Comparison between predicted liquefaction induced settlement and ground damage observed from the Canterbury earthquake sequence

P Power
Tonkin & Taylor Ltd, Christchurch, NZ.
ppower@tonkin.co.nz (Corresponding author)

M Jacka
Tonkin & Taylor Ltd, Christchurch, NZ
mjacka@tonkin.co.nz

Keywords: liquefaction, settlement, earthquake, Canterbury, Christchurch

ABSTRACT

This paper reviews predictions of ground settlement due to post-liquefaction volumetric consolidation, and compares these predictions to ground damage observed from the Canterbury Earthquake Sequence in selected areas of Christchurch with differing ground conditions.

While ground settlement due to volumetric consolidation is only one component of the many liquefaction-related phenomena which can result in ground damage, it is one of the few aspects of post-liquefaction behaviour where simple predictive correlations are currently available to estimate consequential ground damage. So while predicted volumetric consolidation settlements do not capture all aspects of liquefaction-induced ground damage, they can provide a useful index for engineering practitioners to help compare potential ground damage at different sites.

This paper seeks to assist practitioners in their use of settlement predictions as an index of damage by examining how site-specific ground conditions can alter the consequential ground damage from liquefaction. Six sites across Christchurch are examined, two where analysis of CPT data predicts minor volumetric consolidation settlement, two where moderate settlements are predicted, and two where significant settlements are predicted. For one site from each pair, observations of ground damage from the Canterbury Earthquake Sequence are in general agreement with the settlement prediction. For the other site from each pair, observed ground damage was significantly less than would be suggested by the settlement prediction. The reasons for this difference between predicted and observed behaviour are investigated. Factors that are examined include the effect of sand boils, lateral spreading, crust thickness and strength, depth at which liquefaction occurs, and layered soil profiles.

1 INTRODUCTION

Following the 2010 to 2012 earthquake sequence in Canterbury which caused widespread ground damage due to liquefaction, this paper focusses closely on specific site pairs in Christchurch and analyses how they performed in the February 2011 earthquake. The following sites are discussed and compared:

1. Aranui and North New Brighton
2. Parklands and Dallington
3. Shirley and St Martins

Each of the above site pairs has similar predicted settlements.

In each case best estimates of February 2011 earthquake conditions such as earthquake magnitude, peak ground acceleration (PGA) and groundwater level are modelled. Cone penetration test (CPT) data was used to carry out the assessment along with vertical ground subsidence data taken from the Canterbury Geotechnical Database.

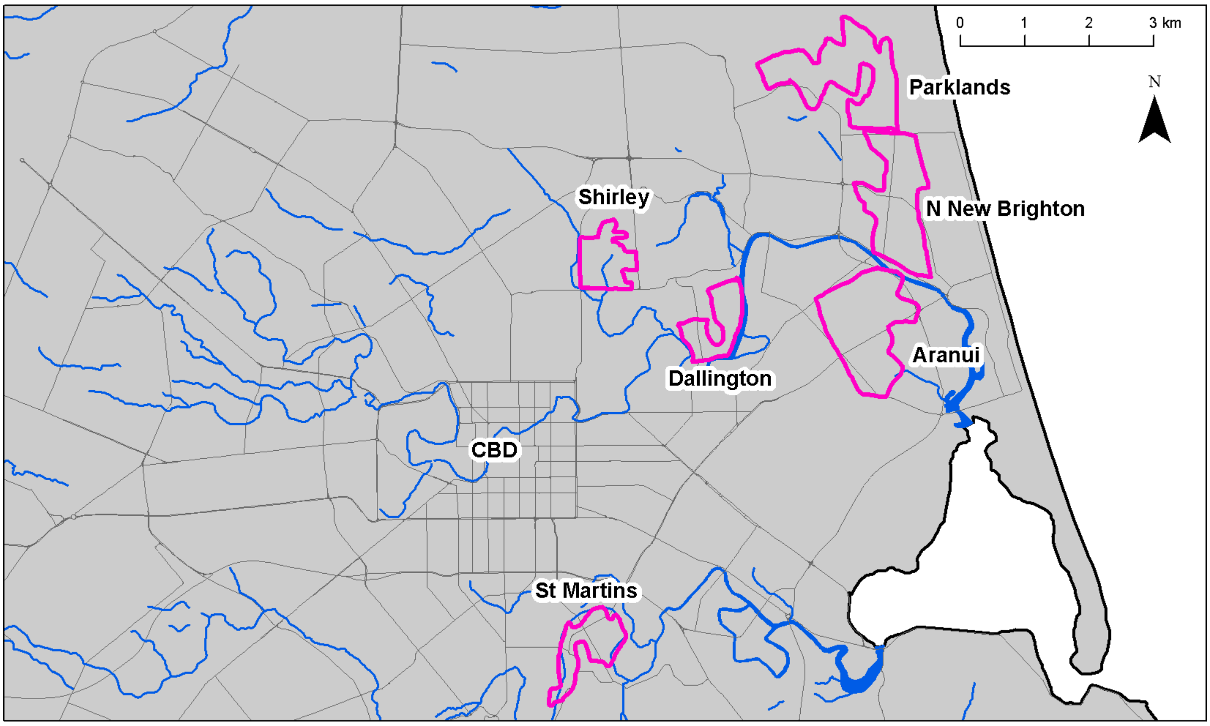


Figure 1: Site Location Plan

For the purposes of this paper measured vertical elevation change of the ground surface is the principal way of assessing ground damage due to liquefaction. For a more detailed assessment of ground damage using a range of measures refer to 'Liquefaction Vulnerability Study' (Tonkin & Taylor, 2013)

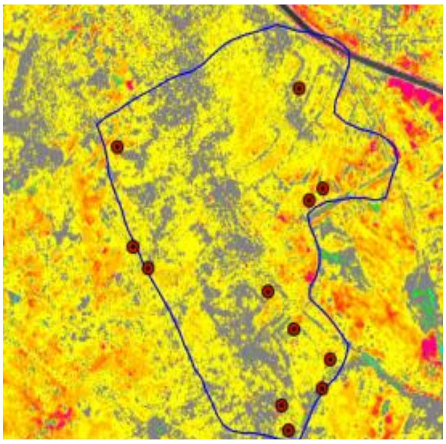
Comparison is made between predicted volumetric consolidation settlement due to liquefaction (based on the liquefaction triggering method of Idriss & Boulanger & post liquefaction settlement method of Zhang et al) and observed vertical elevation change based on LiDAR survey data taken after the February 2011 earthquake event. An analysis of the suitability of predicting likely ground damage due to liquefaction over the upper 10m or upper 20m has been investigated to try to assess which gives the best indication of ground damage occurring due to liquefaction. The estimated volumetric consolidation settlement should not be thought of as the actual ground settlement which will occur due to an earthquake. Rather, it should be used as an index to gauge the relative severity of liquefaction effects. All CPTs analysed have a depth of at least 10m. This paper attempts to look at specific areas to quantify the amount of influence from all factors which have an influence on ground subsidence including lateral spread, sand boils, material strength, crust thickness and depth at which liquefaction occurs.

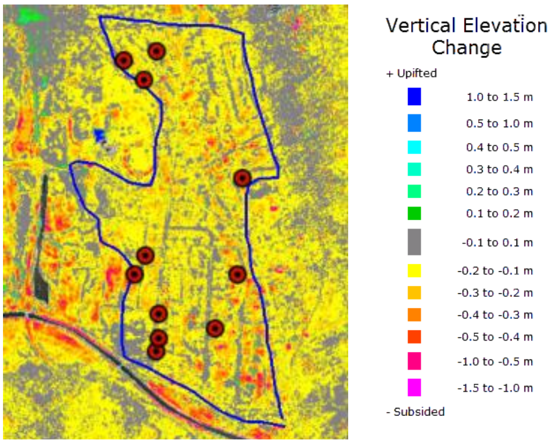
2 ARANUI AND NORTH NEW BRIGHTON

Both Aranui and North New Brighton study areas are located to the north east of Christchurch CBD on opposite sides of the River Avon. They have relatively similar predicted settlements and the areas within the extents of both these study areas have been classified as Technical Category 3 (TC3) according to the DBH residential technical categories. The area of North New Brighton close to the River Avon suffered from major global lateral ground movements due to the 2010 to 2012 earthquake sequence whereas in Aranui the global lateral ground movement wasn't as significant.

Borehole logs indicate that the soil material underlying North New Brighton generally consists of loose to medium dense sands while the subsurface material at Aranui generally consists of loose to medium dense sands with a number of silty sand layers present. In both areas simple liquefaction analysis of CPTs suggest liquefaction could be expected to occur relatively evenly over the upper 10m ground surface profile and the lower ground profile between 10m and 20m. Groundwater levels estimated for the 22 February earthquake range from 1.3m below ground level (bgl) to 3.0mbgl at North New Brighton for the CPTs analysed. At Aranui groundwater levels range from 0.9mbgl to 2.5mbgl for the CPTs analysed.

In each of these areas predicted volumetric consolidation settlement due to liquefaction was calculated based on CPT results from 34 CPTs at each site.





Ground subsidence due to liquefaction taken from LiDAR. (Tectonic component removed).

Figure 2a: Aranui **Figure 2b: North New Brighton**

Figures 2a and 2b above show the recorded observed ground subsidence due to liquefaction at Aranui and North New Brighton based on the February 2011 earthquake. The markers in red show the positions where the CPTs taken for the analyses were advanced. Between one and three CPTs were generally located nearby each marker. Figure 3 shows a comparison between predicted and observed settlement ranges for Aranui and North New Brighton.

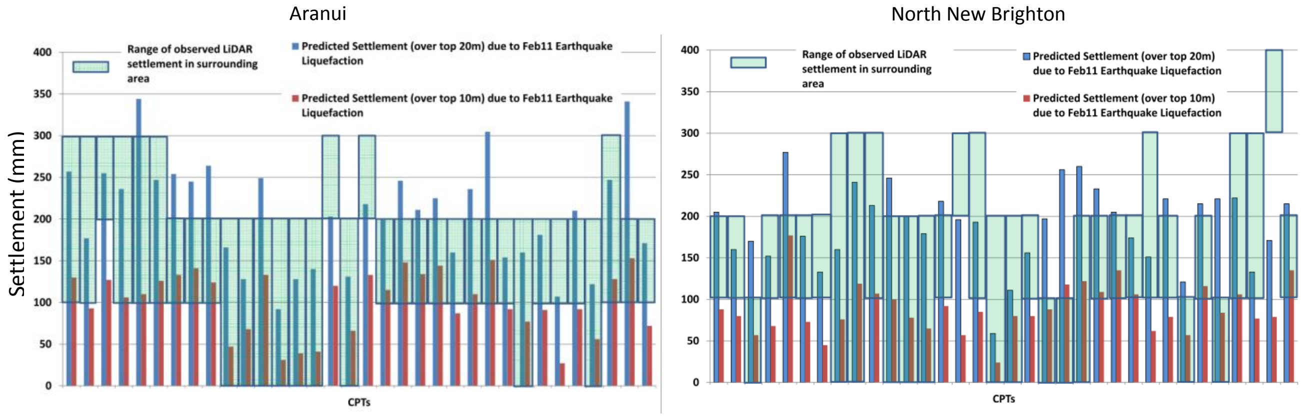


Figure 3: Settlement analyses due to Feb-11 earthquake – Aranui & North New Brighton

At Aranui, in 68% of cases, settlements calculated based on a depth profile of the upper 10m from CPT data was within the range of the vertical ground subsidence recorded LiDAR in the surrounding area. In 65% of cases the settlement calculated over the upper 20m was in the range of the LiDAR survey data in the surrounding area.

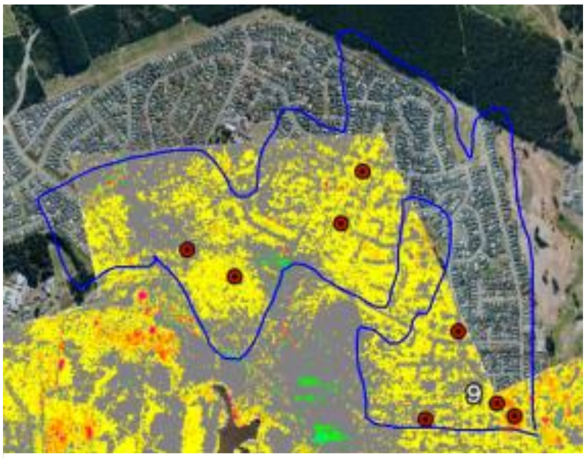
At North New Brighton, the calculated settlement based on a 10m depth profile was within the range of the ground subsidence recorded from LiDAR survey data in 62% of cases. This compares to an agreement in 50% of cases when settlement is calculated over 20m depth.

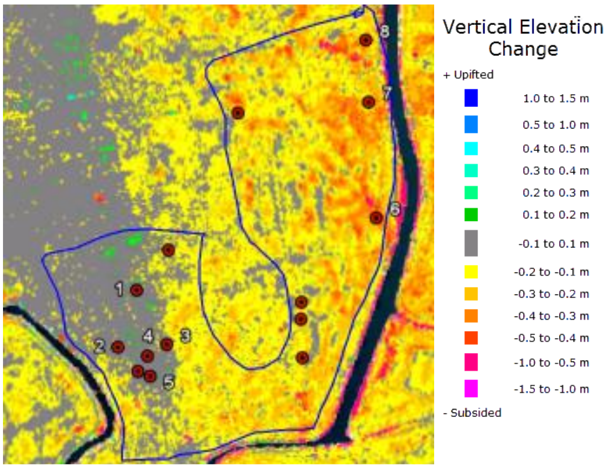
The most likely reason for greater observed ground damage at North New Brighton is the influence of global lateral ground movement. Both Aranui and North New Brighton border the River Avon on opposite sides. It is noted that there is a greater incline towards the river on the North New Brighton side. This would contribute to increased lateral spread. Lateral spreading is horizontal displacement (few centimetres to a metre or more) of superficial blocks of soil towards an open slope face as a result of liquefaction of the underlying soils. The occurrence of lateral spreading here is likely to be due to the presence of a relatively continuous liquefiable layer which extends to the river bank of the River Avon.

The fact that Aranui has a higher ground surface elevation may also contribute to the fact that it performed better than North New Brighton. This means that Aranui generally has a larger crust thickness which contributes to increased protection from liquefaction related damage at depth. The crust thickness is the thickness from ground level to a layer of liquefiable material beneath the water table.

3 PARKLANDS AND DALLINGTON

The Parklands study area is located 8km to the northeast of Christchurch CBD closeby the Pegasus Bay coastline while the Dallington study area is located 4km northeast of the CBD bordering the river Avon. All of the Parklands study area has been classified as TC3 while Dallington consists of a portion of land which has been classified as red zone and another portion which is classified as TC3. The two sites have relatively similar predicted settlements.





Ground subsidence due to liquefaction taken from LiDAR. (Tectonic component removed).

Figure 4a: Parklands **Figure 4b: Dallington**

The underlying soil material at Dallington generally consists of silty sand / sandy silt with a number of gravel layers present. At Parklands the underlying material generally consists of fine to medium sand.

Volumetric consolidation settlement due to liquefaction was calculated based on CPT results from 25 CPTs at Parklands and 26 CPTs at Dallington. Figure 5 shows a comparison between predicted and observed settlement ranges for Parklands and Dallington.

At Parklands, the calculated settlement based on a 10m depth profile was within the range of the ground subsidence recorded from LiDAR survey data in 88% of cases. This is in comparison to an agreement in 76% of cases when settlement is calculated over a 20m depth profile.

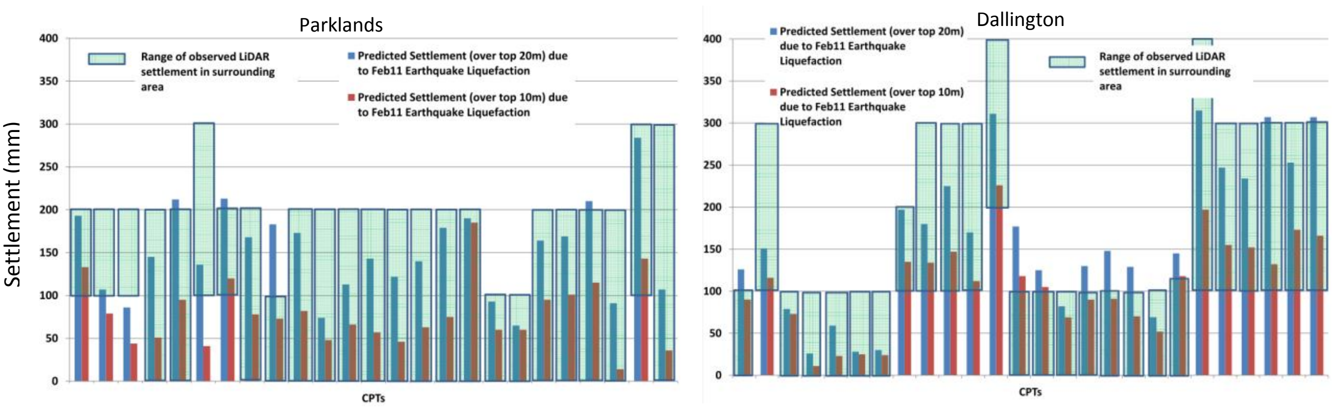


Figure 5: Settlement analyses due to Feb-11 Earthquake – Parklands & Dallington

At Dallington, in 88% of cases settlements calculated based on a depth profile of the upper 10m from CPT data were within the range of the vertical ground subsidence recorded from LiDAR in the surrounding area. In 65% of cases the settlement calculated over the upper 20m was within the range of the LiDAR survey data.

It can be seen that the predicted settlements provide a similar degree of accuracy for both sites. However when the sites are compared using the vertical elevation change from the LiDAR data in figures 4a and 4b it is seen that Dallington suffered considerably more ground damage. This is due to a large amount of variation in observed ground damage over small distances and in many cases CPTs were not advanced in the more severe areas. Groundwater levels at Parklands based on the 22 Febrauary earthquake event range from 0.7mbgl to 2.8mbgl. At Dallington groundwater levels range from 0.7mbgl to 3.0mbgl. The magnitude of vertical ground subsidence which occurred at Dallington was generally larger than the ground subsidence at Parklands.

At Dallington the area to the west bordering the River Avon where markers 1, 2, 3, 4 and 5 are located had significantly deeper groundwater levels (based on 22 February earthquake conditions) than the area to the east of the site where markers 6, 7 and 8 are located. The average groundwater level (based on February 2011 earthquake conditions) at the west of the site was 2.4mbgl while the average along the east of the site was 1.1mbgl approximately. There is a noticeable difference in the ground damage observed at these two locations. The area to the east of the site bordering the River Avon performed much worse. It is seen that in this case crust thickness has a strong influence on the variation in observed ground damage after the February 2011 earthquake. A thicker crust provides a protective effect which reduces the effects of settlement due to liquefaction at the upper ground surface.

As well as the influence of crust thickness significant lateral ground movement occurred at the site of Dallington closeby the River Avon while the lateral ground movement that occurred at Parklands is insignificant in comparison. Lateral spreading causes cracks to open up through the crust, enabling liquefied soil to be more easily ejected, increasing ground damage. Looking at predicted settlement data and ground damage which occurred in this area it can be seen that the recorded ground subsidence in these areas is between 100mm and 400mm generally. It is hard to compare settlement based on CPT data to actual ground subsidence because there is high variation occurring over small distances with the LiDAR data. There were six CPTs analysed in this area. All six CPTs analysed predicted ground subsidence in the observed range when analysed to 10m depth. Based on the analyses to 20m, 4 out of 6 predicted ground subsidence in the observed range. Although the CPTs predicted settlements in the observed range it is clear that lateral spreading caused more significant settlement that what would normally occur. The occurrence of lateral spreading here is likely to be due to the presence of a relatively continuous liquefiable layer which extends to the river bank of the River Avon.

From the CPTs analysed at Parklands generally it is seen that there are a number of examples where more liquefaction is predicted to occur over the depth profile from 10 – 20m than from 0 -10m. There is an interesting example at marker 9 at Parklands (CPT_2791) where minimal liquefaction is predicted to occur in thin layers over the upper 10m while substantial liquefaction is predicted to occur in one complete block between 10m and 20m depth. In this case the settlement due to liquefaction calculated over a 10m depth profile predicted ground subsidence within the observed range (0 -200mm). Although the range of ground subsidence was large it is seen in this case that liquefiable material closer to the surface has greater influence over ground damage than liquefiable material at depth.

At Parklands it is observed that in a number of cases the land which residential properties were constructed on is generally at a higher ground level than nearby road levels. It is noted from the LiDAR data that areas where roads were constructed settled significantly less than the higher ground where residential properties were constructed. This is more than likely due to lateral ground movement of material from higher ground during earthquake shaking which caused ground levels to equalise. As the areas of lower ground levels have a narrower crust thickness there is the possibility of more liquefied material emerging to the surface through cracks in this area.

4 SAINT MARTINS AND SHIRLEY

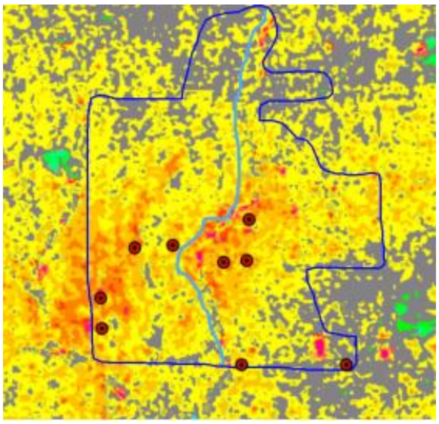
The study area of Saint Martins is located approximately 4km to the south of Christchurch CBD closeby the Heathcote river while the site of Shirley is located approximately 3km to the north of Christchurch CBD. After the February 2011 earthquake it was noted generally that the suburbs to the north east of Christchurch suffered greater land damage than those at the southwest and south.

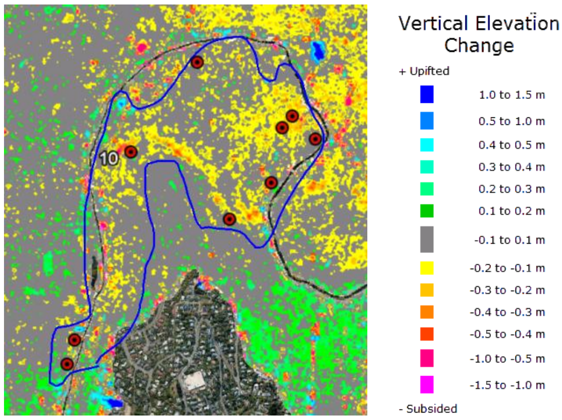
Residential properties within the Saint Martins study area are classified as both TC2 and TC3 according to the DBH residential technical categories. In the Shirley study area all the residential properties are classified as TC3. The subsurface soil material recorded at Saint Martins generally consists of silts, silty sands, occasional layers of organic material and sandy gravels while the subsurface material recorded at Shirley consists of silts, sands and gravelly sands. Groundwater levels at Shirley based on the 22 February earthquake event range from 0.8mbgl to 2.3mbgl. At Saint Martins groundwater levels range from 0.8mbgl to 4.1mbgl.

At Saint Martins all CPTs except for 2 did not achieve their target depth of 20m due to layers of dense gravels located between 10m and 20mbgl. All the CPTs at Shirley reached target depth.

Figures 6a and 6b above show the recorded observed ground subsidence at Shirley and Saint Martins based on the February 2011 & September 2010 earthquakes. The markers in red show the positions where the CPTs taken for the analyses were advanced. Between one and three CPTs were generally located nearby each marker. Unfortunately the vertical elevation change calculated from LiDAR survey data based on the February 2011 earthquake alone is unavailable for the Saint Martins area.

To compare these two sites the vertical elevation change from both the September 2010 and February 2011 earthquakes is compared. It can be seen that the amount of ground damage which occurred at Shirley was much greater than the ground damage which occurred at Saint Martins. Figure 7 compares predicted and observed settlement for Shirley and St Martins.





Ground subsidence due to liquefaction taken from LiDAR. (Tectonic component removed).

Figure 6a: Shirley **Figure 6b: Saint Martins**

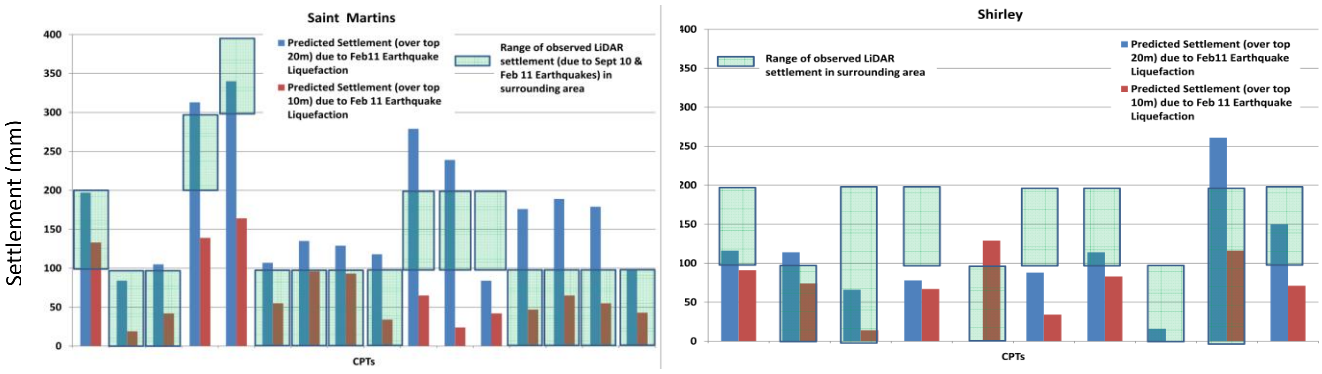


Figure 7: Settlement analyses due to Feb-11 Earthquake – Shirley & St Martins

Considering Shirley, from the 10 CPTs analysed 40 % of CPTs predicted the observed ground subsidence range when analysed to 10m depth. When analysed to 20m depth, 50% of CPTs predicted the observed measured ground subsidence range. In the majority of these cases more ground settlement was observed than predicted.

A watercourse runs through the centre of the Shirley study area from north to south. This is shown on the location plan above in figure 8a above as a blue line. There was significant lateral ground movement recorded in this area. At the Saint Martins study area, the Heathcote River runs along the eastern, northern and western boundary. There are some signs of lateral ground movement but they are less significant than those at Shirley. This is likely to be a significant cause of greater observed land damage at Shirley compared to Saint Martins. Another reason why the observed ground damage at Saint Martins is not as significant as that at Shirley is possibly because there are dense gravel layers located between 10m and 20m depth. At the southern part of Saint Martins rock outcrop from the Port Hills is observed in boreholes at depth occasionally.

At Saint Martins significant ground damage was observed based on the September 2010 and February 2011 earthquakes at marker 10. In this area the predicted ground settlement generally matched the amount of land damage observed when analysed to 20m depth. The reason for the high predicted and observed settlement is simply a high proportion of liquefiable material at this area. Groundwater levels at this specific area from the 2 CPTs analysed were the deepest observed in Saint Martins giving crust thicknesses of 3.7mbgl and 4.1mbgl. In this particular case, sloping ground encouraged lateral ground movements, causing ground cracking which allowed liquefied soil to be ejected.

5 CONCLUSION

In the prediction of ground damage due to liquefaction there are a number of factors which influence how much land damage will occur which have been examined in this paper.

- Vertical volumetric consolidation settlement calculation (due to liquefaction) generally provides a good indicator of land damage that will occur. In general it is seen that both a 10m and a 20m depth profile should be considered in each analysis. From experience this method takes into account material strength to model which materials will liquefy at given PGAs.
- Lateral spread near rivers, watercourses and any ground which slopes steeply causes a change to the ground profile which cannot be predicted using the vertical consolidation settlement due to liquefaction methods. It is something that is site specific. Its influence is discussed in this paper.
- The influence of crust thickness is discussed in relation to observed ground damage in a number of areas in this paper.
- Along with the factors listed above, other factors such as depth at which liquefaction occurs and the effect that thickness of liquefiable layers has on ground damage are discussed referring to specific examples in Christchurch.

6 ACKNOWLEDGEMENTS

This work would not have been possible without the data obtained by the NZ hazard monitoring system, GeoNet and the extensive remote sensing and ground investigation of land and dwelling damage, sponsored by the NZ Government through its agencies, the Earthquake Commission of NZ, and the Ministry of Civil Defence and Emergency Management. The contributions from the University of Canterbury in developing the seismic models for the various major earthquakes are gratefully acknowledged.

REFERENCES

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

Idriss, I.M & Boulanger, R.W. (2008) *Soil Liquefaction During Earthquakes*, MNO-12, Earthquake Engineering Research Institute, 242p

Zhang, G., Robertson, P. K., & Brachman, R. W. I. (2002) *Estimating Liquefaction-Induced Ground Settlements from CPT for Level Ground,* Canadian Geotechnical Journal, 39, 1168-80

Tonkin & Taylor Group Ltd (2013) *Liquefaction Vulnerability Study*

Ishihara, K (1985) *Stability of Natural Deposits During Earthquakes* – Proceedings of the 11th International Conference on Soil Mechanics and Engineering, San Francisco, 1:321-376

Canterbury Geotechnical Database (https://ttgd.projectorbit.com).