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Lateral Spreading Measurements from the 2010 Darfield and 2011 Christchurch Earthquakes

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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. Field investigations were conducted following these two events in order to measure permanent lateral ground displacements in areas significantly affected by lateral spreading. Ground surveying techniques were used to estimate total displacement along specific transects. A total of 148 transects were completed in the areas of Kaiapoi, Spencerville, and various suburbs within Christchurch City. Maximum lateral displacements measured in these areas from both events ranged from about 0.5 - 3.5 m, causing significant damage to nearby structures and lifelines. This paper presents a summary of the locations surveyed and results for each event, assessment of the ground surveying methodology, and a comparison of 22 locations which were surveyed following the September 2010 event and the February 2011 event.

Keywords: 2010 Darfield Earthquake, 2011 Christchurch Earthquake, lateral spreading, liquefaction

1 INTRODUCTION

The Darfield Earthquake of September 4, 2010 (Mw 7.1) and the Christchurch Earthquake of February 22, 2011 (Mw 6.2) triggered extensive liquefaction throughout Christchurch and surrounding suburbs (Cubrinovski et al., 2011). One of the most damaging effects of the liquefaction was the lateral spreading that caused severe damage to structures and lifelines. The lateral spreading was concentrated along the streams and rivers of the liquefied areas as a result of the lateral ground deformation towards the open channel or waterway.

Following the two events, a geotechnical reconnaissance effort was launched to document the lateral spreading in the affected areas. The relatively simple method of ground surveying was used to measure the magnitude and distribution of lateral spreading at approximately 150 locations (some repeated) throughout Christchurch, Spencerville, and Kaiapoi. The ground survey method consists of field documentation of ground cracks and distribution of these cracks from the waterway along a specific alignment (referred to as a "transect") oriented perpendicular (as much as possible) to the adjacent waterway, i.e. oriented in the direction of spreading. The maximum lateral displacement (Ug_{max}) at the bank is obtained by summing the widths of the cracks along the transect.

Table 1:Summary of Lateral Spreading Field Measurements following 4 Sep 2010 and 22 Feb 2011 Earthquakes

Suburb	4 Sep 2010 Darfield		22 Feb 2011 Christchurch[a]	
	Transects	Ug_{max} (m)	Transects	Ug_{max} (m)
CBD	0	-	21	0 – 1.6
Richmond (RD)	0	-	8	0.1 – 1.2
Dallington (DAL)	15	0 - 1.7	9	0.4 – 1.8
Avonside (AS)	9	0 - 1.0	7	0 – 1.5
Wainoni (WN)	1	0.7	3	0.7 – 2.0
Avondale (AD)	2	0.6 - 0.8	7	0.4 – 1.6
Burwood (BU)	3	0.1 – 0.9	0	-
Bexley (BX)	6	0.3 - 0.9	3	0.4 – 2.1
South New Brighton (SB)	5	0.1 – 1.1	4	1.5 – 2.9
St. Martins (SM)	2	0 – 0.1	4[b]	0.2 – 0.3
Woolston (WL)	0	-	2	0.0 – 0.5
Spencerville (SP)	13	0.4 – 1.5	0	-
South Kaiapoi (KS)	12	1.2 – 3.5	2[b]	3.1 – 3.7
North Kaiapoi (KN)	9	0.2 – 3.1	1[b]	2.4

[a] Results reflect cumulative displacements from the 4 Sep and 22 Feb events
[b] Some transects in area were surveyed after the June 2011 (M_W 6.0) earthquake

Details of the ground surveying method employed can be found in Robinson et al. (2010). A list of locations surveyed and corresponding range of maximum lateral displacement for the 2010 and 2011 events is tabulated in Table 1. The approximate locations of these areas are shown in Figure 1.

Figure 1. Location map of areas surveyed during field investigations of lateral spreading

2 ASSESSMENT OF GROUND SURVEY METHOD

Detailed optical geodetic surveying was conducted in South Kaiapoi following the September 2010 earthquake in order to estimate permanent ground displacements from lateral spreading (Waimakariri District Council, 2010). The data was summarized on a parcel map of South Kaiapoi using vectors to show magnitudes and direction of movement at approximately 47 locations. A comparison of lateral displacement measurements was performed using both field transect data and geodetic data located in proximity to our measurements in order to assess the accuracy behind the method of ground surveying. Approximately 30 geodetic data points were used in the analysis which considered only vectors within 50 meters of the transect, though the majority fell within 30 meters.

The comparison considered pairs or groups of geodetic vectors located in a generally parallel alignment to a transect. The angle difference between transect and vector azimuths were computed in order to calculate the vector component in the direction of the transect. Using the groups or pairs of geodetic data, the difference in displacements from the geodetic data were compared with the differences in measured displacements from the transect field data at the equivalent distance from the waterway. This was accomplished by setting the furthest geodetic data point equal to the transect measurement at that distance and subtracting or adding that difference to all vector data points considered in the alignment.

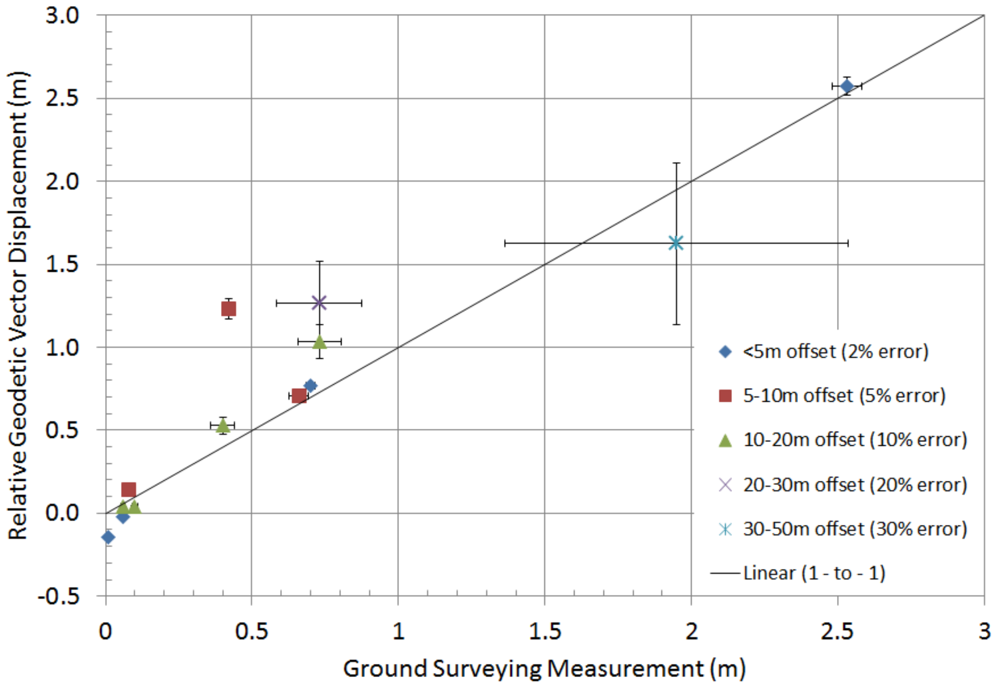

Figure 2. Comparison of relative lateral spreading displacements using the method of ground surveying and geodetic surveying

Figure 2 shows the results of our comparison in South Kaiapoi and is broken down by vector offset (perpendicular distance between vector location and field measurement). Each offset category has been assigned an estimated error associated with the comparison. This is to account for the variability in observed displacements within a specific area, despite being at equal distances from the waterway. In general, the field measurements matched reasonably well with the geodetic data with a majority of the vector data falling within 30% of the corresponding field value. We note that discrepancies between the two datasets are inevitable given the complex nature of lateral spreading and the highly variable field conditions. However, the general agreement between the two data sets serves to validate the simplified method of ground surveying and our results obtained using this technique.

3 LATERAL SPREADING FOLLOWING THE 2010 DARFIELD EARTHQUAKE

The September 2010 earthquake was centred in Darfield, approximately 30 kilometres west of Christchurch City. Peak ground accelerations were calculated for each transect location and ranged from about 0.17 - 0.20g along the Avon River in Christchurch and about 0.17 - 0.23g in Spencerville and Kaiapoi.

77 locations were surveyed throughout Christchurch, Spencerville, and Kaiapoi following the Darfield earthquake. The results of the field investigations are summarized in Figure 1 which shows the distribution of permanent lateral ground displacement (Ug) with distance from the waterway (L) for all transects performed prior to the February 22 event. These plots are obtained by summing up the width of the cracks measured along the perpendicular transect line. The lines plotted are relative to a reference point located at the furthest lateral spreading crack or the right-most portion of the line where displacement is practically zero. The figure shows maximum lateral displacements at the bank ranging from less than ten centimetres to over 3 meters.

Figure 3 also shows the lateral extent subject to these displacements. This distance is typically influenced by one of two types of failure modes: 1) a block-type failure denoted by the steep drop in maximum displacement at large distances from the waterway (up to 250 m) and 2) a distributed failure mode in which the majority of displacement occurs within the first 100 to 150m from the bank. The block-type failure was only observed in South Kaiapoi along Courtenay Stream and in Burwood around Bottle Lake. The majority of the observations exhibited the distributed failure mode. This distribution is more typical of what has been seen in the past, i.e. 1995 Hanshin-Awaji Earthquake (Ishihara, Yoshida, & Kato, 1997). Note that the block-type failure in South Kaiapoi is likely the result of a circular failure wedge associated with the loose soil conditions extending more than 100 metres inland from the bank.

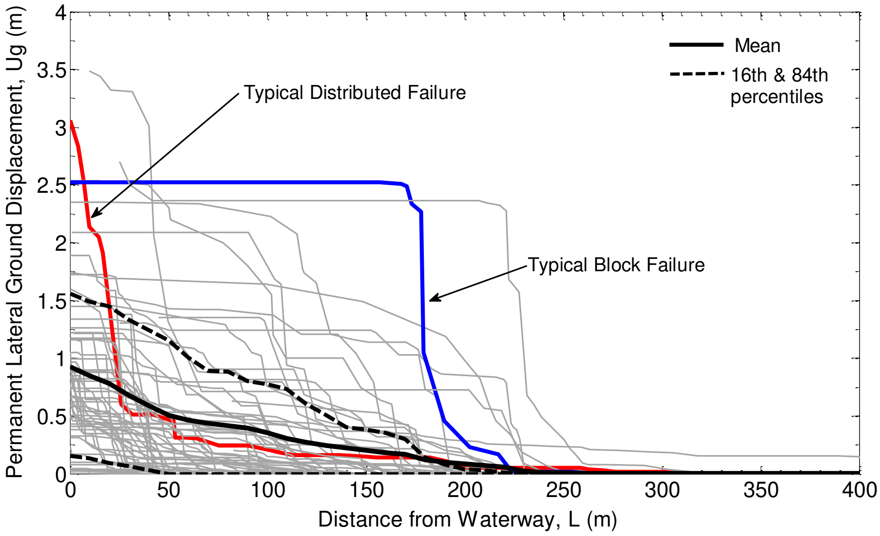

Figure 3. Results of field measurements of lateral spreading following the 4 Sep 2010 earthquake

4 LATERAL SPREADING FOLLOWING THE 2011 CHRISTCHURCH EARTHQUAKE

The epicentre of the February 22 event was located practically within the city boundaries and thus caused much larger accelerations within Christchurch relative to those in the Darfield earthquake. Peak ground accelerations (PGA) in areas subject to lateral spreading generally ranged from about 0.3 - 0.6g within Christchurch and accelerations of about 0.2g were felt in Kaiapoi. As a result of the larger accelerations along the Avon and Heathcote Rivers in Christchurch, an increase in lateral spreading was observed in these areas.

The 2011 lateral spreading field investigation conducted ground surveying at approximately 71 locations with the majority located along the Avon River in Christchurch. Figure 4 shows the results of measurements with respect to distance from the waterway. Again, the block-failure mode can be seen in Figure 4 on the two upper-bound transects that were surveyed along Courtenay Stream (South Kaiapoi). The remainder of transects generally exhibited distributed pattern of lateral spreading. Note that a total of 5 of the 71 transects (including the two transects in South Kaiapoi) were surveyed after the 13 June 2011 Earthquake (Mw 6.0) and hence, the spreading at these locations were likely influenced by the 22 February and 13 June events.

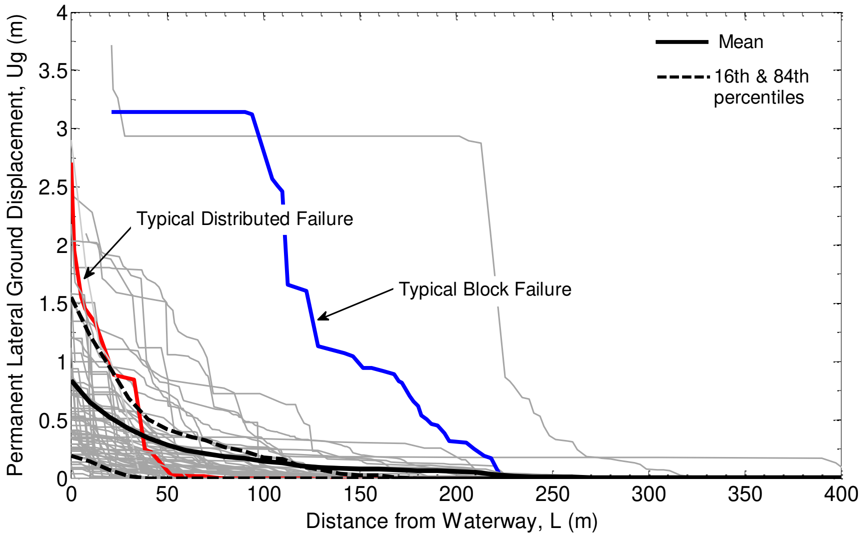

Figure 4. Results of field measurements of lateral spreading following 22 Feb 2011 earthquake

Figure 4 shows a similar range of maximum lateral displacements as in the September event. With the exception of the South Kaiapoi block-failure transects, the results show the majority of lateral spreading generally occurred within the first 100 to 150 metres of the bank.

5 COMPARISON OF LATERAL SPREADING MEASUREMENTS FROM THE TWO EVENTS

Among the locations surveyed following the 4 September event, 22 locations were also surveyed following the 22 February event. Of these 22 transects, five were surveyed after the June 2011 event (Mw6.0) and therefore the potential influences on the results from the subsequent shaking should be noted. A comparison of maximum displacements at these repeated locations is shown in Figure 5. Locations that were surveyed post-June are shown in hollow markers. As can be seen in Figure 5, a large increase in the magnitude of lateral spreading was observed at many locations, some showing maximum displacements more than three times that measured in the September event.

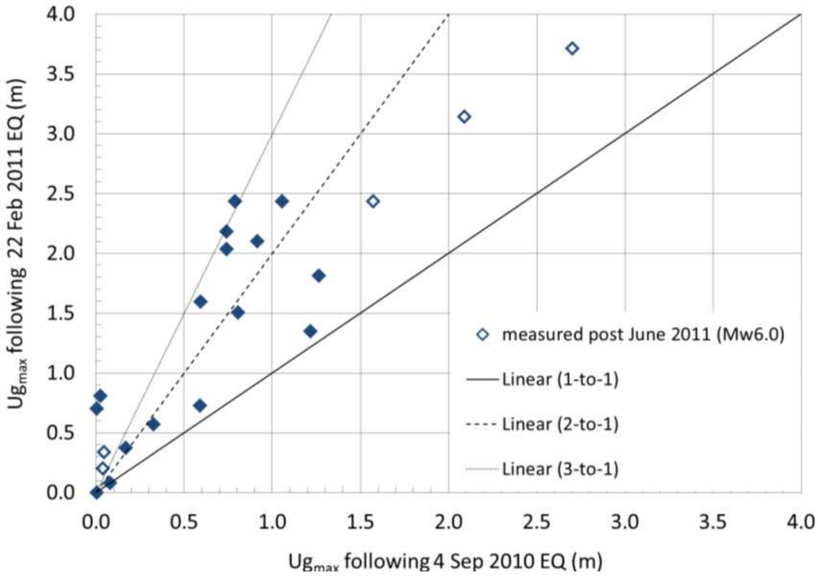

Figure 5. Comparison of maximum lateral displacements from 4 Sep 2010 and 22 Feb 2011 events

There are many factors that may have influenced the observed increase in displacement including seismic, geotechnical, and topographic effects. In addition to the increased accelerations and decreased site-to-source distances (R_{rup}) for areas within Christchurch, the majority of these locations were subject to severe liquefaction in the September event which led to changes in the soil strength and weakening of soil layers. Pre-existing fissures from the first event were likely more susceptible to widening during the subsequent shaking. The lateral spreading from September generally altered the original geometry of the slopes and banks along the rivers with slumping of the stopbanks and an overall decrease in elevation of the land and increase in the ground water table. The rise in ground water leads to a change in pore water distribution (also influenced by the presence of fissures) and thus changes the soils resistance to liquefaction and subsequent lateral spreading. Thus, the cause of lateral spreading is extremely complex. However, the most significant factor affecting the observed increase in displacements is likely associated with the increased seismic demand from the February earthquake on Christchurch.

Ignoring all other factors, we considered the sole effect of increased accelerations on the observed maximum displacements. The cyclic stress ratio (CSR) was calculated in accordance with Youd and Idriss (2001) at each “repeat” location (excluding the 5 post-June measurements) assuming a ground water level at the surface and using computed PGA values for each transect location. The observed maximum ground displacement (Ug_{max}) ratios were plotted against CSR ratios for these 17 locations, as shown in Figure 6.

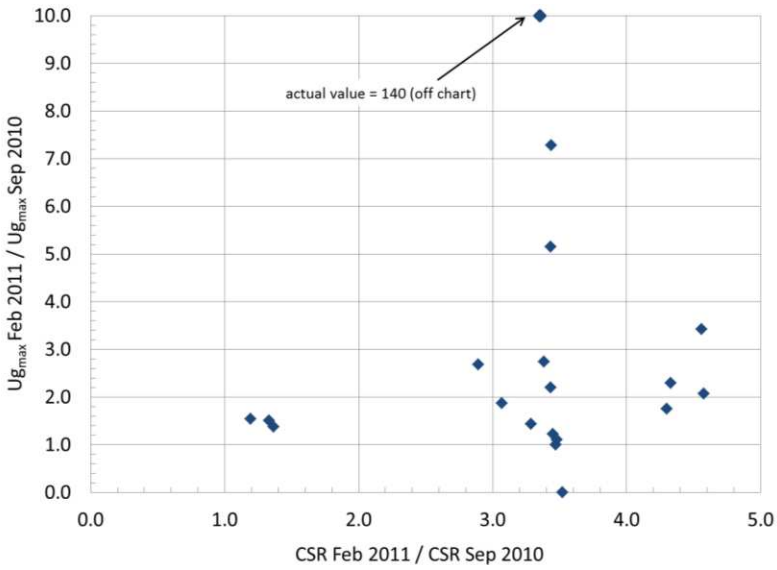

Figure 6. Maximum lateral displacement ratios versus CSR ratios from resurveyed locations

The plot shows a positive correlation between observed maximum displacement and CSR with some data showing an exponential increase in Ug_{max}. We note that the September 2010 accelerations were much less variable among the 17 resurveyed locations than in the February 2011 event (due to the greater R_{rup} distance in the September event). The consistency in CSR from September makes it more difficult to distinguish an exact relationship between Ug_{max} and CSR; however, it is clear that there is some influence on increasing CSR on increasing maximum displacements.

6 CONCLUSIONS

The 2010 Darfield and 2011 Christchurch earthquakes induced significant liquefaction and lateral spreading along the rivers and streams of Christchurch and surrounding suburbs causing extensive damage to buildings and infrastructure. Field investigations were conducted to document the lateral spreading along nearly 150 transects. The following conclusions summarize our findings.

- The method of ground surveying was employed to document the lateral spreading at 77 locations following the 2010 Darfield Earthquake and at 71 locations following the 2011 Christchurch Earthquake. The data shows magnitudes of displacement from both events ranging from less than 10 centimetres to over 3 metres.
- Two types of failure modes were observed. A block-type failure was seen along Courtenay Stream in South Kaiapoi and along Bottle Lake in Burwood, affecting areas up to 250 meters from the stream. The majority of failures followed a more typical, distributed pattern of lateral spreading which generally occurred within the first 100 to 150 metres of the waterway.
- Measurements from the method of ground surveying were compared with geodetic survey data to assess the differences in measurements of lateral displacement. The analysis showed the results of the ground survey method to be in good agreement with the geodetic survey data in South Kaiapoi.
- 22 locations were “resurveyed” following the 2011 event and showed increased displacements, some areas showing more than three times the post-September measurement.
- Maximum displacement ratios from the resurveyed transect locations were plotted against CSR ratios and showed a positive correlation. However, many factors can attribute to the increase in lateral spread displacements including change in subsurface conditions and topography which were not considered in the Ug_{max}-CSR comparison.

7 ACKNOWLEDGEMENTS

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