Analysis of Liquefaction-Induced Lateral Spreading Data from the 2010 Darfield and 2011 Christchurch Earthquakes

K. Robinson, B. A. Bradley, & M. Cubrinovski

University of Canterbury, Christchurch, New Zealand

2012 NZSEE Conference

ABSTRACT: The 4 September 2010 Darfield and 22 February 2011 Christchurch earthquakes caused significant damage to Christchurch and surrounding suburbs as a result of the widespread liquefaction and lateral spreading that occurred. Ground surveying-based field investigations were conducted following these two events in order to measure permanent ground displacements in areas significantly affected by lateral spreading. Data was analysed with respect to the distribution of lateral spreading vs. distance from the waterway, and the failure patterns observed. Two types of failure distribution patterns were observed, a typical distributed pattern and an atypical block failure. Differences in lateral spreading measurements along adjacent banks of the Avon River in the area of Dallington were also examined. The spreading patterns between the adjacent banks varied with the respective river geometry and/or geotechnical conditions at the banks.

1 INTRODUCTION

Following the 4 September 2010 M_W7.1 Darfield and 22 February 2011 M_W6.2 Christchurch earthquakes, extensive field investigations were performed to document observed lateral spreading along rivers and streams in Christchurch and surrounding suburbs. Approximately 150 transects were surveyed, using the method of ground surveying as described by Robinson et al. (2010), which consists of recording crack dimensions and distance from the waterway in a line oriented perpendicular to the direction of spreading. Additional information regarding location details and comparisons of transects performed following the two events can be found in Robinson et al. (2012). This paper provides results of various analyses performed using the data from both events in order to gain a better understanding of the failures observed.

2 LATERAL SPREADING DISTRIBUTION PATTERNS FROM THE 2010 SEPTEMBER AND 2011 FEBRUARY EARTHQUAKES

It is important to understand the distribution of lateral spreading cracks with respect to distance from the waterway in order to comprehend the consequential effects on structures and lifelines within the zone of deformation. As seen in previous events (Cubrinovski & Ishihara, 2003), lateral spreading displacements typically decrease exponentially with increasing distance from the waterway and generally become negligible at distances greater than 100 to 150 m. In the 1995 Kobe Earthquake, lateral spreading at the quay walls typically extended 150 m inland (Cubrinovski & Ishihara, 2003). Reports of lateral spreading along Izmit Bay in the 1999 Kocaeli (Turkey) earthquake were generally limited to within 70 m of the shoreline (Cetin et al., 2004).

In the 2010 Darfield and 2011 Christchurch earthquakes, a distribution pattern similar to the aforementioned observations was observed throughout most of the areas surveyed; however, two areas showed an atypical spreading pattern associated with a block failure mode creating a notably larger "zone" of influence. The distribution of lateral displacement was plotted against distance from the waterway in order to gain a better understanding of the area subject to the relatively large horizontal ground deformations. In general, two types of distribution patterns were observed. The first being a “distributed” failure pattern where the majority of displacement occurred close the water’s edge and rapidly decreased with distance from the waterway; generally becoming negligible at distances greater than 150 meters from the bank. A plot of all “distributed” type failures from the September 2010 and February 2011 earthquakes are plotted in Figure 1. The distributed failures occurred in the majority of locations surveyed throughout Christchurch, Spencerville/Brooklands, and North Kaiapoi.

The best-fit line based on data from the 1964 Niigata Earthquake (Bartlett & Youd, 1995) was multiplied by a factor of 1/3 and plotted on Figure 1 as the dotted line to show the shape or failure pattern from that event. As can be seen in Figure 1, the “distributed” failure data from the Christchurch events follows a similar distribution (though of smaller magnitude) to that of the Niigata earthquake. The mean or best-fit line from the Canterbury data is presented in bold and shows that, on average, relatively small (< 10 cm) displacements occurred at distances greater than 100 m.

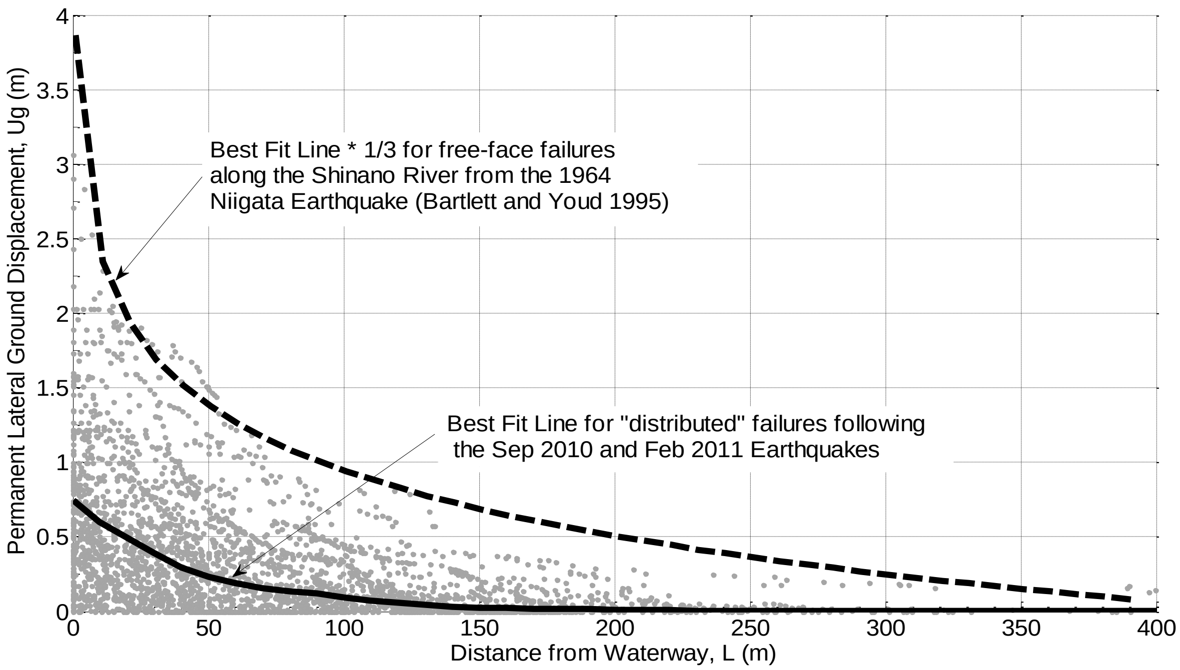


Figure 1. Observed permanent lateral displacement (Ug) with distance from the waterway (L) for all distributed-type failures in the 4 Sept 2010 Darfield and 22 Feb 2011 Christchurch earthquakes.

“Block” type failures found in the areas of South Kaiapoi and Burwood are plotted in Figure 2 and show a significantly different trend to the distributed failures in Figure 1. Again, the best-fit line from the 1964 Niigata data (multiplied by 1/3) is presented as the dotted line and emphasizes the differences in the two types of failure patterns, as seen in the different shapes of the trend lines. The Canterbury data best-fit line shows, on average, relatively large displacements of about a half meter still occurring at distances of 200 m from the river bank. The general pattern of these failures appears to follow a ‘step-like’ pattern, rather than the typical exponential decrease seen in previous events other locations surveyed.

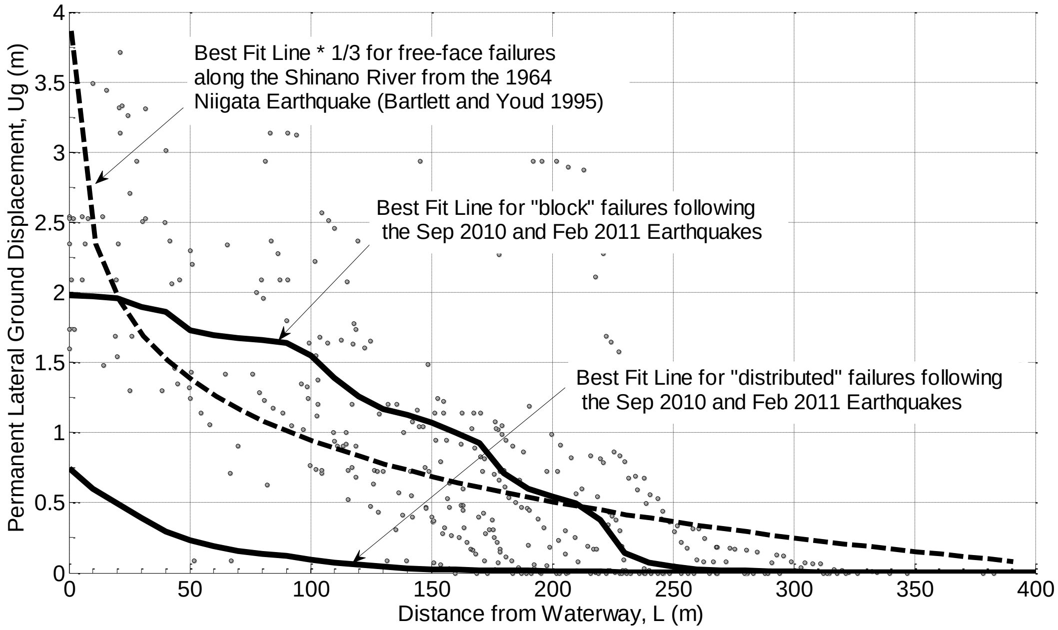
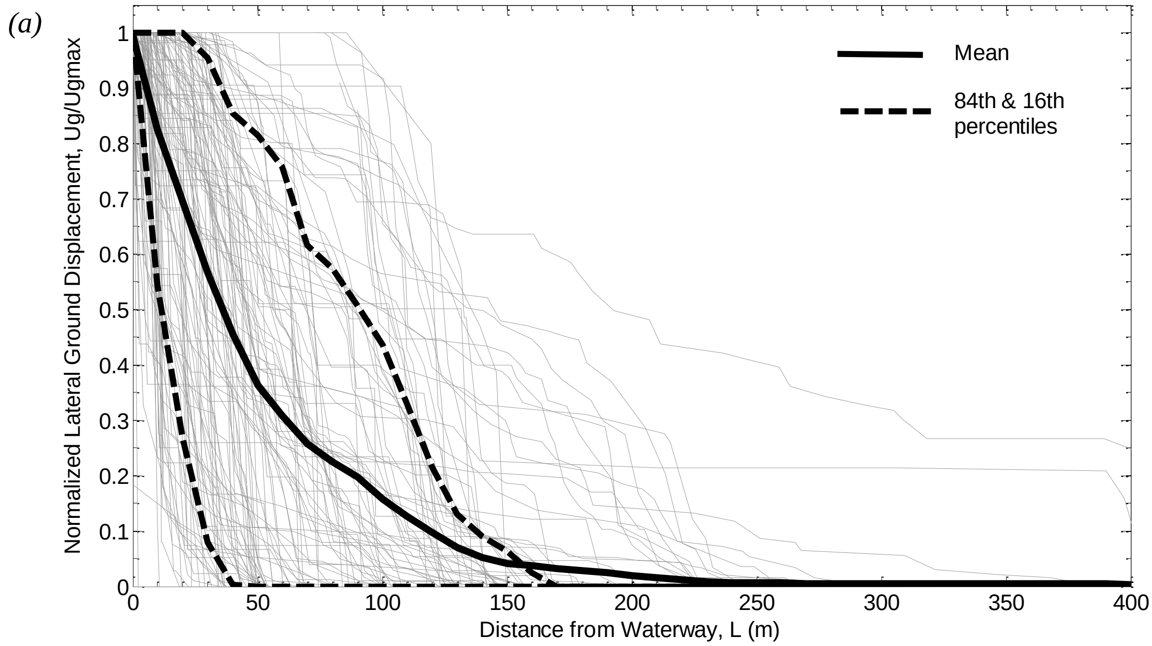


Figure 2. Observed permanent lateral displacement (Ug) with distance from the waterway (L) for all distributed-type failures in the 4 Sept 2010 Darfield and 22 Feb 2011 Christchurch earthquakes.

2.2 **Normalized Displacements**

In order to show a more detailed representation of the lateral spreading distribution, lateral spreading data from the September 2010 and February 2011 events was normalized by the free-face displacement, and is shown in Figure 3(a) and (b) for each failure type. The mean is shown in bold and the 84th and 16th percentiles (corresponding to +/- one standard deviation for a normal distribution) are shown as dotted lines. For the distributed failures, the mean shows that on average, half of the maximum displacement occurred within about 50 m of the waterway, whereas the block failures show on average 50% of the maximum displacement occurred at about 150 m from the waterway.

It is inferred that the observed block failures are likely associated with a circular failure wedge as a result of a combination of very loose soil conditions and historic geologic conditions in the area. Wotherspoon et al. (2012), for example, indicate a branch of the Waimakariri River once flowed through the area of block failure in South Kaiapoi. Preliminary assessment of CPT data in this area indicated the soils to be relatively uniform in the upper 4 to 6 meters with CPT tip resistances, q_c, generally less than 6 MPa (Tonkin & Taylor Limited). This low-resistance layer, highly susceptible to liquefaction, appeared to extend more than 150 m inland from Courtenay Stream. Furthermore, a compilation of the 1856 "Black Maps" of Christchurch (Scott & Christchurch Drainage, 1963) indicates that the area south of Bottle Lake in Burwood (where the block failure was observed) previously consisted of "wet swamp." CPT data from explorations located between about 150 and 200 m from Bottle Lake showed a generally consistent liquefiable layer in the upper 4-6 m with q_c-values of less than 5-6 MPa (Tonkin & Taylor Limited, 2011). Further research is however necessary to confirm the above anecdotal inferences.



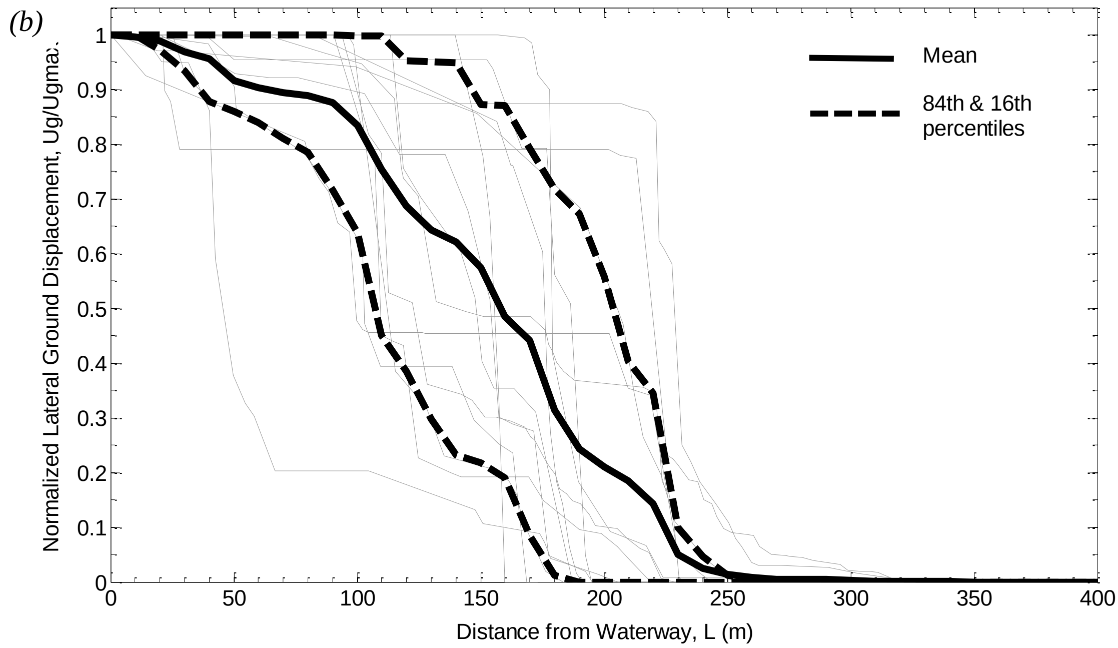


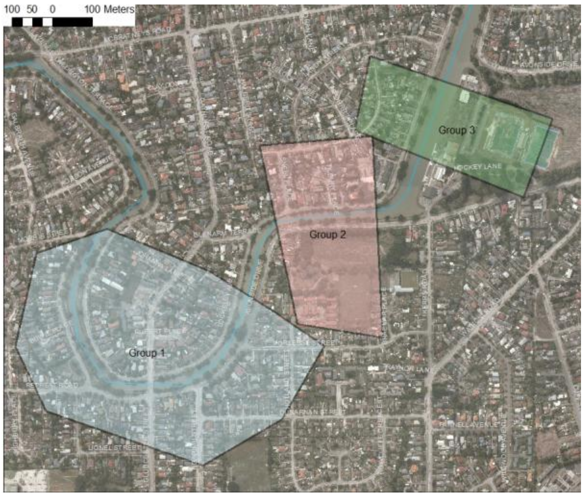
Figure 3: Normalized lateral displacement versus distance from the waterway: (a)distributed failures; and (b) block failures

While similar loose soil conditions can be found in some explorations along the river banks in the areas of distributed failures, the thickness of this liquefiable material in the upper 5-6 m typically decreases with distance from the river and is generally not as uniform as observed in these block failure zones. The reason for the large extent of loose soils in the block failure zones can likely be attributed to the historic geologic conditions mentioned.

3 **INFLUENCE OF LOCAL GEOGRAPHIC FEATURES IN THE DALLINGTON AREA**

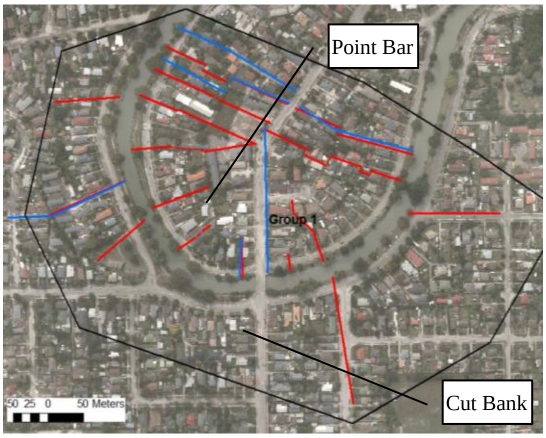
An interesting geographic pattern along the Avon River is the meandering loop in Dallington/Avonside which creates a point bar and cut bank features, as shown in Figure 4.

Downstream of the loop, the river bends into a near 90-degree angle to create two relatively straight segments. An analysis was performed to compare the different spreading patterns observed along the various geometrically different areas of the river by breaking the region into three groups, as shown in Figure 4. Within each group, the maximum displacements from selected transects located on one side of the bank were compared with those on the opposite bank.

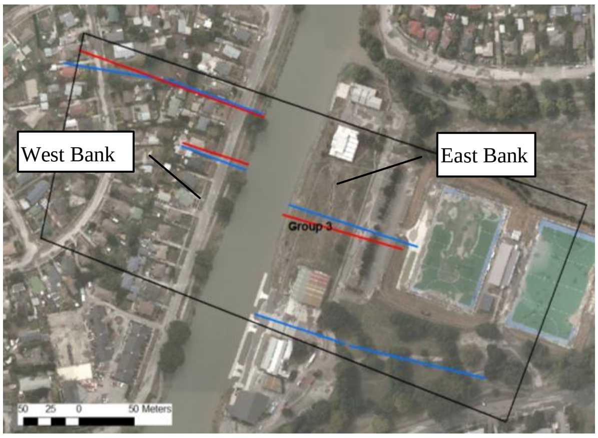


(a) Group locations

(c) Group 2 transect locations



(b) Group 1 transect locations



(d) Group 3 transect locations

Figure 4. Location of lateral spreading transects within selected area of Dallington, Avonside, and Wainoni (red lines correspond to 2010 Darfield data, blue lines correspond to 2011 Christchurch data)

The maximum lateral displacements (Ug_{max}) computed from transects within the point bar area and cut bank area are summarized in Figure 5 (Group 1). The figure shows the majority of displacements are much higher in the point bar area than along the cut bank. The point bar data indicates a maximum displacement of about 1.8 m and an average of approximately 1.0 m; while the cut bank data shows a maximum displacement of about 1 m and an average of only 0.3 m. The differences in the observed displacements within such a relatively small geographic area (where ground accelerations and general topography are relatively constant) may be attributed to the difference in soil conditions as a result of the unusual river geometry of the meandering loop. From a geologic perspective, one might assume the river to “cut out” the soils along the cut bank, exposing stiffer materials, and deposit loose materials on the inner bank (point bar) where the velocity of the river would be lower. In order to provide an independent assessment of the above arguments based on observed lateral spreading displacements, a preliminary review of CPT data (Tonkin & Taylor Limited, 2011) was performed to gain a better understanding of the geotechnical conditions at the locations of interest. The CPT data revealed a complex pattern of soil conditions along the bank. In general, however there appears to be a greater total thickness of loose (q_c < ~10 MPa) liquefiable material within the upper 6 meters associated with CPTs located along the point bar.

Looking at the maximum displacements from Group 2 in Figure 5c, there is an obvious variability in the results with respect to the north and south banks, and even at different locations along a given bank. Given the straight-away section of the river in this area, one might anticipate the results from these transects to be more similar. The large variability in observed transect data is however consistent with the complex soil pattern with highly variable conditions ascertained from CPT data (Tonkin & Taylor Limited, 2011).

The transects in Group 3, shown in Figure 5d, indicate significantly larger displacements occurring on the east bank. Although this section appears to have similar river geometry to that of Group 2 and therefore one might assume to see the same variability in the data, Group 3 shows an obvious bias to the east bank displacements. Review of a historical map provided in Scott & Christchurch Drainage (1963) and compiled from the 1856 "Black Maps", indicates the original Avon River actually flowed east of the present-day bend along the channel of the current stream surrounding Porritt Park. CPT data (Tonkin & Taylor Limited) in this area indicate a drastic difference in soil conditions on either side of the bank. Data from the west bank indicates relatively dense material (q_c > 20MPa) occurring at a depth of about 3.5 m; whereas, a CPT located near the east bank shows loose material (q_c < 10 MPa) extending to a depth of about 6 m.

In conclusion, there is significant variability in the lateral spreading data along the banks of the Avon River. While some areas exhibit a clear trend to one side and obvious geotechnical data to support the bias, other areas are more complex and will require further analyses. In general however, it is clear that the historical geology, river geometry, and insitu conditions (as evident in geotechnical data) all play an influential role in the lateral spreading damage observed.

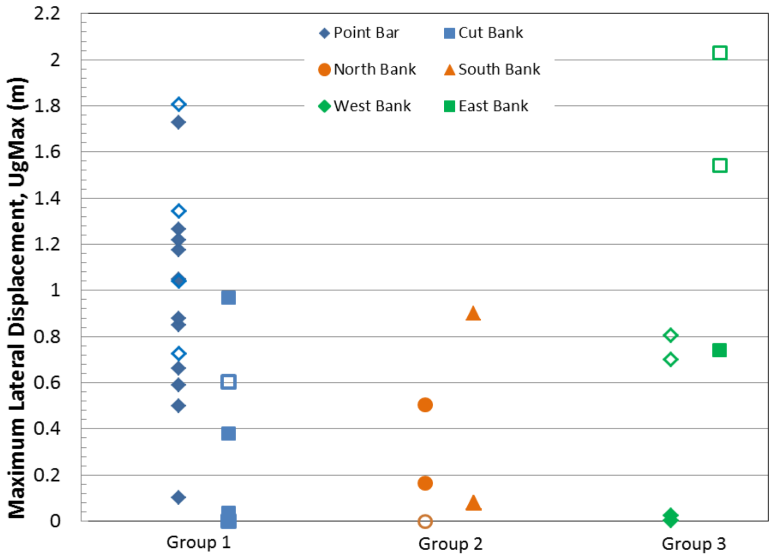


Figure 5. Comparison of lateral spreading measurements within specific areas along the Avon River (solid symbols correspond to 2010 Darfield data, hollow symbols correspond to 2011 Christchurch data)

5 **CONCLUSIONS**

Approximately 150 transects were surveyed following the September 2010 and February 2011 Canterbury earthquakes to document the liquefaction-induced lateral displacements along the streams and rivers of Christchurch and surrounding suburbs. Field investigations measured crack widths and their location with respect to distance from the waterway. Field data was analysed to better understand the distribution of lateral spreading displacement observed with distance from the waterway and the effects of local geographic. The following conclusions can be made with respect to the analyses conducted:

1) Two distinct types of failure patterns were observed: (i) a distributed failure pattern typical of lateral spreading seen in previous events and (ii) an atypical block failure pattern. The distributed failures occurred in most of the locations surveyed in Christchurch, Spencerville, and North Kaiapoi. Block failures were only observed along Courtenay Stream in South Kaiapoi and along Bottle Lake in Burwood.

2) Distributed failures observed appear to follow a similar distribution pattern to lateral spreading displacements documented after the 1964 Niigata Earthquake, and other previous events. There is a clear atypical behaviour in the block-failure modes. Historical geologic maps and recent geotechnical data indicate these block failures are associated with relatively uniform loose soil conditions in the upper 4-6 m and covering an area over 100 m from the banks.

3) Normalized plots of distributed and block failures show the key differences in the location of relative displacement with respect to distance from the waterway. While on average less than 5% of the maximum displacement occurs at distances greater than 150m in distributed failures, the block failures show on average 10 times that of distributed failures (about 50% at 150 m).

4) The meandering loop of the Avon River in Dallington creates a unique geographic feature of a point bar and cut bank. It is expected that the unusual river pattern in this area would lead to variable soil conditions along the river banks and subsequent variation in observed lateral spreading. Lateral spreading measurements performed along each side of the bank within this feature were compared and it was found that larger displacements occurring within the point bar. Geotechnical data indicates that, in general, soils along the point bar are looser than those along the cut bank.

5) In addition to the meandering loop, transects performed along both sides of nearby straight segments of the Avon were compared. Despite the similar bank geometry, the results between the two groups were very different with Group 2 showing no obvious pattern in spreading patterns with regards to the bank and Group 3 clearly indicating larger displacements associated with the east bank. Soil conditions in the area support both the findings in the complex soil behaviour in the area of Group 2 transects (no clear "looser" strata along one bank) and the obvious weaker materials encountered on the east bank of Group 3 transects where the larger displacements took place.

6 ACKNOWLEDGEMENTS

The authors would like to acknowledge all of those that contributed in the collection of data following the 2010 September and 2011 February events. Details of the fellow contributors can be found in Robinson et al (2010). In addition, we would like to acknowledge all of the contributions on the Project Orbit site (Tonkin & Taylor Limited, 2011).

REFERENCES:

Bartlett, S. F., & Youd, T. L. (1995). Empirical prediction of liquefaction-induced lateral spread. *Journal of geotechnical engineering, 121*(4), 316-329.

Cetin, K. O., Youd, T. L., Seed, R. B., Bray, J. D., Stewart, J. P., Durgunoglu, H. T., . . . Yilmaz, M. T. (2004). Liquefaction-induced lateral spreading at Izmit Bay during the Kocaeli (Izmit)-Turkey earthquake. *Journal of Geotechnical and Geoenvironmental Engineering, 130*(12), 1300-1313. doi: 10.1061/(asce)1090-0241(2004)130:12(1300)

Cubrinovski, M., & Ishihara, K. (2003, 27-31 Aug 2003). *Liquefaction-induced ground deformation and damage to piles in the 1995 Kobe Earthquake.* Paper presented at the International Conference Skopje Earthquake 40 Years of European Earthquake Engineering, Skopje-Ohrid, Macedonia.

Robinson, K., Cubrinovski, M., & Bradley, B. (2012). *Lateral Spreading Measurements from the 2010 Darfield and 2011 Christchurch Earthquakes*. Paper presented at the Australia New Zealand Conference on Geomechanics (ANZ), Melbourne, Australia.

Robinson, K., Cubrinovski, M., Kailey, P., & Orense, R. (2010). *Field Measurements of lateral spreading following the 2010 Darfield earthquake*. Paper presented at the 9th Pacific Conference on Earthquake

Engineering, Aukland.

Scott, E. F., & Christchurch Drainage, B. (1963). *Christchurch data: notes and comments on the Christchurch drainage and sewerage systems*. Christchurch: Photo Process Printers.

Tonkin & Taylor Limited. (2011). Projectorbit site developed for EQC. https://canterburyrecovery.projectorbit.com/SitePages/home.aspx, 2012

Wotherspoon, L., Pender, M., & Orense, R. (2012). Relationship between observed liquefaction at Kaiapoi following the 2010 Darfield earthquake and former channels of the Waimakariri River. *Engineering Geology*, *125*, 45-55.