Geotechnical Aspects of the 2010 Darfield (Canterbury) Earthquake

Misko Cubrinovski[1]

[1]*Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand*

ABSTRACT

On 4 September 2010, a magnitude M_w 7.1 earthquake struck the Canterbury region on the South Island of New Zealand. The epicentre of the earthquake was located in the Darfield area about 40 km west of the city of Christchurch. Extensive damage was inflicted to lifelines and residential houses due to widespread liquefaction and lateral spreading in areas close to major streams, rivers and wetlands throughout Christchurch and Kaiapoi. Unreinforced masonry buildings also suffered extensive damage throughout the region. Despite the severe damage to infrastructure and residential houses, fortunately, no deaths occurred and only two injuries were reported in this earthquake. From an engineering viewpoint, one may argue that the most significant aspects of the 2010 Darfield Earthquake were geotechnical in nature, with liquefaction and lateral spreading being the principal culprits for the inflicted damage. Following the earthquake, an intensive geotechnical reconnaissance was conducted to capture evidence and perishable data from this event. This paper summarizes the observations and preliminary findings from this early reconnaissance work.

Keywords : Darfield earthquake, liquefaction, lateral spreading, settlement, structural damage

1 THE 2010 DARFIELD (CANTERBURY) EARTHQUAKE

New Zealand straddles the boundary between the Australian Plate and the Pacific Plate which passes through the South Island (Figure 1). The relative plate motion across the boundary is obliquely convergent at about 50 mm/yr in the north of New Zealand, 40 mm/yr in the centre and 30 mm/yr in the south (De Mets et al., 1994). The plate collision results in a disturbed zone of active faults in the South Island each capable of producing large earthquakes. The dominant tectonic feature of the South Island is the Alpine Fault, which accommodates about 70-75 % of the total relative plate motion (Norris and Cooper, 2001). The remaining 25-30 % of the plate motion is accommodated by a slip on a series of faults throughout the Southern Alps and Canterbury Plains. The Darfield earthquake occurred on one of these faults in the Canterbury plains, which was not recognized prior to the earthquake.

The magnitude M_W7.1 Darfield (Canterbury) Earthquake occurred at 4.35 am local time, on 4 September 2010. The epicentre was near the town of Darfield about 40 km west of the city of Christchurch. The earthquake was caused by a rupture of a previously unrecognized strike-slip fault, now well-known as the Greendale fault. As indicated in Figure 2, the earthquake resulted in a surface rupture approximately 29 km long in the east-west direction. The length of the fault rupture at depth is estimated to be on the order of about 40 km. Aerial photos of the surface rupture expression taken from a helicopter flyover on 10 September are shown in Figure 3. It is interesting to note that the faulting resulted in a narrow rupture zone despite hundreds metres of thick gravels at the ground surface.

Early finite fault inversions indicate that the nucleation point was approximately at the centre of the ruptured fault plane (Figure 4) and that the rupture was bi-lateral in nature. The latter feature resulted in a notably shorter duration of intense ground shaking than would have been the case, had the rupture have occurred in a uni-lateral fashion. The fault model shown in Figure 4 indicates one large aspherity of high slip to the west of the hypocentre, which is also an important feature to consider when evaluating the characteristics of the ground motions recorded throughout the Canterbury plains.

The ground motion produced by the mainshock of the Darfield earthquake was recorded at nearly 40 strong motion stations within the epicentral region. In the city of Christchurch and the town of Kaiapoi, peak horizontal ground accelerations

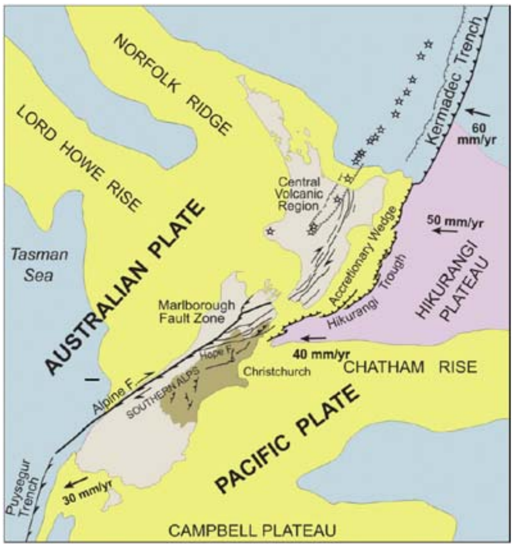


Figure 1. Plate boundaries and rate of movement through New Zealand (Image courtesy of Jarg Pettinga)

Figure 2. Aerial image of Christchurch area indicating the surface fault rupture and the epicentre of the Darfield earthquake (Image courtesy of Mark Quigley); Google Inc. 2010

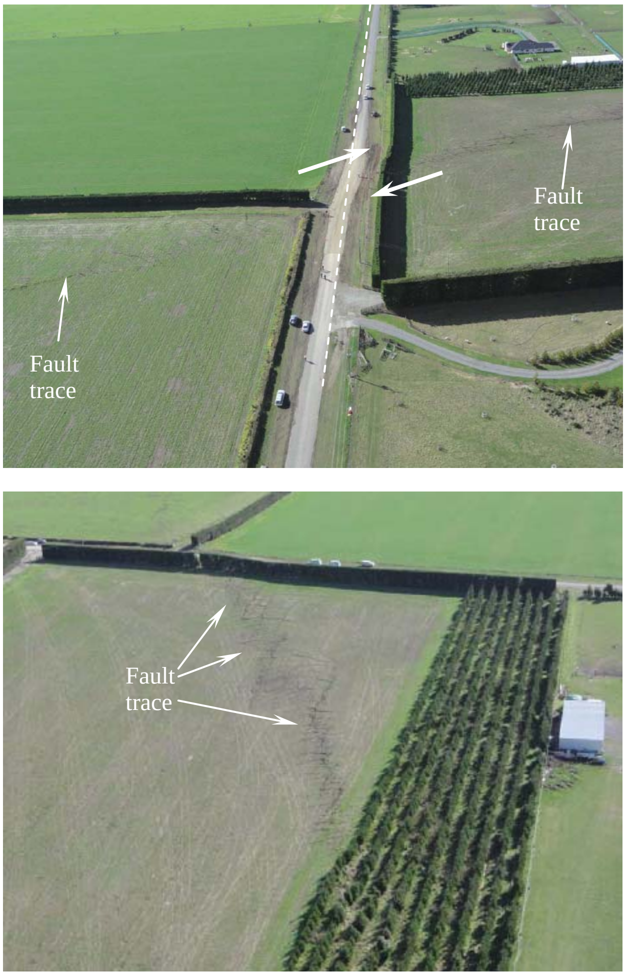


Figure 3. ~4 m offset of road and tree line (top photo) and rupture expression on farm land (both photos)

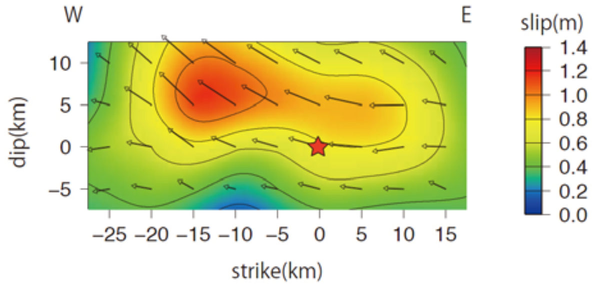
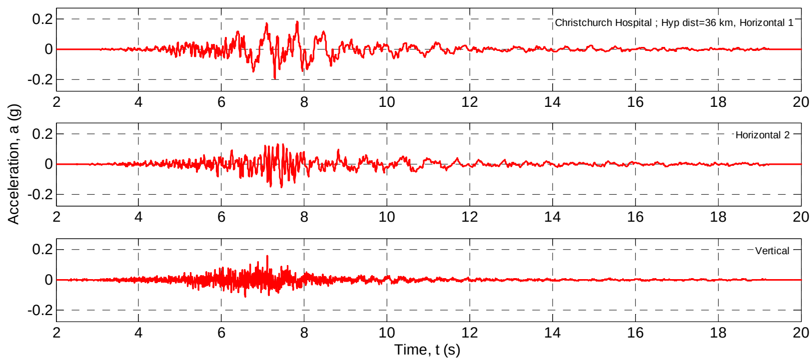


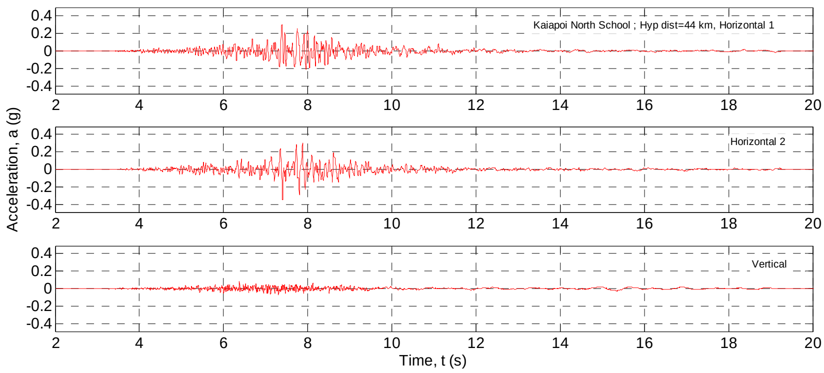
Figure 4. Finite fault inversion from ERI (http://outreach.eri.u-tokyo.ac.jp/2010/09/201009_nz_eng/)

on the order of 0.15-0.35 g were recorded indicating moderate-to-strong ground shaking in the urban areas. Acceleration time histories recorded at the Christchurch Hospital and Kaiapoi North School are shown in Figures 5a and 5b respectively.

Extensive damage occurred to unreinforced masonry buildings throughout the region during the mainshock and subsequent large aftershocks. Particularly extensive damage was inflicted to lifelines and residential houses due to widespread liquefaction and lateral spreading in areas close to major streams, rivers and wetlands throughout Christchurch and Kaiapoi. Despite the severe damage to infrastructure and residential houses, fortunately, no deaths occurred and only two injuries were reported in this earthquake. From an engineering viewpoint, one may argue that the most significant aspects of the 2010 Darfield Earthquake were geotechnical in nature, with liquefaction and lateral spreading being the principal culprits for the inflicted damage. This paper summarizes the observations and preliminary findings from geotechnical reconnaissance conducted following the earthquake and focuses on damage related to liquefaction and lateral spreading. A comprehensive report on the geotechnical reconnaissance is given in Cubrinovski et al. (2010a).



(a) Christchurch Hospital



(b) Kiapoi North School

Figure 5. Recorded acceleration time histories during the 2010 Darfield Earthquake: (a) Christchurch Hospital; (b) Kaiapoi North School

2 REGIONAL GEOMORPHOLOGY

2.1 *The City of Christchurch*

The city of Christchurch is situated in the middle part of the east coast of South Island. It has a population of about 350,000 (the second largest city in New Zealand) and an urban area that covers approximately 450 km^2. It is sparsely developed with approximately 150,000 dwellings (predominantly single-storey houses with a smaller number of two-storey houses) spread across a large area with many parks, natural reserves and recreation grounds. The Central Business District (CBD) is more densely developed with multi-storey buildings and a relatively large number of historic buildings. The epicentre of the 2010 Darfield Earthquake was located approximately 40 km west of the Christchurch CBD (Figure 2).

Christchurch is located on Holocene deposits of the Canterbury Plains, except for its southern edge, which is located on the slopes of the Port Hills of Banks Peninsula. The river floodplain and the loess sediments of the Port Hills are the dominant geomorphic features of the Christchurch urban area.

The Canterbury Plains are complex fans deposited by eastward-flowing rivers from the Southern Alps to the Pegasus Bay coast. The fan surfaces cover an area 50-km wide by 160-km long. At Christchurch, surface postglacial sediments have a thickness between 15 and 40 m and overlie 300-400 m thick inter-layered gravelly formations (Brown and Webber, 1992). The surface sediments are either fluvial gravels, sands and silts (Springston formation, with a maximum thickness of 20 m to the west of Christchurch) or estuarine, lagoon, beach, and coastal swamp deposits of sand, silt, clay and peat (Christchurch formation, with a maximum thickness of 40 m at New Brighton coast, east of CBD). The soil deposits at relatively shallow depths of up to 15-20 m vary significantly within short distances, both horizontally and vertically.

Brown and Webber (1992) describe the original site of Christchurch as *"mainly swamp lying behind beach dune sand, estuaries and lagoons, and gravel, sand and silt of river channel and flood deposits of the coastal Waimakariri River flood plain. The Waimakariri River regularly flooded Christchurch prior to stopbank construction and river realignment. Since European settlement in the 1850s, extensive drainage and infilling of swamps has been undertaken."* Brown and Webber also state that surface deposits are still actively accumulating and that the present day river channel deposits are excluded from the above-mentioned Christchurch and Springston formations.

Canterbury has an abundant water supply through open-channels (rivers, streams) and very rich aquifers. The dominant features of present day Christchurch are the Avon and Heathcote rivers that originate from springs in western Christchurch, meander through the city, and feed the estuary at the southeast end of the city. The ground water table is deepest at the west end of the city (at about 5 m depth), gradually increases towards east, and approaches the ground surface near the coastline. The water table is within 1.0-1.5 m of the ground surface for most of the city east of the CBD.

The high liquefaction hazard in Christchurch was well recognized before the earthquake, with publicly available liquefaction hazard maps provided by the Environment Canterbury (ECan, 2004) indicating a potential for severe damage due to liquefaction for most of the city to the east of CBD.

2.2 *The Town of Kaiapoi*

The town of Kaiapoi (population ~10,000; area ~5 km^2) is situated about 17 km north of Christchurch, near the north-eastern end of the Canterbury Plains (Figure 2). At Kaiapoi, recent Holocene sediments, approximately 100 m thick, overlie

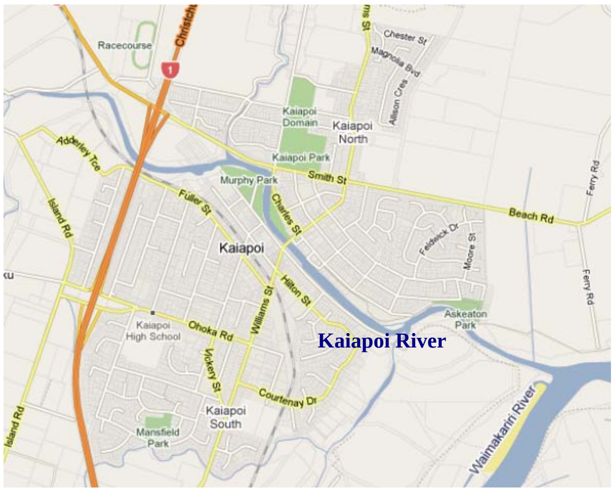


Figure 6. Map of present day Kaiapoi (Google Inc., 2010)

300-400 m of late Pleistocene sands and gravels, which in turn rest on rock and a greywacke basement rock (Brown and Webber, 1992).

Present day Kaiapoi is divided into North Kaiapoi and South Kaiapoi by the Kaiapoi River (Figure 6). At the southeast end of Kaiapoi, the Waimakariri River meets the Kaiapoi River. The Waimakariri River and its abandoned channels significantly influenced liquefaction susceptibility of Kaiapoi. As discussed in the following sections and in Berrill et al. (1994), before 1868 the Waimakariri River had two branches. The north branch flowed in the channel of the present Kaiapoi River, and the south branch flowed in the now abandoned channel that was located between the present Kaiapoi River and Waimakariri River channels. Several old meander loops of pre-1868 Waimakariri River have deposited loose silty sands both north and south of the present Kaiapoi River. In this area, the ground water table is generally shallow within 1-2 m of the ground surface. In the following section, typical manifestation of liquefaction and lateral spreading, and their effects on residential houses are discussed.

3 LIQUEFACTION AND LATERAL SPREADING DURING THE 2010 DARFIELD EARTHQUAKE

The Darfield earthquake caused widespread liquefaction in the eastern suburbs of Christchurch along the Avon River, particularly in Avonside, Dallington, Burwood and Bexley. Other suburbs, particularly to the east and northeast of CBD, were also affected by liquefaction, but to a lesser extent. Widespread liquefaction also occurred in Halswell, at the southwest end of the city. Pockets of limited or partial liquefaction were observed in various parts of Christchurch, though these were much fewer to the west of CBD. Figure 7 shows areas of observed liquefaction in the urban area of Christchurch based on surface manifestation of liquefaction visible in aerial photographs and initial observations from ground surveying. The areas most severely affected by liquefaction were close to waterways (rivers, streams, swamps). The effects of liquefaction were often localized and changed substantially over a relatively short distance (50-100 m) from very severe to low or no manifestation of liquefaction.

3.1 *Avonside and Dallington*

Widespread liquefaction occurred in Avonside and Dallington, particularly in the areas enclosed within the meandering loops of the Avon River. In these areas, the extensive liquefaction was

Figure 7. Areas of observed liquefaction (red shaded regions and red points) in Christchurch due to the 2010 Darfield Earthquake (the liquefaction map is based on surface manifestation of liquefaction visible in aerial photographs and compiled evidence from ground surveying)

accompanied by a complex pattern of lateral spreading. Large sand boils adjacent to houses and silty-sand and water covering the streets indicated extensive liquefaction in this area. Ground cracks with complex patterns indicated either lateral spreading features and/or ground distortion due to liquefaction including bearing failures. A large number of residential houses settled, tilted and suffered structural/foundation damage.

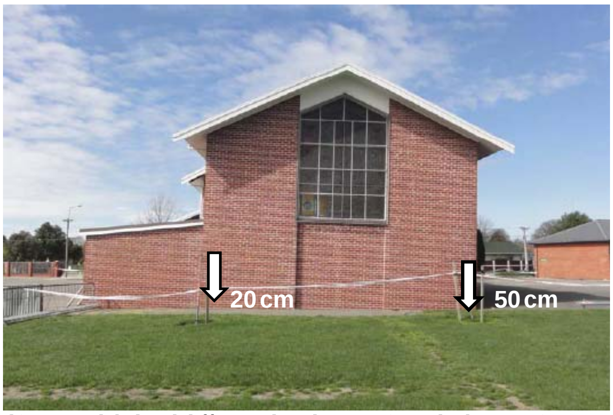
Typical manifestation of liquefaction in the backyard of a residential property is shown in Figure 8. Sand boil ejecta covered most of the lawn and was about 20 cm thick in places. There was evidence of massive liquefaction and large surface distortion in the neighbouring streets. The potable water and sewer systems were out of service at the time of the inspections. Despite significant amounts of liquefaction ejecta and broken utilities throughout the neighbourhood, the house shown in the pictures suffered relatively minor damage in terms of differential settlement and cracking.

A detailed survey was conducted at St Paul's Church (Dallington) which suffered severe damage due to liquefaction in the foundation soils and lateral spreading. Figure 9 shows a complex pattern of ground distortion including large cracks and vertical offsets around the building. Extensive sand boils covered the paved area around the building, backyard lawn, and around the perimeter of the building and its foundations. The building suffered large differential settlements and severe structural damage.

Specifically, the west (northwest) side of the building suffered structural separation due to a combination of large differential settlements and lateral movement. This site is centrally located in a meandering loop of the Avon River and bounded by the river on all sides at distances of about 150-250 m, except to the north/northeast. There was apparent evidence of lateral spreading in this area, despite being located more than 150 m from the free-face of the river. The tension cracks and fissures around the building were much bigger than those near the river channel, and hence further investigations are required to clarify these details. The building tilted between 2 and 4 degrees, and settled about 50 cm at the southwest corner (Figure 9b). The resulting differential settlement was approximately 30 cm.

Figure 8. Evidence of extensive liquefaction (massive sand boils) in residential areas of Avonside

(a) 50-90 cm wide ground crack with a vertical offset of 33 cm at its maximum (view looking north)



(b) Large global and differential settlements (view looking east)

(c) Evidence of liquefaction in foundation soils (view looking north; east side of building)

Figure 9. Liquefaction and lateral spreading induced ground failure and structural damage in Dallington (St Paul's Church)

Further to the east of Dallington, extensive liquefaction, including substantial lateral spreading, was observed in Porritt Park (Wainoni), which is enclosed by the Avon River and a diverted stream around the park. Large sand boils covered substantial areas of the park (Figure 10). Parallel cracks spaced regularly along drainage lines were indicative of slumping and spreading towards the north and south branches of the stream. A couple of hockey fields located in the park were severely damaged by the liquefaction, resulting in a very uneven, bumpy surface of the fields.

Figure 10. Evidence of extensive liquefaction (massive sand boils) in Porritt Park; using the vehicles (bottom of photo) or the hockey field (top of photo) for scale gives a good indication of the significant volume of sand ejecta

3.2 *Bexley*

Bexley is located further to the east along the Avon River, approximately one kilometre from the Avon-Heathcote Estuary. It is bounded by the Avon River on the east-side and by the Bexley Wetland on the south. The residential area was developed in several stages, with the southern portion being reclaimed from the wetlands and developed in the late 1990s and later on.

Widespread liquefaction occurred in Bexley, affecting a large number of residential houses (Figure 11). Ground distortion (i.e., differential settlement, large ground cracks, deformation of paved surfaces and substantial sand boils) was observed in the southern part of Bexley. Residential properties along the wetland walkway were severely affected by lateral spreading. Large movement of the walkway towards the water, slumping of the terrace fill and large ground cracks on residential properties were observed in this area. In areas severely affected by lateral spreading, damage to foundation slabs was common, as illustrated in Figure 11(c). Typically, the slabs of one-storey houses were without reinforcement.

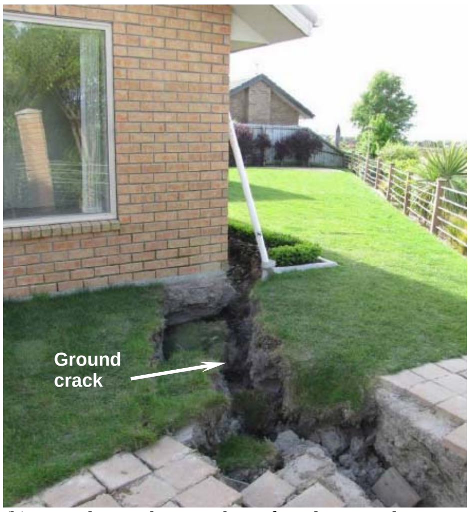
3.3 *North Kaiapoi*

In the Darfield earthquake, widespread liquefaction occurred north of the Kaiapoi River affecting a large number of residential houses in the town of Kaiapoi. The houses in this area are typically single or two-storey brick/stone block masonry or timber structures on spread footings. Figure 12 shows areas of severe and moderate-to-low liquefaction in the town of Kaiapoi observed from ground surveying and aerial photos. The strong motion records shown in Figure 5b were recorded in North Kaiapoi, outside the liquefied area shown in Figure 12.

The liquefaction was particularly intense, producing massive sand boils of grey, silty sand, at Cassia Place and at the east end of Charles and Sewell streets. In the worst hit area, the silty sand ejecta was about 400 mm thick (Figure 13). Some residents reported geysers appearing in the backyard following the earthquake, often forming a small pond near the house that remained for several days after the event.

In this general area, including near the east end of Charles St and Sewell St, the liquefaction led to large settlement of many houses, including differential settlement that resulted in structural damage. The large ground distortion, cracks and fissures in the ground caused significant damage to buried

(a) Large volume of sand ejecta on residential land



(b) Lateral spreading cracks in foundation soils

(c) Cracked foundation slab due to lateral spreading

Figure 11. Liquefaction and lateral spreading severely affecting residential houses in Bexley

lifelines. The intensity of liquefaction gradually decreased from severe to moderate-to-mild and no liquefaction when moving away to the north or west from the Beswick St-Cass St-Askeaton Dr block.

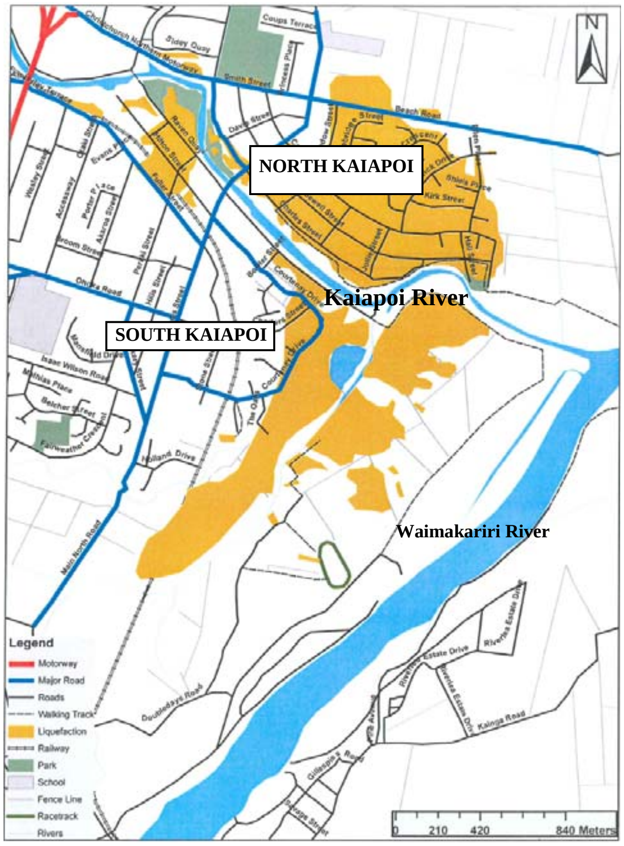


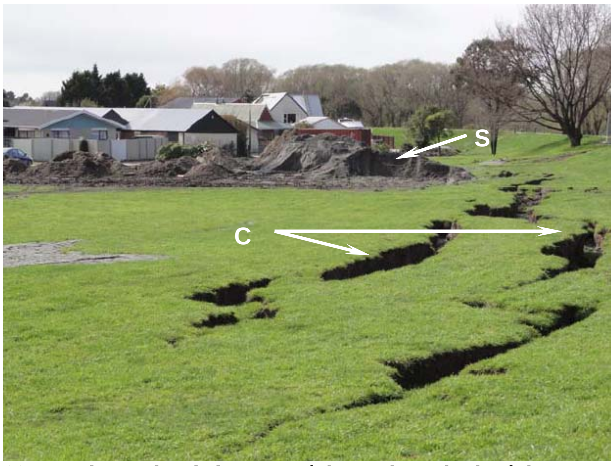
Figure 12. Areas of observed liquefaction in the town of Kaiapoi due to the 2010 Darfield Earthquake; the liquefaction map is based on surface manifestation of liquefaction visible on aerial photographs and compiled evidence from ground surveying

Figure 13. Manifestation of very severe liquefaction in residential area of North Kaiapoi; ~40 cm thick layer of silt-sand-water mixture covering a residential property affected by very severe liquefaction; the house suffered structural damage and large settlement

The area along the Pegasus Bay Walkway (from the Kaiapoi Visitor Information Centre on the east to Askeaton Park on the west) was affected by significant lateral spreading with large cracks and fissures in the sloping ground towards Charles St. Residential houses in this area were severely affected both by liquefaction and lateral spreading. Figure 14 illustrates the

(a) Aerial view of North Kaiapoi (from a helicopter flyover on 10 September)

(b) Lateral spreading crack running through residential house



(c) Lateral spread and slumping of the north stopbank of the Kaiapoi River, near the east end of Charles St; note the huge piles of cleaned up sand obstructing the view of the houses

Figure 14. Liquefaction and lateral spreading in North Kaiapoi

severity of liquefaction and lateral spreading damage induced in this area. Large size sand ejecta, spread across the area between the stopbank and Charles St, are seen in Figure 14a. The huge piles of cleaned up sand indicated as position S in Figures 14a and 14c clearly illustrate the massive liquefaction that occurred in the area. The liquefaction was accompanied by a significant lateral spreading towards the Kaiapoi River (Figures 14a and 14c) that affected a number of houses along Charles St (Figure 14b). Note that, at this exact location liquefaction was observed during the 1901 Cheviot earthquake (Berrill et al., 1994).

3.4 *South Kaiapoi*

In South Kaiapoi, the most dominant ground failure feature was the liquefaction and massive lateral spreading that affected the eastern branch of Courtenay Drive. The area affected by lateral spreading, shown in Figure 15, was approximately 1-km long in the north-south direction and extended between 200 m and 300 m inland from the Courtenay Stream and Courtenay Lake. The lake was artificially created during the construction of the northern end of Courtenay Dr. Borrow material was removed from the area where the lake is presently located and used as hydraulic fill (about 1 m thick) for the northern branch of Courtenay Dr (WDC, 2010).

The area where massive lateral spreading occurred coincides with the old Waimakariri River channel from 1865. On the eastern side of South Kaiapoi, the old channel passes underneath the present day Courtenay Dr area shown as position 1 in Figure 15, where severe damage to residential properties occurred due to lateral spreading. Further south at positions A and B (Figure 16), large cracks due to lateral spreading towards Courtenay Stream are evident. Along this stretch from position A to the north-east corner of Courtenay Dr (slightly north of position 1), detailed ground surveys were conducted along ten transects including measurement and mapping of width of cracks, vertical offsets, and geo-tagging of major cracks and other lateral spreading features. Figure 17 indicates geo-tagged major cracks and four transects of detailed measurements at position A. Using the vehicles in the photo for scale gives a good indication of the significant size of these cracks and the volume of ejecta.

Lateral spreading resulted in large permanent lateral displacements on the order of 1.0-3.5 m with large ground cracks of about 0.5-1.5 m wide running through residential properties and houses along the east branch of Courtenay Dr. In this area, position 1 in Figure 15, single storey and two storey houses suffered very severe damage due to large lateral ground movements including substantial tilt, loss of foundation support, tension cracks in foundations and slabs (Figure 18). It was significant that despite the extreme lateral movement of the immediate foundation soils and the foundations themselves, all houses showed large ductile deformation capacity and continued to carry gravity loads, despite literally being ripped in half in some cases. Detailed inspections and mapping of damage to houses were performed in this area. There was clear evidence that the lateral movement, at least in some parts of the affected area, continued to develop/increase well after the main event. Two consecutive measurements of the width of a large ground crack carried out on 11 and 15 September showed an increase in width of 20 cm over this period (i.e. from 1.4 m to 1.6 m). The residents of the neighbouring property reported new extensive cracks appearing in their house over the same time period. It is believed that this continued deformation was the result of a combination of creep due to static driving shear stresses, significantly softened soils and effects of aftershocks on a structure marginally stable under gravity loads.

4 CHARACTERISTICS OF LIQUEFIED SOILS

4.1 *Grain-size composition*

The ejecta from sand boils in areas affected by liquefaction were generally very similar and had several distinctive features. They were non-plastic fine sands and silty sands with an easily recognizable grey/blue colour.

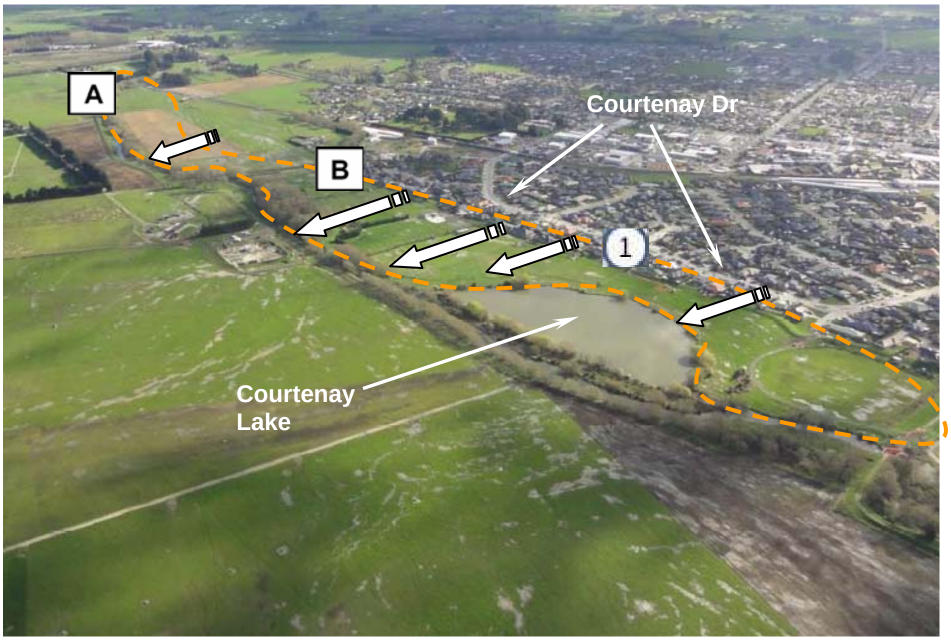


Figure 15. Massive lateral spreading at South Kaiapoi; sand ejecta and area affected by lateral spreading around Courtenay Lake

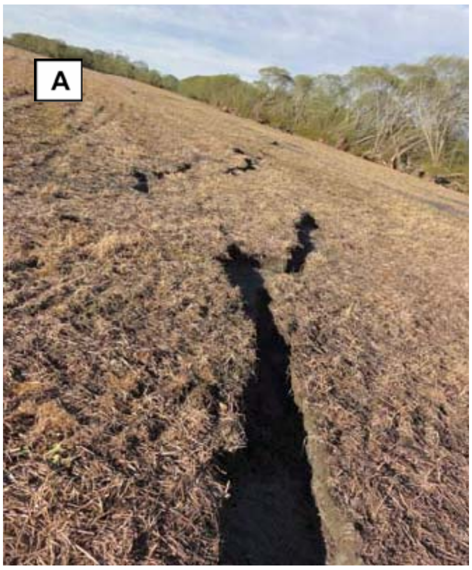


Figure 16. Large lateral spread cracks in farm land (positions A and B shown in Figure 15)

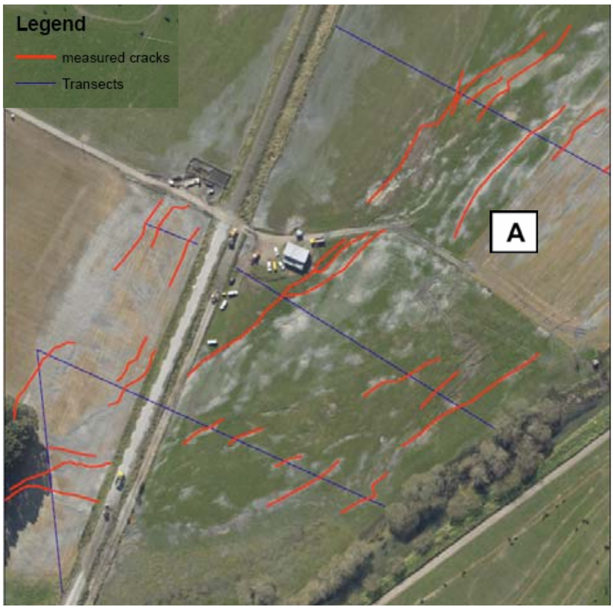


Figure 17. Aerial view of the lateral spread area at position A at South Kaiapoi showing four transects of detailed ground surveys

Grain-size distribution curves of ejecta samples taken from Dallington, Porritt Park and South Kaiapoi are shown in Figure 19a. Figure 19b shows grain size distribution of soil samples taken from the SWS screw point (representative of the deepest layer penetrated in a SWS test), indicating that the deeper soils have higher fines content.

The author, together with a number of postgraduate students has been investigating the undrained behaviour and liquefaction resistance of Christchurch soils since 2005 (Cubrinovski and Rees, 2008; Cubrinovski et al., 2010b; Rees, 2010). These studies focused on the effects of fines on the steady state line and liquefaction resistance, and included sampling of soils from several locations within the CBD, in the period 2006-2008. Figure 19c shows grain size distribution curves of sandy soils

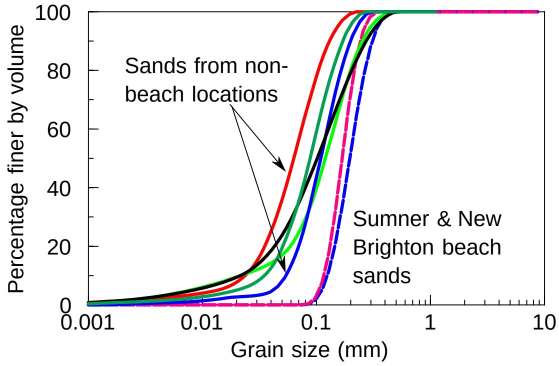
(a) Lateral spreading crack running through residential house

(b) Excessive tilt and uplift of foundations due to lateral spreading displacements of about 1.5 m

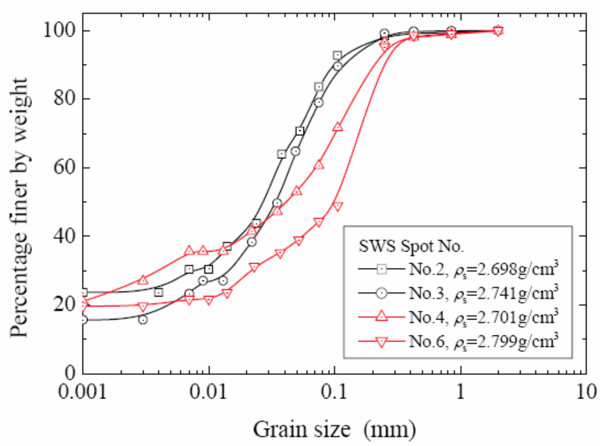
(c) Severe damage to residential house due to lateral spreading displacements of about 1.5 m

Figure 18. Severe damage to residential houses/properties due to lateral spreading at Courtenay Dr, South Kaiapoi

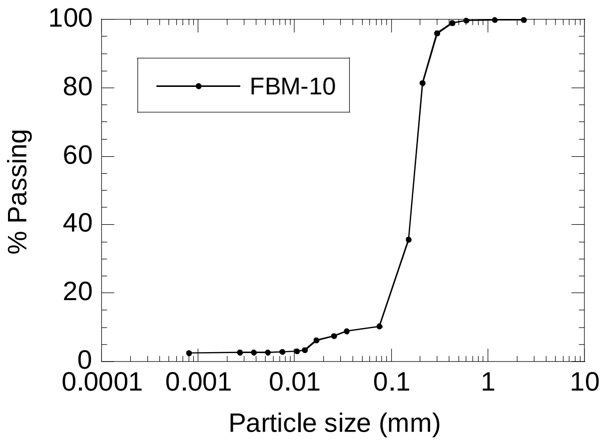
sampled from one of those locations where fines content of about 10 % was encountered. Apparently, there is a remarkable similarity between the sand fractions of the soils shown in



(a) Grain-size distribution curves of sand ejecta obtained by laser diffraction analysis (courtesy of Michael Pender)



(b) Grain-size distribution curves of soil samples taken from the SWS screw point (deepest tested layer in Swedish Weight Soundings test) obtained by sieve and hydrometer analyses (courtesy of Hirofumi Toyota)



(c) Grain-size distribution curves of soil samples taken from the Fitzgerald Bridge site in Christchurch (Cubrinovski and Rees, 2008)

Figure 19. Grain-size distribution curves of Christchurch soils

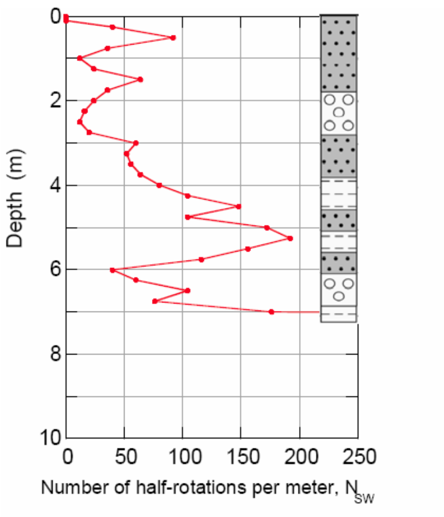
Figures 19a and 19c. By and large, clean sands and non-plastic silty sands with fines content predominantly between 10 and 30% liquefied during the Darfield earthquake.

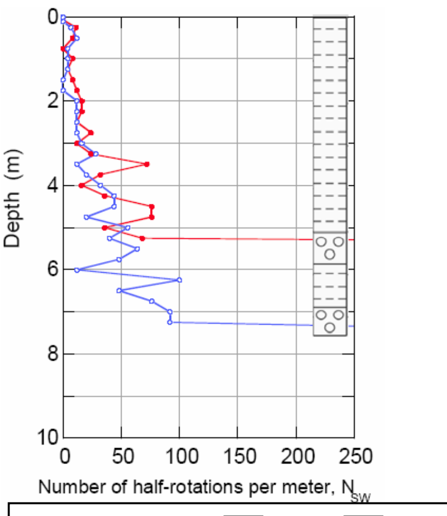
4.2 *Penetration resistance*

After the earthquake, Swedish Weight Sounding (SWS) tests were performed at several locations affected by liquefaction and lateral spreading. By 15 October 2010, about 80 SWS tests have been conducted in Avonside, Dallington, Bexley, South Kaiapoi and North Kaiapoi. Here, the results of only few of the initial tests are reported.

SWS is a simple manually operated penetration test under a dead-load of 100 kg in which the number of half-rotations required for a 25 cm penetration of a rod (screw point) is recorded (JIS, 1995). One of the advantages of the SWS test which was heavily utilized in this investigation is the ability to perform the test within a confined space in backyards of residential properties. Other advantages include the fact that SWS has been successfully utilized in liquefaction studies and that SWS penetration resistance N_{SW} can be expressed in terms of conventional SPT blow count using established N-N_{SW} empirical correlation (Tsukamoto et al., 2004; Inada, 1960). Even though manually operated, the test setup used in the reconnaissance could probe soils up to 9 m depth.

Figure 20 shows the penetration resistance measured in the SWS tests conducted at two locations in Dallington and Avonside, expressed in terms of the number of half-rotations per metre, N_{SW}. The N-value correlations are not presented herein, however, the respective SPT blow count for the penetration resistance shown in Figure 20 is roughly in the range between 5 and 15.





Soil profile symbols: sandy silty with gravel

Figure 20. Post-event penetration resistance in Dallington and Avonside measured in SWS tests

5 RE-LIQUEFACTION AT HOON HAY

On 19 October 2010, a M_W 5.0 aftershock struck the region, with an epicentre about 10 km southwest of the CBD. The aftershock caused re-liquefaction in the area of Hoon Hay, a suburb located at an epicentral distance of about 8 km. Figure 21a shows large amount of sand ejecta covering the lawn of a residential property due to the re-liquefaction caused by the aftershock. Many residents in the area reported that houses suffered additional damage during the aftershock including widening of the cracks in walls and foundations due to lateral movement of foundation soils. This area of Hoon Hay heavily liquefied during the mainshock of the Darfield earthquake.

(a) Sand ejecta at the perimeter of house foundations

(b) Sand ejecta and damage to foundations (the size of the crack doubled during the re-liquefaction caused by the aftershock)

Figure 21. Re-liquefaction at Hoon Hay due to a M_W 5 aftershock

6 SUMMARY AND CONCLUSIONS

The magnitude M_W 7.1 Darfield earthquake caused widespread liquefaction and lateral spreading in areas close to rivers and wetlands throughout Christchurch and Kaiapoi. Relatively loose sandy soils with 0-30 % non-plastic silts heavily liquefied causing damage to residential houses and lifeline systems. Particularly severe damage was inflicted to houses affected by lateral spreading. Significant volume of sand ejecta, ground distortion, settlement, slumping and large lateral ground movement were evident in the areas affected by liquefaction and lateral spreading. In the liquefied areas, a large number of residential houses suffered global and differential settlements, and some structural/foundation damage. In areas severely affected by lateral spreading, large ground cracks about 0.5-1.5m wide run through residential properties/houses causing very severe structural and foundation damage, and nearly collapse in some cases. Preliminary estimates indicate an economic loss associated with the earthquake of about 4 billion NZ dollars. It seems that at last half of that cost is directly related to ground damage and its impacts on residential areas and lifeline systems.

ACKNOWLEDGEMENTS

Following the earthquake, a geotechnical reconnaissance was conducted over a period of six days (10–15 September 2010) by a team of geotechnical/earthquake engineers from New Zealand, USA (GEER) and Japan (JGS). The team included the following members: Misko Cubrinovski (University of Canterbury, NZ), Russell Green (Virginia Tech, USA), John Allen (TRI Environmental, Inc, TX, USA), Scott Ashford (Oregon State University, USA), Elisabeth Bowman (University of Canterbury, NZ), Brendon Bradley (University of Canterbury, NZ), Brady Cox (University of Arkansas, USA), Tara Hutchinson (University of California, San Diego, USA), Edward Kavazanjian (Arizona State University, USA), Takashi Kiyota (IIS, University of Tokyo, Japan), Mitsu Okamura (Ehime University, Japan), Rolando Orense (University of Auckland, NZ), Michael Pender (University of Auckland, NZ) and Liam Wotherspoon (University of Auckland, NZ). The NZ, GEER and JGS members worked as one team and shared resources, information and logistics in order to conduct thorough and most efficient reconnaissance covering a large area over a very limited time period. This paper summarises some of the evidence and findings from the reconnaissance. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the author and do not necessarily reflect the views of the associated organisations and funding agencies.

Primary support for the New Zealand participants was provided by the University of Canterbury and University of Auckland. Additional support was provided through data/information sharing and ‘clearing house’ activities of a large research group re-convening every night at Environment Canterbury (ECan), following the intense field reconnaissance during the day. The support of Peter Wood (President of New Zealand Society for Earthquake Engineering), Dr. Grant Dellow (GNS), Dr. Kelvin Berryman (Natural Hazards Platform Manager, GNS) and Helen Grant (ECan) for the overall assistance and providing quick access to properties/areas of interest is greatly appreciated. This also included a helicopter flyover of the affected area for three members of the team, in order to jump-start the reconnaissance effort. Mike Jacka and Kirsti Murahidy, from Tonkin and Taylor, Christchurch, provided valuable information related to liquefaction-induced damage to residential properties. The author would like to acknowledge the great support and effort of a number of postgraduate students from the University of Canterbury, and in particular Merrick Taylor, Kelly Robinson, Jawad Arefi, Joshua Bird, Kim Rait, Patrick Kailey, Yusa Mohamed and Kam Wang throughout the reconnaissance and follow-up investigations.

REFERENCES

Berrill, J.B., Mulqueen, P.C. and Ooi, E.T.C. (1994). Liquefaction at Kaiapoi in the 1901 Cheviot, *New Zealand, Earthquake. Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. 27, No. 3, 178-189.

Brown, L.J. and Weeber, J.H. (1992). *Geology of the Christchurch Urban Area*. Institute of Geological and Nuclear Sciences.

Japanese Standards Association (1975). Japanese Industrial Standard: *Method of Swedish Weight Sounding* – JIS A 1221 (1975), 1995 Revision.

Cubrinovski, M. and Rees, S. (2008). Effects of Fines on Undrained Behaviour of Sands. *ASCE Geotechnical Special Publication 181*p. 1-11.

Cubrinovski, M., Green, R., Allen, J., Ashford, S., Bowman, E., Bradley, B., Cox, B., Hutchinson, T., Kavazanjian, E., Orense, R., Pender, M., Quigley, M., Wilson, T. and Wotherspoon, L. (2010a). Geotechnical reconnaissance of the 2010 Darfield (New Zealand) earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. 43, No. 4, (in print).

Cubrinovski, M., Rees, S. and Bowman, E. (2010b). Chapter 6: Effects of non-plastic fines on liquefaction resistance of sandy soils. *Earthquake Engineering in Europe, Springer*, 125-144.

DeMets, C., Gordon, R. G., Argus, D. F., Stein, S. (1994). Effect of recent revisions to the geomagnetic time scale on estimates of current plate motion, *Geophysical Research Letters*, 21, 2191-2194.

Environment Canterbury (ECan): http://ecan.govt.nz/publications/General/solid-facts-christchurch-liquefaction.pdf.

Inada, M. (1960). Use of Swedish weight sounding tests, *Tsuchi-to-Kiso, Japanese Geotechnical Society*, 8(1), 13-18 (in Japanese).

Norris, R.J. & Cooper, A.F., 2001. Late Quaternary slip rates and slip partitioning on the Alpine Fault, New Zealand, J. Structural Geol., 23, 507– 520.

Rees, S. (2010). Effects of fines on undrained behaviour of Christchurch sandy soils. *PhD Thesis, University of Canterbury*, p. 276.

Tsukamoto, Y., Ishihara, K. and Sawada, S. (2004). Correlation between penetration resistance of Swedish Weight sounding tests and SPT blow counts in sandy soils. *Soils and Foundations, 44(3)*, 13-24.