June 2011 (M_w 5.6 and M_w 6.0 separated by 80 minutes), and 23 December 2011 (M_w 5.8 and M_w 5.9 separated by 80 minutes). The liquefaction affected 51,000 residential properties and damaged approximately 15,000 residential houses beyond economic repair (Rogers et al., 2015).

Housing New Zealand Corporation (HNZC), the government owned social housing provider, owned over 5,500 light weight residential houses on shallow foundations across Christchurch prior to the CES. Many HNZC properties were located within the suburbs affected by liquefaction-related land damage. School buildings owned by the Ministry of Education (MOE), typically on shallow foundations, also suffered damage as a result of the liquefaction triggered

[1]Geotechnical Engineer, Tonkin & Taylor Ltd, Auckland, New Zealand, lchapman@tonkin.co.nz
[2] Senior Geotechnical Engineer, Tonkin & Taylor Ltd, Auckland, New Zealand, svanballegooy@tonkin.co.nz
[3]Senior Geotechnical Engineer, Tonkin & Taylor Ltd, Christchurch, New Zealand, gashby@tonkin.co.nz
[4]Geotechnical Engineer, Tonkin & Taylor Ltd, Auckland, New Zealand, vlacrosse@tonkin.co.nz
[5] Engineering Assistant, Tonkin & Taylor Ltd, Christchurch, New Zealand, sburgess@tonkin.co.nz

by the main CES events. In order to inform both building damage assessments (for insurance purposes) and repair strategies, both HNZC and MOE undertook structural assessments of their buildings. These assessments also included completing floor level surveys to measure differential movement over the building footprints from which the maximum measured differential floor level (referred to herein as Building Differential Settlement or BDS) was calculated. The spatial location of the 923 HNZC and 593 MOE buildings for which BDS results are included in this study relative to the observed land damage and liquefaction related subsidence for the CES are shown in Figure 1.

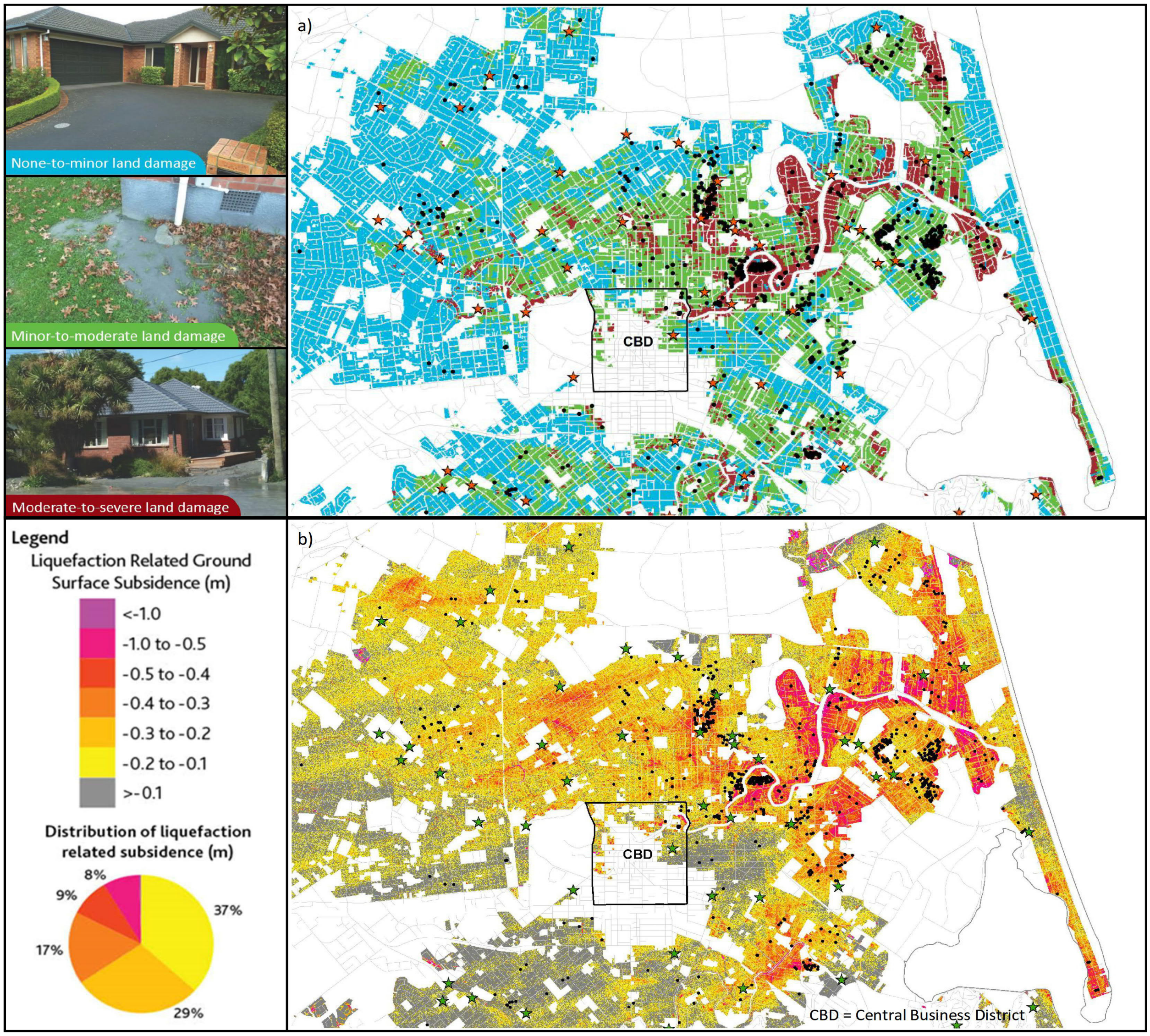

Figure 1: (a) Map of the observed land damage and (b) the liquefaction related subsidence as a result of the CES. Black dots show the location of HNZC houses with BDS surveys and orange or green stars (a and b) show the location of the MOE school buildings with BDS surveys.

Visual assessment of foundation damage was carried out on 60,000 residential houses in Christchurch by geotechnical engineers as part of detailed land damage assessments for the New

Zealand Earthquake Commission (EQC). Assessments were predominantly focused in the suburbs where the houses were affected by liquefaction related land damage. The results of these assessments are described in Rogers et al. (2015). Visually observed liquefaction related damage to residential house foundations, was assessed based on criteria reflecting the type of damage and its severity. The visual assessments were categorised on the EQC property assessment forms into one of three foundation damage categories comprising either none to minor (BDS < 20 mm), moderate (BDS ranging from 20 to 50 mm) or major (> 50 mm). Roger et.al. 2015 shows that the 16,000 houses which were assessed as having experienced major differential settlement were likely to have experienced moderate-to-severe mapped land damage and more than 200 mm of liquefaction related subsidence (Rogers et al., 2015). It is noted that the EQC dataset is based on visual observations that have a higher degree of uncertainty and are also discretely categorised whilst the HNZC and MOE dataset is based on measured survey data with a lower degree of uncertainty and is also a continuous measurement. The purpose for including the larger EQC foundation damage assessments dataset is that it has less spatial bias compared with the HNZC and MOE dataset and provides a useful basis for comparing correlations.

A major focus of researchers, practitioners, and regulators has been to maximise the learnings from the CES and develop approaches for evaluating risks associated with damage to buildings due to liquefaction in future earthquakes. To support this, the study presented herein aims to establish correlations between measured BDS for residential-type buildings on shallow foundations with observed land damage and liquefaction related ground surface subsidence (shown in Figure 1) as well as five Cone Penetration Test (CPT)-based Liquefaction Vulnerability Parameters (LVP). These LVPs are described in van Ballegooy et al. (2015) and include Cumulative Thickness of the Liquefying soil layers (CTL), one-dimensional post-liquefaction reconsolidation settlement (S_{V1D}), Liquefaction Potential Index (LPI), modified Liquefaction Potential Index (LPI_{ISH}) and Liquefaction Severity Number (LSN).

Building Construction Type and Building Differential Settlement Surveys

HNZC houses in Christchurch are timber framed buildings that are typically one or two storey, single or twin occupancy dwellings with an average size of approximately 100 m^2 and relatively simple floor plans. The building foundations typically consist of either short bearing piles with a concrete sub-floor perimeter wall on a strip foundation (described as a Type B foundation in the MBIE, 2012 guidelines), or, short bearing piles without a perimeter wall (Type A foundation). A relatively small number have concrete slab on grade foundations (Type C). Approximately two thirds of the MOE school buildings were constructed before 1990 and one third after 1990. The majority of structures are relatively light-weight single or two storey timber framed buildings. Larger hall and gymnasium type buildings are essentially “warehouse” type buildings with larger span portal frames and at least partial-height concrete or brick/masonry block walls. Typically classroom buildings built prior to 1990, have Type B foundations, whereas buildings typically constructed after 1990, often comprise reinforced concrete slab footings with local thickenings for load bearing walls and columns (Type C). Within the dataset used for this study, the MOE building floor areas varied from 41 m^2 to 1657 m^2 with a median floor size of 240 m^2.

The floor level surveys which were used to assess the BDS are considered to be accurate to ± 3 mm. The survey procedures ensured suitable coverage of floor areas and were undertaken in a manner that enabled construction features to be identified and factored into BDS assessments. From these surveys the BDS was calculated between the two most out of level points (i.e., the highest and lowest elevation points across the building footprint). The floor level assessments were predominantly completed for buildings in areas with higher levels of liquefaction related land damage and liquefaction related subsidence (as shown in Figure 1) and hence there is bias in the dataset. It is noted that the available BDS data was independent of the length over which the differential settlement occurs. This is a limitation of the BDS data, because the angular distortion component (which was not recorded) is also an important factor affecting the superstructure damage. A limited floor level survey of HNZC houses of similar construction type and age to the Christchurch building stock was undertaken outside of Canterbury. This provided an indication of the typical BDS (i.e. the construction tolerance) for such houses in other parts of New Zealand with similar ground conditions that had not experienced major earthquake shaking. The results indicate that the average BDS (i.e. the construction tolerance) for the different foundation types is typically < 25 mm (summarised in Table 1 below).

Table 1: Average measured differential floor levels for HNZC houses outside of Canterbury.

	Foundation Type			**Total**
	Type A	Type B	Type C	
Number of houses surveyed	22	29	7	58
Average differential floor level	27 mm	23 mm	15 mm	23 mm

Correlation between BDS, Observed Land Damage and Liquefaction Related Subsidence

The BDS data correlates strongly with the observed land damage across the CES. The histogram in Figure 2a shows the frequency distribution of measured BDS for the none-to-minor, minor-to-moderate and moderate-to-severe land damage groupings. The majority of buildings with smaller measured BDS (i.e., 25 to 50 mm range) were on land with none-to-minor observed land damage. Conversely, the majority of buildings with larger measured BDS (i.e., 125 to 150 mm range) were on land with minor-to-moderate observed land damage. The distribution of land damage for the buildings with BDS < 25 mm (i.e. within construction tolerances) is approximately 50% none-to-minor, 40% minor-to-moderate and 10% moderate-to-severe (refer to Figure 2b). When compared to the EQC dataset of residential houses with none-to-minor foundation damage (corresponding to < 25 mm of visually observed foundation differential settlement), the distribution of land damage is approximately 70% none-to-minor, 25% minor-to-moderate and 5% moderate-to-severe (refer to Figure 2c). The difference in the distributions between the datasets is probably because there is relatively little BDS data for HNZC and MOE buildings in areas with no observed land damage. This is because buildings in such areas were generally not reported to have significant foundation damage and hence were not surveyed.

Both the HNZC and MOE and EQC datasets show that BDS > 50 mm, which indicates when foundation re-levelling or repair/rebuild is recommended (MBIE, 2012), predominantly occurs in areas subject to minor-to-moderate and moderate-to-severe liquefaction-induced land damage. Both datasets also show that BDS < 25 mm (i.e. within construction tolerance) generally occurs on land with none-to-minor observed land damage. However, between about 30% and 50% of such buildings are also on land that experienced minor-to-moderate and moderate-to-severe liquefaction induced land damage. This is because not all liquefaction-induced land damage results in significant BDS as some buildings subside reasonably uniformly.

The HNZC and MOE dataset also correlates closely with liquefaction related land subsidence across the CES. The histogram in Figure 2d shows the frequency distribution of measured BDS for three groupings of liquefaction related subsidence 0 to 200 mm, 200 to 400 mm and > 400mm. The majority of buildings with smaller measured BDS (i.e. 25 to 50 mm range) were on land where the liquefaction related subsidence was < 200 mm. Conversely, buildings with larger measured BDS (i.e. > 100 mm) were on typically land where the liquefaction related subsidence was > 400 mm. The histogram in Figure 2e shows the frequency distribution of liquefaction related subsidence for four groupings of measured BDS for the HNZC and MOE dataset; 0 to 25 mm, 25 to 50 mm, 50 to 100 mm and > 100 mm. These distributions can be directly compared to the histogram in Figure 2f, which shows the frequency distribution of liquefaction related subsidence for three groupings of visually observed foundation damage for the EQC dataset, which were classified as either none to minor (which approximately equates to 0 to 25 mm of BDS), moderate (which approximately equates to 25 to 50 mm of BDS) or major (which approximately equates to > 50 mm of BDS).

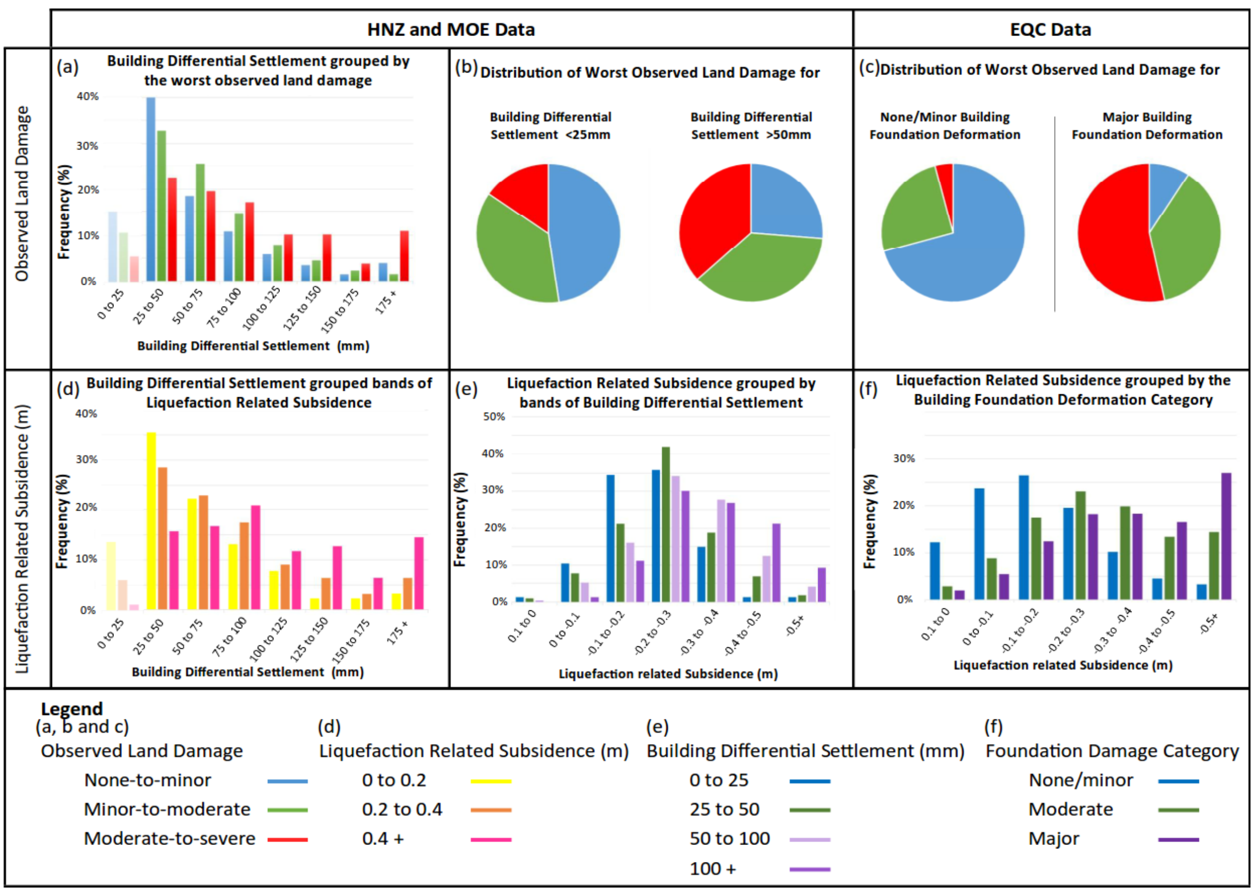

Figure 2: (a and b) show the correlation between the observed land damage and BDS and (d and e) show the correlation between the estimated liquefaction related subsidence and BDS at the HNZ and MOE sites where BDS measurements were undertaken. (c and f) show the equivalent correlations with the observed EQC foundation damage dataset (right column).

Both the HNZC and MOE and EQC datasets show that as liquefaction related subsidence increases the proportion of buildings with measured BDS or visually observed differential settlement > 50 mm increases. Conversely, the proportion of buildings with measured BDS or visually observed differential settlement < 25 mm decreases. These observations are consistent with the results from blast-induced liquefaction trials summarised in Wentz et al. (2015), which found that the measured differential ground surface settlement increased with measured total liquefaction related ground surface settlement, and was generally of the order of 20% to 50% of the total liquefaction related ground surface subsidence. No statistically significant differences were observed between measured BDS for Type A, B or C foundations within the HNZC and MOE dataset. This is consistent with the observations made in Rogers et al. (2015), which showed that the BDS is independent of foundation type.

Correlation between BDS and Liquefaction Vulnerability Parameters

While the correlation between BDS and land damage (shown in Figure 2) is useful, prediction of BDS requires prediction of the expected land performance. CPT-based LVPs are typically used to predict land damage (i.e., CTL, S_{V1D}, LPI, LPI_{ISH} and LSN) as discussed in van Ballegooy et at. (2015). However, there is dispersion in the correlation between the LVPs and observed liquefaction related land damage and similarly, there is dispersion in the in the correlation between BDS and land damage. Therefore, in order not to compound uncertainty the BDS dataset has been directly correlated to the CPT-based LVPs (Figure 3). These LVPs all use a liquefaction triggering analysis as one step in their calculation. For the present study, the liquefaction triggering analyses were performed using the Boulanger and Idriss (2014) liquefaction triggering procedure assuming a Probability of Liquefaction (P_L) of 15%, the default Boulanger and Idriss (2014) Fines Content (FC) correlation with the soil behaviour type index (I_c) with a FC-I_c correlation fitting parameter of C_{FC} = 0. Soils with an I_c > 2.6 were assumed to be non-liquefiable. The Peak Ground Acceleration (PGA) values for each of the main CES events were obtained from the PGA contour maps prepared by Bradley and Hughes (2012) and the groundwater levels at each building for each main earthquake event were obtained from the Tonkin & Taylor (2013) event specific ground water models. All five LVPs were computed based on only the top 10 m of any CPT sounding; this cut-off depth had negligible effect on the relationship between computed LVPs and observed damage because the liquefiable sediments are generally at shallower depths and the depth weighting functions in the LPI, LIP_{ISH}, and LSN vulnerability parameters reduce the impacts of any liquefiable soil layers at depth.

Calculated LVPs have been interpolated between CPT investigation locations (available from the Canterbury Geotechnical Database; https://canterburygeotechnicaldatabase.projectorbit.com) using a proximity-weighted technique to determine characteristic values at each of the HNZC properties and the MOE building footprints. This involves simplifications which do not allow for the detailed examination of site-specific conditions that can influence the evaluation of potential ground deformations e.g., local geologic details, horizontal or vertical continuity of liquefiable layers, thickness and competency of the non-liquefiable crust layer, thin-layer effects, information from site-specific laboratory test data, or site geometry. This contributes to dispersion in the BDS correlations shown in Figure 3. Nonetheless, the automated analyses provide an ability to broadly correlate the calculated event specific LVPs with the measured BDS for the purpose of damage prediction of a building portfolio built on liquefaction susceptible soils at various design levels of earthquake shaking in other parts of New Zealand.

One of the main limitations of the measured BDS dataset is that it represents the cumulative measured BDS at the end of the CES (as a result of all the earthquakes) and it is not possible to apportion the cumulative BDS to the individual earthquake events. Therefore, an assumption was made to correlate the BDS data to the maximum calculated LVP value at each building location for the four main CES events. Figure 3 shows the correlation between the maximum calculated liquefaction vulnerability parameter for the four events with the measured BDS for the HNZC and MOE datasets. All of the calculated LVPs show similar trends, lower values of BDS, i.e. < 50mm, at lower values of the LVPs and higher values of BDS, i.e. > 50mm, at higher values of the LVPs. For example, the results show that if the calculated LSN is between 0 and 5, 55% of properties have a BDS of < 25 mm and only 25% have a BDS of > 50 mm. Conversely, if the LSN is > 30, 70% of properties have a BDS of > 50 mm and only 10% of properties have a BDS of < 25 mm. It is important to note that some properties which have been subjected to high levels of land damage and hence and have corresponding high LVP values, have low BDS values. This is due to variances in the LVP predictions and because not all buildings settle differentially and a proportion have either settled relatively uniformly, and hence have not suffered significant BDS, or re-levelled naturally following subsequent seismic events.

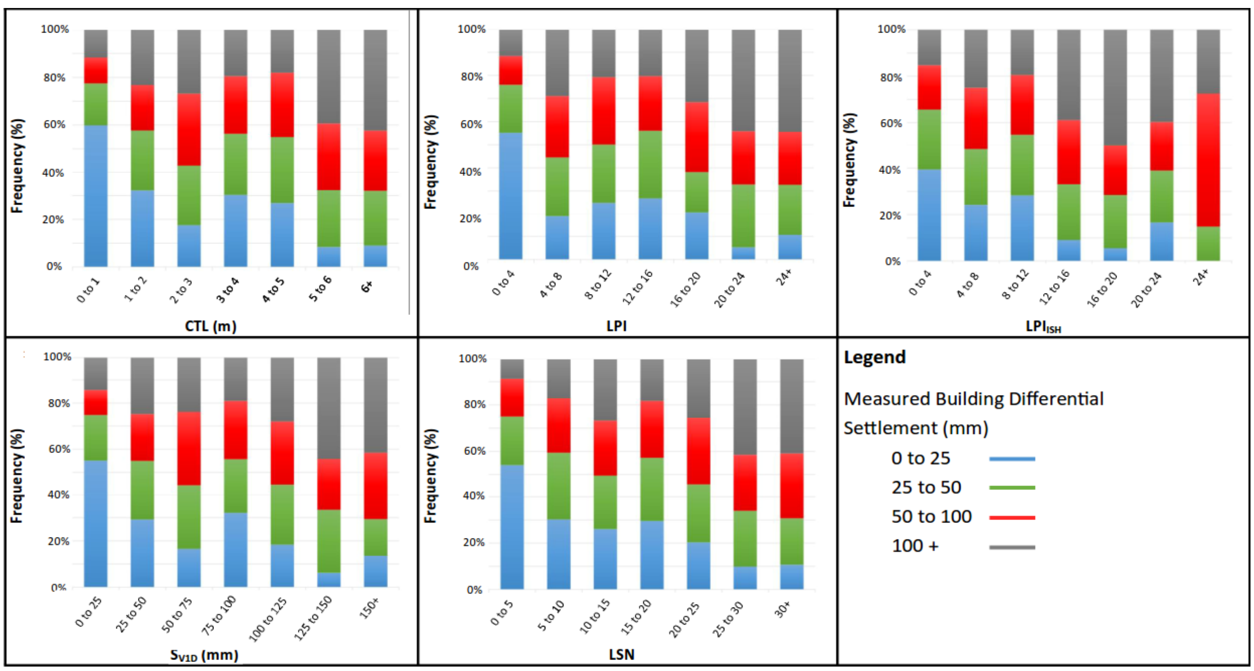

Figure 3: The distribution of worst calculated LVPs (CTL, LPI, LPI_{ISH}, S_{V1D} and LSN) for the CES events based on the CPT dataset for various bands of HNZC and MOE BDS survey results.

Discussion and Conclusions

Based on the results of the correlations developed it is evident that there is a link between BDS and land damage as well as BDS and liquefaction related subsidence. BDS is typically low when there is no liquefaction related land damage and liquefaction related subsidence is small. When liquefaction related land damage is moderate to severe and the liquefaction related subsidence is greater than 200mm then there is a high likelihood of high BDS (> 50mm). No statistically significant differences were observed between measured BDS for Type A, B or C foundations within the HNZC and MOE dataset. This is consistent with the observations made in Rogers et al. (2015), which showed that the BDS is independent of foundation type.

The LVPs analysed as part of this paper all show a similar correlation with BDS. As the value of calculated LVP increases then the likelihood of significant differential settlement within a building foundation increases. Low calculated LVP values correlate with a high percentage of properties with low BDS while high calculated LVP values correlate to a high percentage of properties with high BDS and a low percentage of properties with low BDS. These relationships can be used to estimate the likelihood of damaging differential building settlements for loss modelling purposes, and can also be used to help estimate potential foundation reinstatement costs using simplified CPT-based liquefaction assessment methods. It is noted that not all liquefaction-related land settlement results in damaging differential settlement within a building. Some buildings appear to settle fairly uniformly even though they might be located in areas with higher levels of overall liquefaction related subsidence.

The floor level surveys were predominantly completed in areas that experienced higher levels of liquefaction related land damage and have higher calculated LVPs. Therefore, there is bias in the HNZC and MOE dataset. The authors consider that undertaking further BDS surveys within areas that have suffered none to minor levels of liquefaction related land damage and have lower calculated LVPs is likely to greatly improve the balance of the dataset and reduce the dispersion in the correlations. Notwithstanding, the simplifications which have been used to calculate the LVPs make the correlations more suitable for regional studies rather than site specific liquefaction assessments. Site specific assessment of FC-I_c correlations, I_c cutoff thresholds and detailed evaluation of site specific groundwater levels are likely to improve the correlations and further reduce the dispersion.

Acknowledgments

This work was made possible by the BDS dataset provided courtesy of HNZC and MOE and the EQC foundation damage dataset provided courtesy of the EQC. In addition, the site investigation data used to calculate the LVPs have been accessed through the CGD.

References

Boulanger, R. W., & Idriss, I. M. (2014). *CPT and SPT based liquefaction triggering procedures.* Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis, CA. Report No. UCD/CGM-14/01.

Bradley, B. A., & 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. April 2012.

MBIE. (2012). *Repairing and rebuilding houses affected by the Canterbury earthquakes.* Ministry of Business, Innovation and Employment. December 2012.

Rogers, N., van Ballegooy, S., & Williams, K. (2015). *Considering Post-Disaster Damage to Residential Building Construction - Is Our Modern Building Construction Resilient?* Proceedings of the 6th International Conference on

Earthquake Geotechnical Engineering. Christchurch, NZ: ISSMGE.

Tonkin & Taylor. (2013). *Liquefaction Vulnerability Study. Report to Earthquake Commission.* Tonkin & Taylor Ltd. Report 52020.0200/v1.0. February 2013.

van Ballegooy, S., Wentz, F., & Boulanger, R. W. (2015). Evaluation of a CPT-based liquefaction procedure at regional scale. *Soil Dynamics and Earthquake Engineering*, Special Issue: Liquefaction in New Zealand and Japan (In review).

Wentz, F., van Ballegooy, S., Rollins, K., Ashford, S., & Olsen, M. (2015). *Large scale testing of shallow ground improvements using blast-induced liquefaction.* Proceedings of the 6th International Conference on Earthquake Geotechnical Engineering. Christchurch, NZ: ISSMGE.