4. LIQUEFACTION AND LATERAL SPREADING

In the 2010 Darfield Earthquake widespread liquefaction and lateral spreading occurred in various parts of Christchurch City (most extensively in the suburbs to the east of the city center, but also in more localized areas to the north and southwest of the city), the town of Kaiapoi and the beachside settlements near the Waimakariri River. The liquefaction and associated ground deformation/failure led to significant damage to residential houses and lifeline systems. Particularly heavy damage was induced by lateral spreading, which was very extensive and severe in areas of South Kaiapoi (Courtenay Dr), and very severe but localized in some areas of Bexley, Spencerville, and North Kaiapoi. Along the meandering loops of the Avon River in Avonside and Dallington, post-earthquake settlement and lateral spreading was widespread, but lateral displacements were relatively moderate. Loose to very loose alluvial fine- to silty sand deposits in areas of old (abandoned) river channels, lagoons, wetlands and near waterways (streams, rivers) were responsible for the widespread liquefaction, lateral spreading and ground failures. In view of the extensiveness and severity of the effects, one may argue that the most significant engineering aspects of the 2010 Darfield Earthquake were geotechnical in nature, with liquefaction and lateral spreading being the principal culprits for the inflicted damage.

The observations made by the GEER-NZ reconnaissance team in these areas are briefly described below. The surveys were performed on foot, by car, and from a helicopter mainly over a period of six days. A broad-brush field reconnaissance was conducted in the first two days, followed by pin-point investigations at specific locations including detailed site inspections and field testing using: Dynamic Cone Penetration Test (DCPT), Swedish Weight Sounding (SWS), and Spectral Analysis of Surface Waves (SASW). Both DCPT and SWS results correlate to the Standard Penetration Test (SPT) N-values, and the SASW provides the shear wave velocity profiles. The observations from these inspections/in situ tests are also detailed below. Figure 4.1 shows the area most affected by the earthquake.

Christchurch

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-story houses with a smaller number of two-story 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-story buildings and a relatively large number of historic buildings. The epicenter of the 2010 Darfield Earthquake was located approximately 40 km west of Christchurch's Central Business District (CBD).

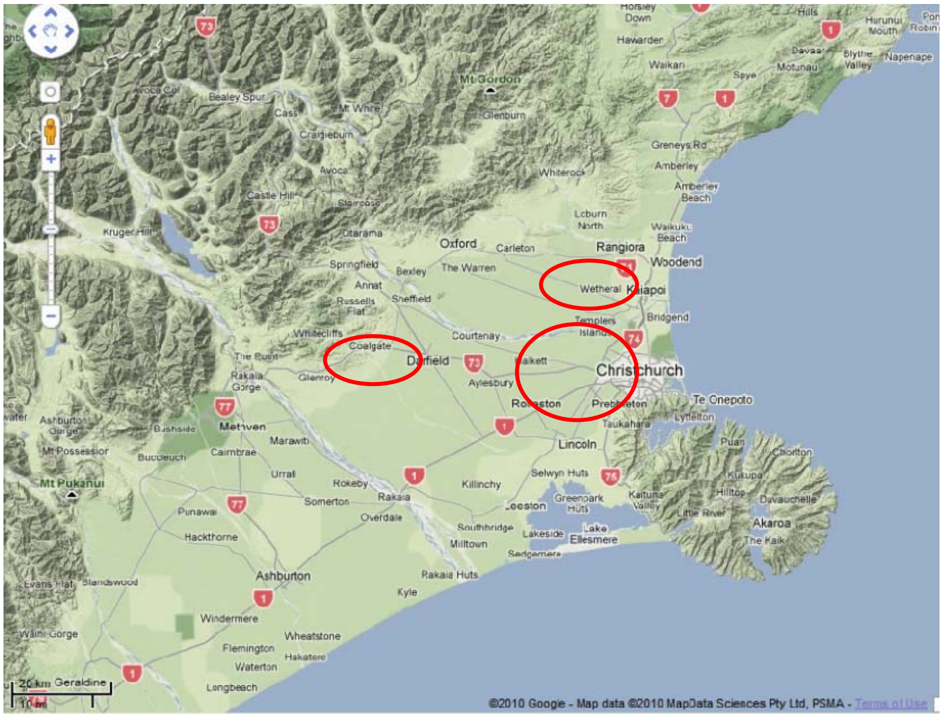


Figure 4.1 Canterbury region, CBD, and eastern suburbs of Christchurch. (Google Inc. 2010)

Local geology and liquefaction hazard

The city of 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 conditions and development of Christchurch as follows: *"Originally the site of Christchurch was 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* [levee] *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 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 (with 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 known prior to the earthquake, as illustrated by the liquefaction hazard map (Figure 4.2) and information provided by the Environment Canterbury (ECan: http://ecan.govt.nz/publications/General/solid-facts-christchurch-liquefaction.pdf) to residents, based on a study from 2004.

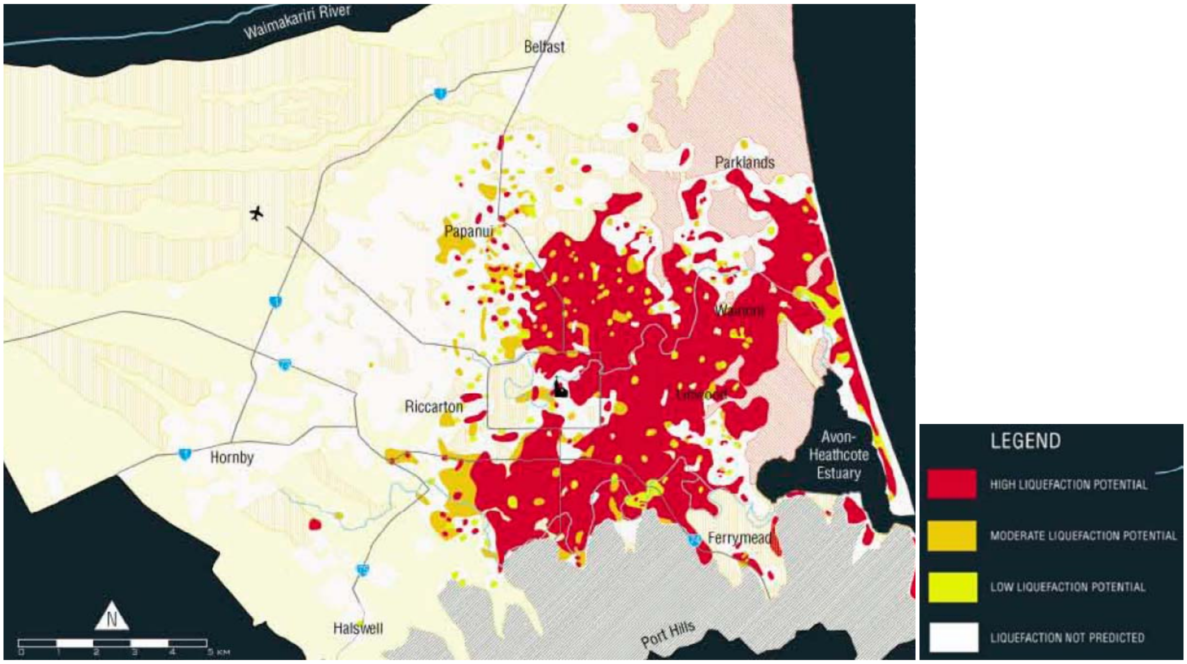


Figure 4.2 High ground-water table liquefaction potential hazard map for Christchurch. (http://ecan.govt.nz/publications/General/solid-facts-christchurch-liquefaction.pdf; pre-event information provided to residents and public by ECan)

Liquefaction manifestation during the 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 4.3 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 surveys. 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 little or no manifestation of liquefaction.

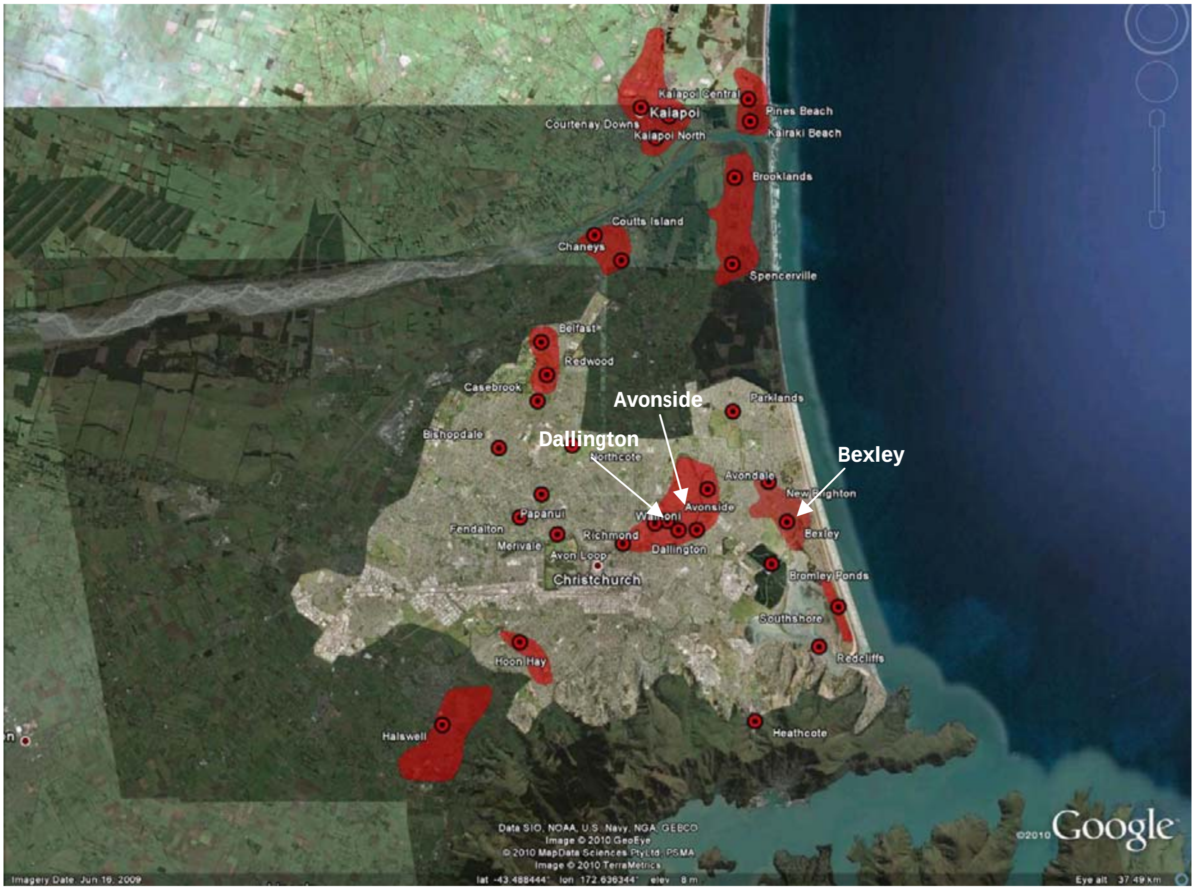


Figure 4.3 Areas of observed liquefaction (red shaded regions and red points) in Christchurch due to the 2010 Darfield earthquake (the liquefaction map is based on surface manifestation of liquefaction visible in aerial photographs and compiled evidence from ground surveys).

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 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 4.4 (Bracken St, Avonside). 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 on Bracken St. 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 minor damage in terms of differential settlement and cracking.

(a)

(b)

Figure 4.4 Evidence of extensive liquefaction in residential areas of Avonside: (a) Massive sand boils in residential area of Avonside (Bracken St); and (b) The sand boil (grey non-plastic silty sand) in the bottom half of the photo to the left was typical of many locations across Christchurch and Kaiapoi where massive liquefaction was observed; at this location, a brown silty sand was also found on the ground surface (upper half of the sand boil); photo to the right: University of Canterbury postgraduate students perform Swedish Weight Sounding (SWS) test (Bracken St: -43.520833°, 172.663750°).

The geotechnical reconnaissance team performed a detailed survey at St Paul's Church (Gayhurst Rd, Dallington), which suffered damage due to liquefaction in the foundation soils (Chapter 5). Figure 4.5 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.

(a)

(b)

Figure 4.5 Liquefaction-induced bearing failure at St Paul's Church, Gayhurst Rd, Dallington: (a) Bearing failure in liquefied soils; the crack is 50-90-cm wide with a vertical offset of 33 cm, at its maximum; and (b) Evidence of liquefaction in foundation soils resulting in large total and differential settlements. (-43.519670°, 172.672240°).

Specifically, the northwest side of the building was ripped in half due to a combination of differential settlement 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. Lateral spreading was observed in this area, despite being located more than 150 m from the free-face of the river. (Note, however, that this distance is not necessarily anomalous. Evidence of lateral spreading has been found at distances of up to 2 km from a free-face in the New Madrid, Missouri, USA, area (Obermeier, S.F., per. comm.). These features manifested during the 1811-1812 earthquakes that occurred in that region.) The tension cracks and fissures around the building were much bigger than those near the river channel, and hence it is possible that they are not only the result of lateral spreading. Further investigations are required to clarify these details.

Ten days after the event, the team performed Swedish Weight Sounding (SWS) tests at Bracken St and in the backyard of St Paul's Church. 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. Figure 4.6 shows the penetration resistance measured in the SWS tests conducted at Bracken St and St Paul's Church, expressed in terms of the number of half-rotations per meter, N_{SW}. Correlations exist relating this penetration resistance to an equivalent SPT N-value (JIS, 1995). However, the N-value correlations are not presented herein.

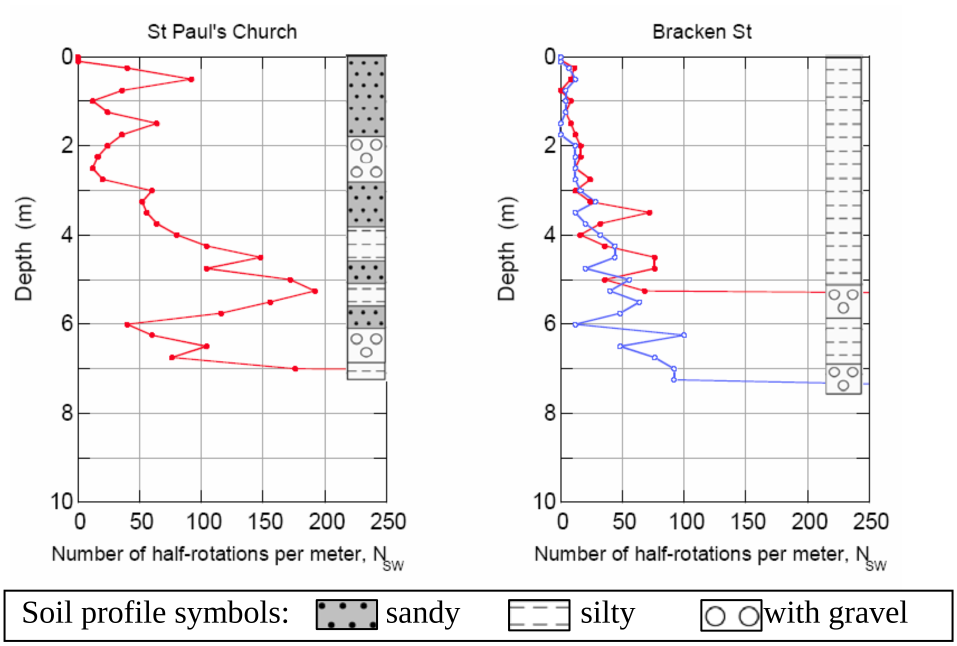


Figure 4.6 Post-event penetration resistance in Dallington (St Paul's Church/School) and Avonside (Bracken St) measured in SWS tests.

Additionally, two Dynamic Cone Penetration Tests (DCPT) were performed at the residence shown in Figure 4.4, one in the backyard and one in the front yard. The results of the DCPTs are shown in Figure 4.7. At each of the test locations, a hand auger was used to bore a hole down to the layer that liquefied. This layer was identified by comparing ejecta material with soil extracted by the hand auger. Once at the liquefied layer, the DCPTs were performed until the blow count significantly increased or the team ran out of DCPT rods (i.e., ~4.6 m below the ground surface).

There are several different configurations of the DCPT equipment available. The one used in these investigations was designed by Sowers and Hedges (1966) and built by Humboldt Manufacturing Co. This system utilizes a 6.8-kg mass (15-lb drop weight) on an E-rod slide drive to penetrate an oversized 45° apex angle cone. The cone is oversized to act as a friction reducer for the rods. The DCPT blow count is the number of drops of the weight required to drive the cone ~4.5 cm.

The ground water table at both sounding locations at the Bracken Dr residence was at ~0.8m, and the top of the liquefiable layer was at a depth of ~2.1 to 2.4 m. The strata overlying the liquefiable layer were clayey. For one of the tests, the DCPT rods sank under their own weight 20+ cm, indicating very loose sand. Because no samples are recovered with the DCPT, the thickness of the liquefied sand layer cannot be determined for certain. However, from looking at the results shown in Figure 4.7, the penetration resistance sharply increases at a depth of ~3.5 m. Additionally, there is a very wet, very soft, thin (~10 to 15 cm) clay/plastic silt layer that overlies the liquefied layer. It is unknown whether this is a very sensitive material that softened as a result of earthquake shaking and/or sampling or whether it is a result of a water film that formed between the liquefied layer and the overlying clay layer.

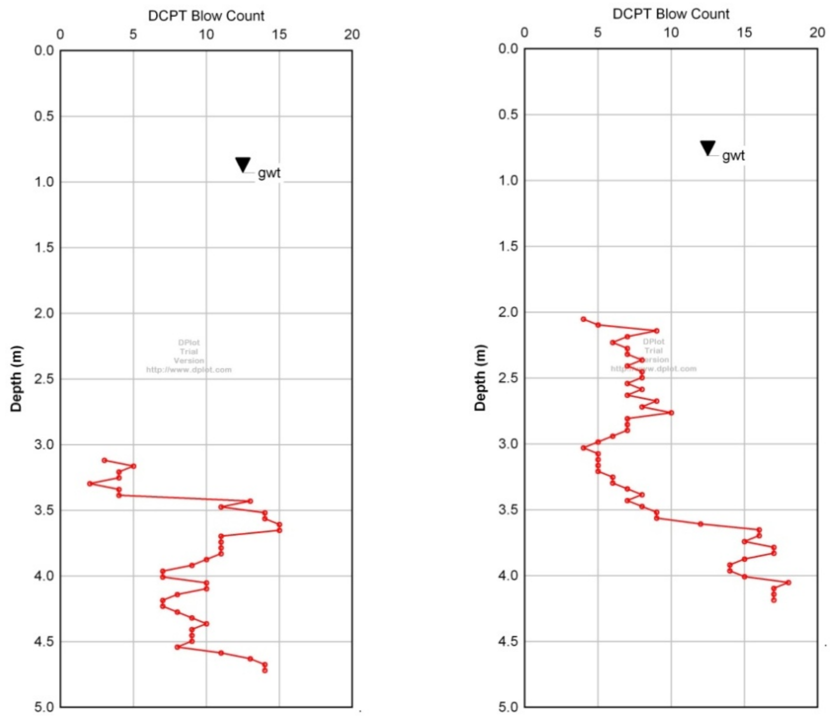


Figure 4.7. Results of DCPT performed at a residence on Bracken St, Avonside.

A DCPT and SASW test were also performed at St Paul's Church. The results of these tests are shown in Figure 4.8. Based on the bore hole augered for the DCPT test, the water table was at a depth of about 2.3 m and the top of the liquefied layer was at a depth of about 2.8 m. The SASW test was performed approximately 20 m away from the DCPT location.

The nonintrusive SASW (Spectral Analysis of Surface Waves) method is a common procedure used for obtaining shear wave velocity (Vs) profiles for liquefaction analyses (Stokoe et al. 1994, Andrus and Stokoe 2000, Youd et al. 2001). The SASW method is particularly well-suited for relatively shallow surveys conducted in areas with limited space where conventional multi-channel (MASW) arrays may not fit. Furthermore, the equipment used for the tests discussed herein is extremely light-weight and portable, and can be transported in a small backpack, which makes it ideal for earthquake reconnaissance work. Specifically, these SASW tests were conducted using three 4.5-Hz geophones and a ‘pocket portable’ dynamic signal analyzer (Quattro system) manufactured by Data Physics Corporation. The Quattro is USB-powered off a laptop and, despite its small size, has four input channels, two output channels, 205 kHz simultaneous sampling rate, 24 bit ADC’s, 110 dB dynamic range, and 100 dB anti-alias filters. A common 4- to 6-kg sledge hammer can typically be used as a dynamic source to profile approximately 6- to 10-m deep with this equipment in less than 15 minutes.

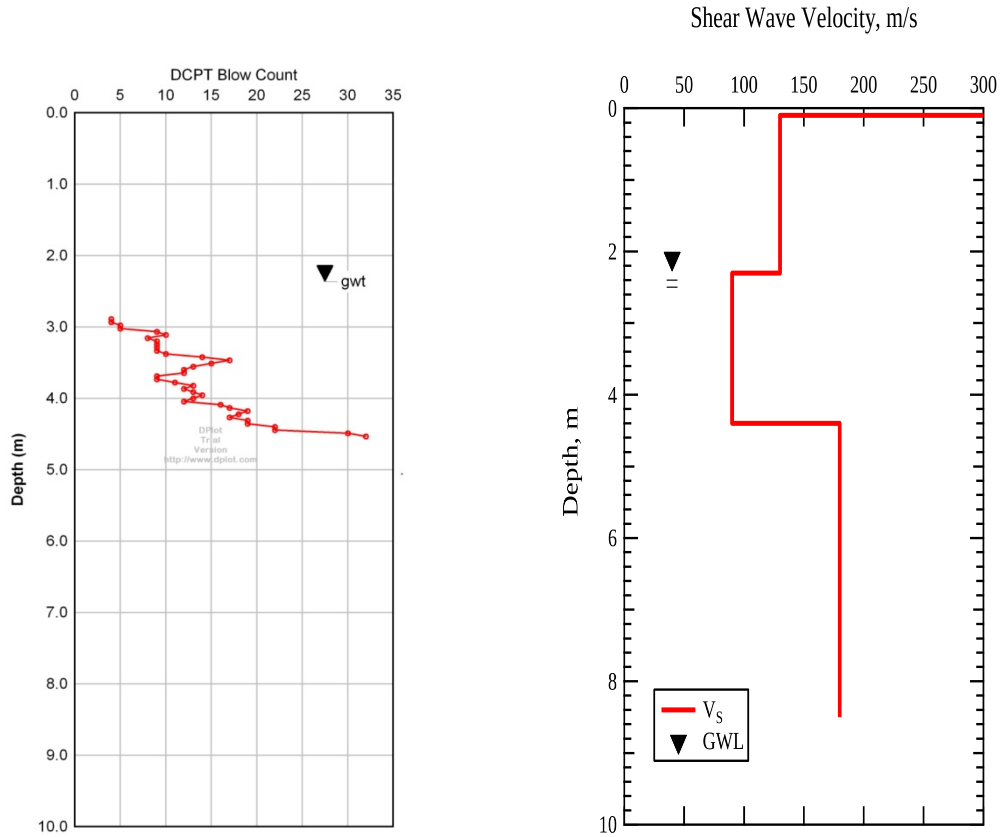


Figure 4.8. Results of DCPT and SASW tests performed at St Paul's Church in Dallington.

The Vs profiles must be corrected for overburden pressure (Vs1) prior to evaluating soil liquefaction triggering. Generally speaking, even without this correction any soil layers with Vs less than 150 m/s are quite soft and may be potentially liquefiable. However, it will be noted that Vs measurements alone cannot definitively determine liquefaction susceptibility, as the type of soil (i.e. clay or sand), not just its stiffness/velocity, is a key factor. The Vs profile shown in Figure 4.8 indicates soft soils down to 8 m depth, with the softest soils between approximately 2-4 m.

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 4.9). Parallel cracks spaced regularly along drainage lines were indicative of slumping and spreading towards the north and south branches of the stream. Two hockey fields located in the park were severely damaged by the liquefaction, resulting in a very uneven, bumpy surface of the fields.

(a)

(b)

Figure 4.9 Massive sand boils and lateral spreading cracks at Porritt Park: (a) Aerial view showing massive sand boils with large number of parallel cracks along drainage lines (from a helicopter flyover on the afternoon of Friday, 10 September 2010); and (b) ~ 10 cm wide lateral spread crack. (-43.516278°, 172.689917°).

Bexley

Bexley is located further to the east along the Avon River, approximately one kilometer from the Avon-Heathcote Estuary. It is bounded by the Avon River on the east-side and by the Bexley Wetland on the south (Figure 4.10a). 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 4.10). Ground distortion (i.e., differential settlement, large ground cracks, deformation of paved surfaces and substantial sand boils) was observed at Seabreeze St and Kokopu Ln. Residential properties along the southern edge of Bexley (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. Similarly, severe manifestation of lateral spreading was observed at the east end of Bexley (Parenga Pl).

An SWS test, DCPT, and SASW test were performed in the backyard of a house in Bexley; the results are shown in Figure 4.11. Based on the bore hole augered for the DCPT test, the ground water table was at a depth of ~1.5 m and the top of the liquefied layer was at a depth of ~1.6 m. The SASW test was performed ~10 m away from the DCPT sounding.

(a)

(b)

(c) (d)

Figure 4.10 Evidence of extensive liquefaction severely affecting residential houses in Bexley: (a) Aerial view of the southern edge of Bexley which was severely affected by liquefaction and lateral spreading; (b) Evidence of liquefaction in residential area (Seabreeze St); (c) Large ground cracks due to lateral spreading at Kokopu Pl (-43.5184167°, 172.7221667°); (d) Cracks in unreinforced slab induced by lateral spreading (-43.5193889°, 172.6705555°).

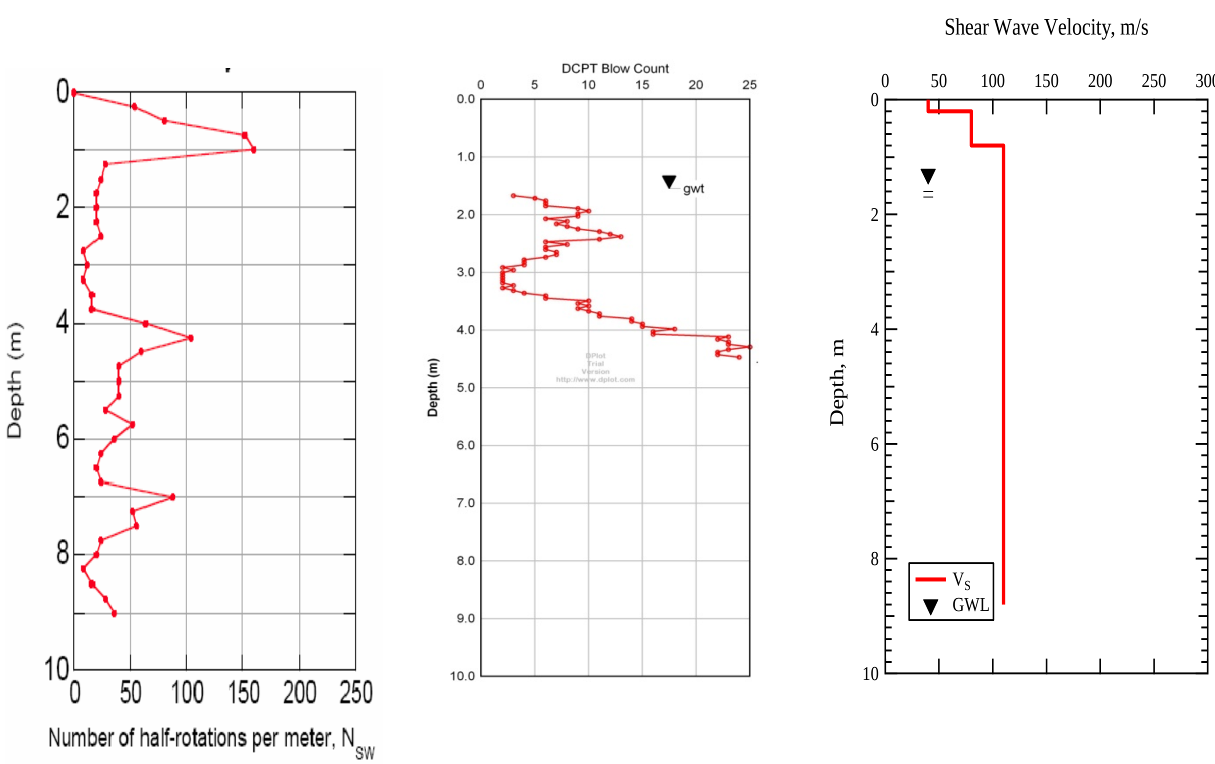


Figure 4.11 Results of SWS test, DCPT, and SASW test performed in the backyard of a house in Bexley.

Liquefaction manifestation in other areas of Christchurch

Widespread liquefaction also occurred in the suburbs of Halswell (southwest of Christchurch) and Brooklands (northeast of Christchurch). In Spencerville (also north-east of Christchurch), liquefaction occurred and lateral spreading affected a limited area. In these suburbs, the manifestation of liquefaction and its effects on residential houses and lifeline systems were similar to those previously described. Again, the severity of liquefaction and associated building damage varied even within a given neighbourhood, depending on the soil profile, distance from the free face, slope grade, and/or structural and foundation details.

Limited or partial liquefaction was observed at numerous locations across the city, which manifested as scattered and relatively small (or within limited area) sand boils. In these places there was damage to roads, footpaths, and driveways as well as some house damage, but the liquefaction effects were moderate or mild. Figure 4.12 shows typical manifestation of limited liquefaction in CBD (Peterborough St) and in the backyard of a power sub-station on the Greers Rd in Bishopdale. Other areas where liquefaction of limited extent was observed include Belfast (Engelfield Rd, near Main North Rd), Redwood (Barnes Rd, near Main North Rd), Fendalton (Queens Av), vicinity of English Park in St Alban's (Cranford St, Westminster St, Courtenay St, Trafalgar St, Sheppard St) and Burwood (DeVille Pl and DeBlog Pl). These areas of partial/limited liquefaction are shown in the liquefaction map in Figure 4.3.

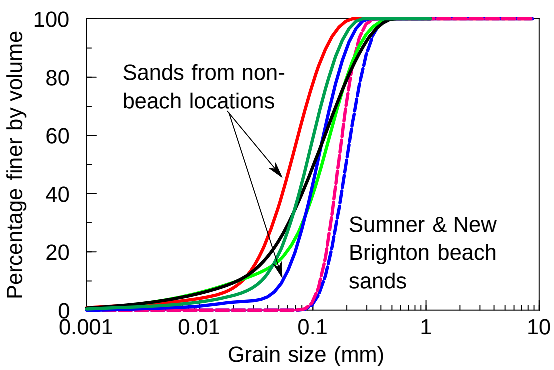
The geotechnical reconnaissance team also conducted a quick drive-through reconnaissance along the Heathcote River, specifically targeting areas that were denoted as having high-potential for liquefaction-induced damage on the ECan liquefaction hazard maps (ECan, 2004). However, there was very little evidence of ground distortion and liquefaction in this area, with only a few sand boils found in a period of about two hours of drive-through and on foot surveys.

Figure 4.12 Evidence of limited/partial liquefaction in areas of Christchurch: (a) Evidence of liquefaction at Peterborough St - Madras St (CBD) ; (b) Sand boil in the foundation soils of a transmission tower (sub-station northeast of Greers Rd – Ruddenklau Ln, Bishopdale) (-43.4928055°, 172.5918055°).

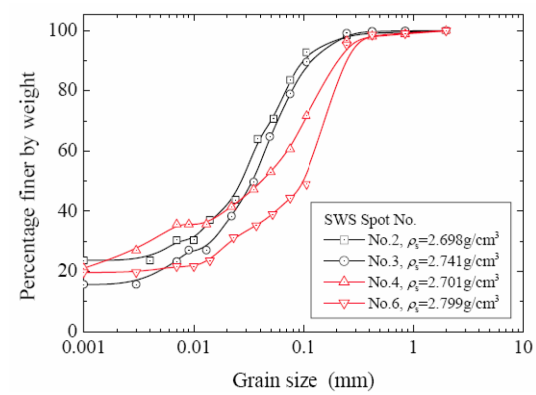
Characteristics of liquefied soils

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 color.

Grain-size distribution curves of ejecta samples taken from Dallington (Gayhurst Rd), Porritt Park and South Kaiapoi (Courtenay Dr) are shown in Figure 4.13a. Figure 4.13b shows grain size distribution of soil samples taken from the SWS screw point (representative of the deepest layer penetrated in a SWS test), which shows significantly higher fines content.



(a)



(b)

Figure 4.13 Grain-size distribution curves of Christchurch and Kaiapoi soils: (a) Grain size distribution curves of sand boil samples obtained by laser diffraction analysis; and (b) Grain size distribution curves of soil samples taken from the SWS screw point (deepest tested layer) obtained by sieve and hydrometer analyses: Dallington (No. 2 and 3) and Bexley (No. 4 and 6).

Figure 4.14 shows the large sandboil at Featherstone Reserve at Pines Beach, from which a bulk sample of the sand was recovered. Figures 4.15-4.18 give electron micrographs of various fractions of the sand in relation to sieve size. The micrographs are all at the same magnification, 100 times, and show that the particles tend to be angular to subrounded in shape. As the particle size decreases the angularity of the particles increases.

Figure 4.14 Sandboil in the Featherstone Reserve Pines Beach from which sand was taken for electron microscope pictures. (Approximate position: -43.381111°, 172.703611°)

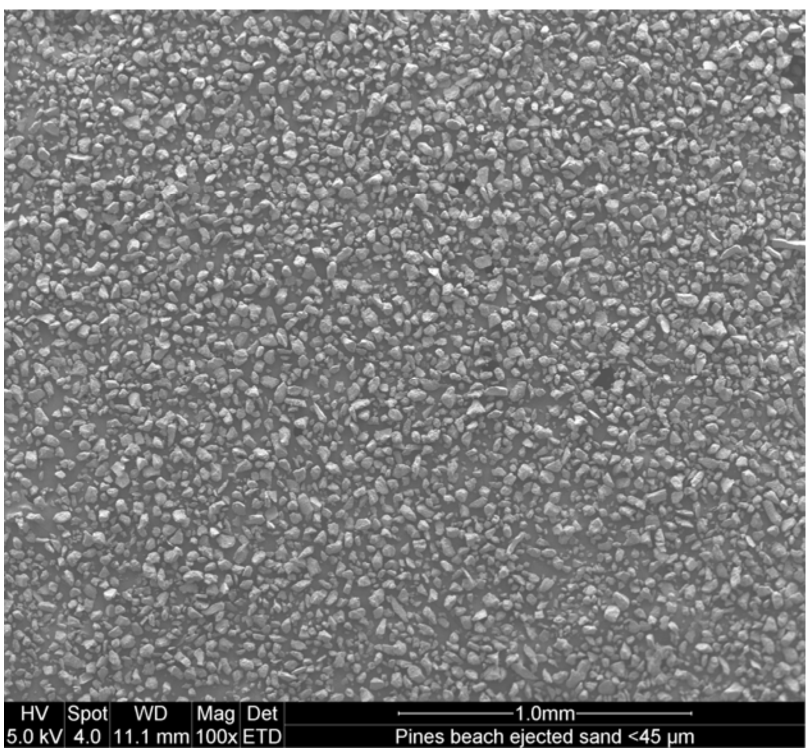


Figure 4.15 Sand particles passing the 0.045 mm sieve (No. 325).

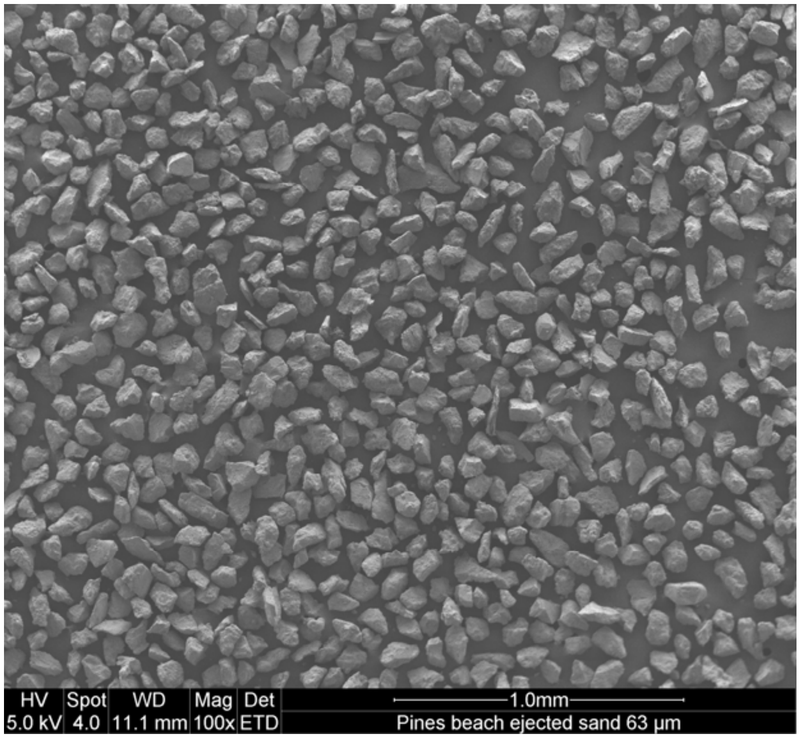


Figure 4.16 Sand particles retained on the 0.063 mm sieve (No. 230).

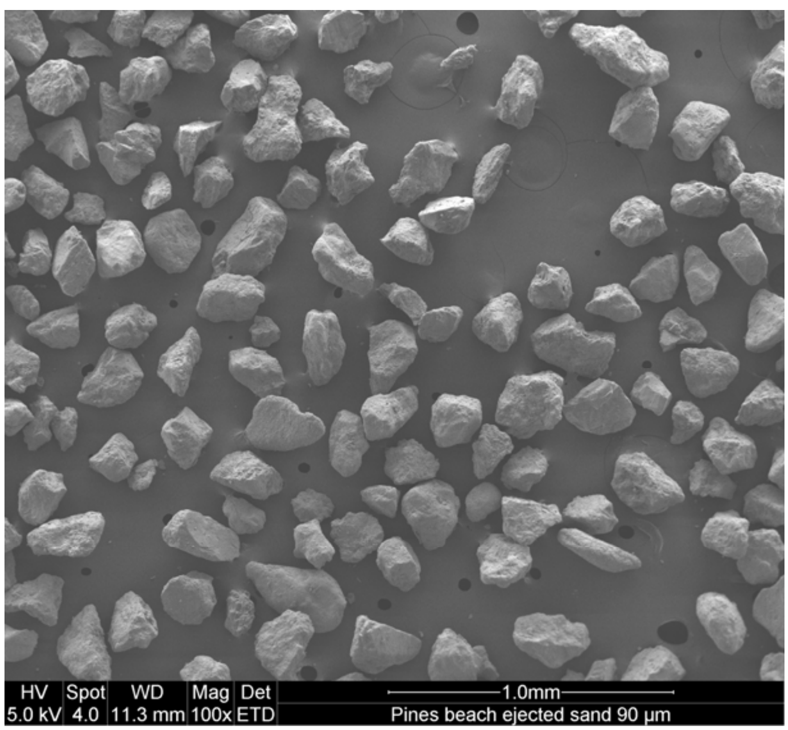


Figure 4.17 Sand particles retained on the 0.090 mm sieve (No. 170).

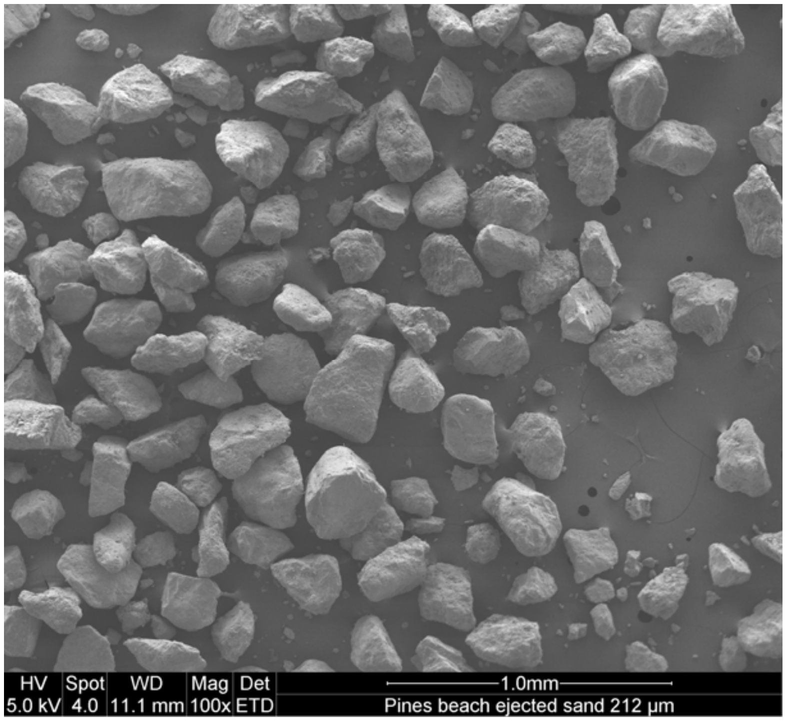


Figure 4.18 Sand particles retained on the 0.212 mm sieve (No. 70).

Effects of liquefaction and lateral spreading on streambeds and wetlands

Residents of the Bexley area commented on the effect of the earthquake on the Bexley Wetlands. Figure 4.19 shows a view from walking path around the south of the subdivision. Many sand boils are seen in the bed of the wetland area (at high tide on 29 September) which was inundated at high tide prior to the earthquake.

Stream beds were also noticed to be heaved (Figure 4.20). A local resident confirmed that this was not how the stream bed appeared prior to the earthquake. In some places it was necessary to clear the stream bed soon after the earthquake.

Figure 4.19 View of the Bexley Wetland at near high tide on Wednesday 29 September 2010. Prior to the earthquake this area was inundated at high tide.

Figure 4.20 Photograph of the stream near Porritt Park on Wednesday, 15 September 2010. There is lateral spreading towards this stream from both sides. It is just possible to make out a sand boil in the midst of the stream bed debris to the right of the duck. Several other sand boils were visible along the stretch of heaved stream bed.

Google imaging as evidence of liquefaction

A few hours after the earthquake, a GeoEye image of part of the area affected by the earthquake was captured. Since Saturday 4 September 2010 was a clear day, this image provided good evidence of liquefaction in some parts of the city. Figure 4.21 shows part of the GeoEye image covering Porritt Park. Figure 4.9a shows a picture of Porritt Park taken from a helicopter on the afternoon of Friday, 10 September 2010.

Comparison of these two images (Figs. 4.9a and 4.21), and also observations from on-ground reconnaissance, demonstrates that GeoEye aerial images are able to be used to identify liquefaction. Not surprisingly, it turns out that the key to this identification is contrast. The light color of the ejected sand contrasts very well with the underlying green turf. In areas where the ejected sand covered the pavement, such as Bexley, the GeoEye image was not as useful for identifying liquefaction.

Local residents commented that on the morning after the earthquake the Avon and Heathcote rivers had a milky appearance. This is because the ejected sand contained enough fine material (typically 10 % finer than about 0.050 mm (No. 270 sieve)) to stay in suspension for some time when mixed with water. A GeoEye image of part of the Halswell area is shown in Figure 4.22. This figure suggests that there are some areas of Halswell where extensive liquefaction occurred. However, discussions with local residents revealed that a considerable volume of water came to the ground surface along with ejected sand, and this water had a milky color. So, the ejected sand could not be distinguished from the water in the satellite image. Some days after the earthquake this water had subsided.

In conclusion, comparison of the GeoEye image with on-ground reconnaissance confirms that, provided there is enough color contrast between the ejecta and the surrounding ground, the satellite image can be used to identiry liquefaction. However, when large volumes of water are ejected with the sand there may be a false indication of the amount of ejecta present.

Figure 4.21 Image of Porritt Park extracted from the GeoEye image taken a few hours after the earthquake. From the left to the right edge of the image is ~0.62 km (Google Inc., 2010). (-43.516154°, 172.684855°)

Figure 4.22 Part of Halswell as imaged by GeoEye after the earthquake. The ejected sand is accompanied by considerable volumes of water forming mini-lakes having a similar color to the ejected sand. From the left to the right edge of the image is ~2.74 km (Google Inc., 2010). (-43.598349˚, 172.566383˚)

Town of Kaiapoi

The town of Kaiapoi (population ~10,000; area ~5 km^2) is situated about 17 km north of Christchurch's Central Business District, near the north-eastern end of the Canterbury Plains. At Kaiapoi, recent Holocene sediments, approximately 100-m thick, overlie 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 4.23). 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 Geology chapter of this report 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 (Figure 2.9). Several old meander loops of pre-1868 Waimakariri River have deposited loose silty sands both north and south of the present Kaiapoi River. Also, the ground water table is generally shallow within 1-2 m of the ground surface.

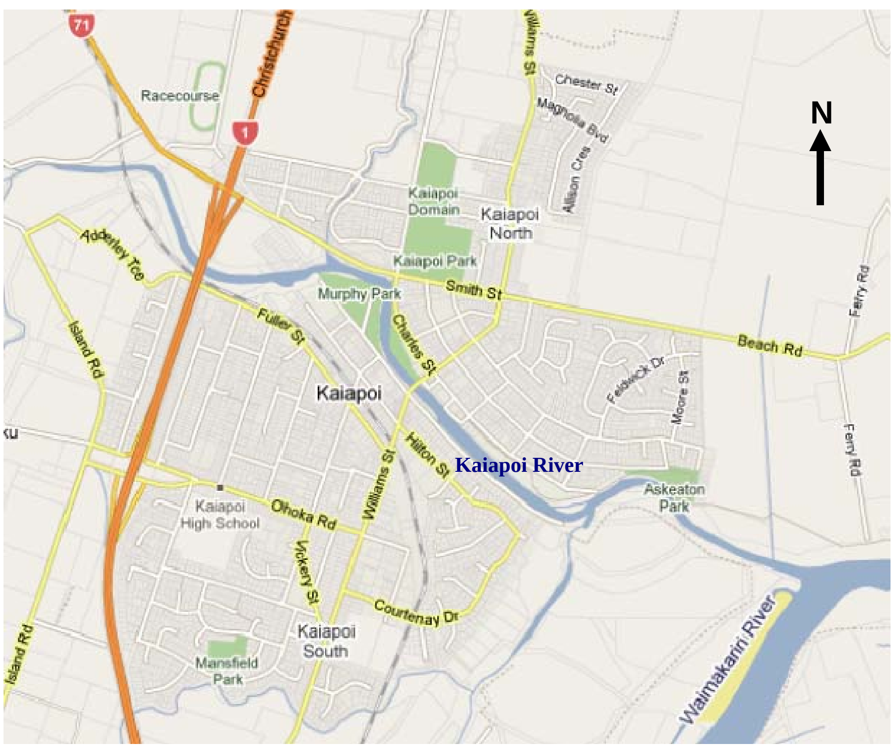


Figure 4.23 Map of present day Kaiapoi (Google Inc., 2010). From the left to the right edges of the map is ~4.1 km.

Parts of North Kaiapoi liquefied during the 1901 Cheviot Earthquake. Berrill et al. (1994) provide an excellent summary of the liquefaction that occurred in Kaiapoi during the 1901 event. Particularly, they presented historical evidence of the occurrence of liquefaction in the northeast section of Kaiapoi, at the east end of Charles and Sewell streets.

North Kaiapoi

In the 2010 Darfield Earthquake, widespread liquefaction occurred north of the Kaiapoi River (Charles St, Sewell St, Cassia St) affecting a large number of residential houses. The houses in this area are typically single- or two-story brick/stone block masonry or timber structures on spread footings. Figure 4.24 shows areas of severe and moderate-to-low liquefaction in the town of Kaiapoi. A strong motion station located in north Kaiapoi recorded a PGA of approximately 0.32g (geometric mean of the horizontal components) during the earthquake.

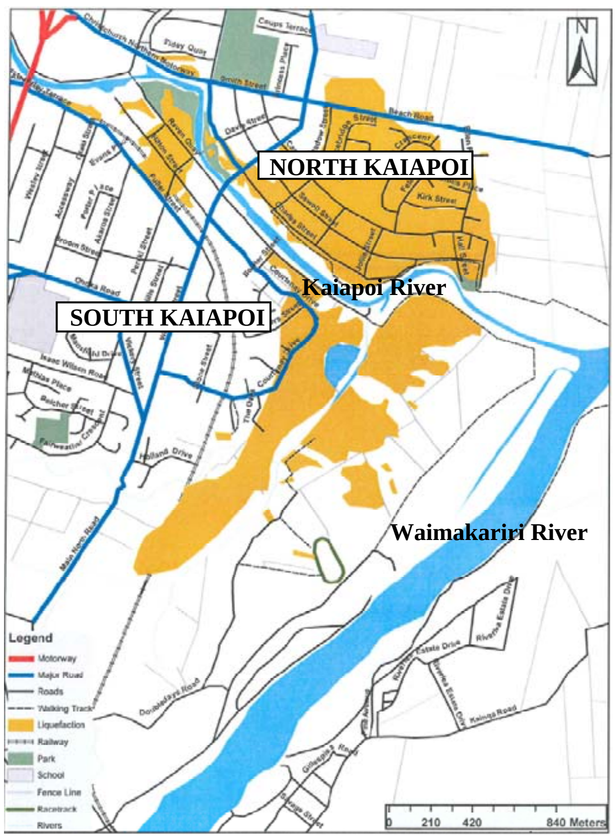


Figure 4.24 Areas of observed liquefaction in the town of Kaiapoi due to the 2010 Darfield earthquake (the liquefaction map is based on surface manifestation of liquefaction visible on aerial photographs and compiled evidence from ground surveys).

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, as shown in Figure 4.25. 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. An SWS test and DPTs were performed by the GEER-NZ Team in this area, with the SWS test indicating loose/soft soils up to depths of 8-9 m (Figure 4.26).

(a)

(b)

(c)

(d)

Figure 4.25 Manifestation of very severe liquefaction in residential area at Cass Pl, North Kaiapoi (-43.387944°, 172.670111°): (a) ~40 cm thick layer of silt-sand-water mixture covering a residential property affected by very severe liquefaction; (b) same-angle view, but after the clean up of sand boils; (c) View from the street (before clean up); and (d) liquefied silt-sand-water mixture covering the ground outside the house and a rug inside the house (seen through a window from inside the house).

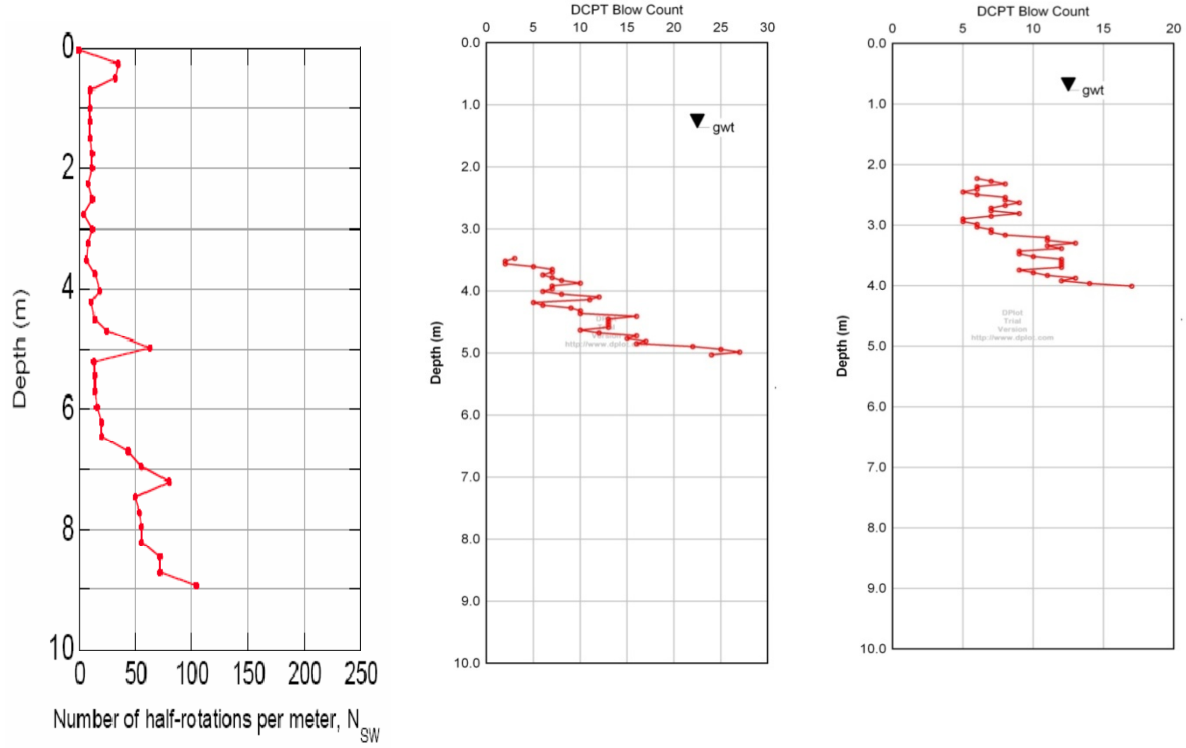


Figure 4.26 Results of SWS test and DCPTs performed in the backyard of a house at Cassia Pl.

As determined from the bore holes augered for the DCPTs, the depth to the ground water table and to the top of the liquefied layer differed between the two test locations at Cassia Pl although the test locations were only ~25 m apart. However, the surface elevation of the two test locations differed by about 0.5 m. As a result, the elevations of the ground water table are similar for the two test locations, with the depth to the top of the liquefied layer differing slightly. As with the site on Bracken St (Figure 4.4), a 10- to 15-cm thick, very wet, very soft clay/plastic silt layer overlies the liquefied layer.

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

The area along the Pegasus Bay Walkway (from the Kaiapoi Visitor Information Center 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 (Figure 4.27). Residential houses in this area were affected both by liquefaction and lateral spreading (Figure 4.28). The reconnaissance team carried out detailed ground surveys of lateral spreading along several profiles at this location, which will be presented in detail in subsequent publications. Additionally, two bore holes were made using a hand auger. However, the profile largely consisted of random fill (gravels/cobbles and wood), making it difficult to advance the auger. One of the bore holes went down to a depth of ~5.5 m, yet a thick liquefied layer could not be found. However, thin (< 10 cm) alternating layers of loose saturated sand and very wet, very soft clay/plastic silt were encountered, particularly near a large lateral spread crack (Figure 4.27b). This lateral spread crack had no traces of ejecta in and/or immediately near it. This crack was closer to the river than ones that were filled with ejecta, which were an additional 30 m further from the river. It is possible, that the overlying soil layers slid on these alternating layers of loose sand and clay/plastic silt that likely liquefied/softened during the earthquake shaking.

(a) (b)

Figure 4.27 Evidence of liquefaction and lateral spreading along Charles St and the north levee of the Kaiapoi River (-43.384694°, 172.660944°). Note the huge piles of cleaned up sand obstructing the view of the houses in (a).

(a)

(b) (c)

Figure 4.28 Liquefaction and lateral spreading in North Kaiapoi: (a) Evidence of extensive liquefaction at the east end of Charles St (-43.386805°, 172.667166°); and (b) lateral spreading resulting in a large ground distortion in foundation soils (Charles St) (-43.386666°, 172.666111°)

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 4.29, 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 (~1-m thick) for the northern branch of Courtenay Dr (WDC, 2010).

(a)

(b)

Figure 4.29 Massive lateral spreading at South Kaiapoi: (a) Sand boils and area affected by lateral spreading around Courtenay Lake (from a helicopter flyover on Friday, 10 September 2010); and (b) Large lateral spread cracks in farm land (at B: -43.3941389°, 172.659750°).

The eastern edge of Kaiapoi is shown in aerial photographs taken after the Darfield earthquake (Figure 4.30). The outline of the 1865 Waimakariri river channel (Figure 2.9) is shown by the dashed red line. On the eastern side of Kaiapoi, the old channel passes underneath the present day Courtenay Dr area shown as position 1, where severe damage to residential properties occurred due to lateral spreading (Figure 4.34). Further south at positions A and B (Figure 4.29), 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 4.31 indicates geo-tagged major cracks and four transects of detailed measurements at position A.

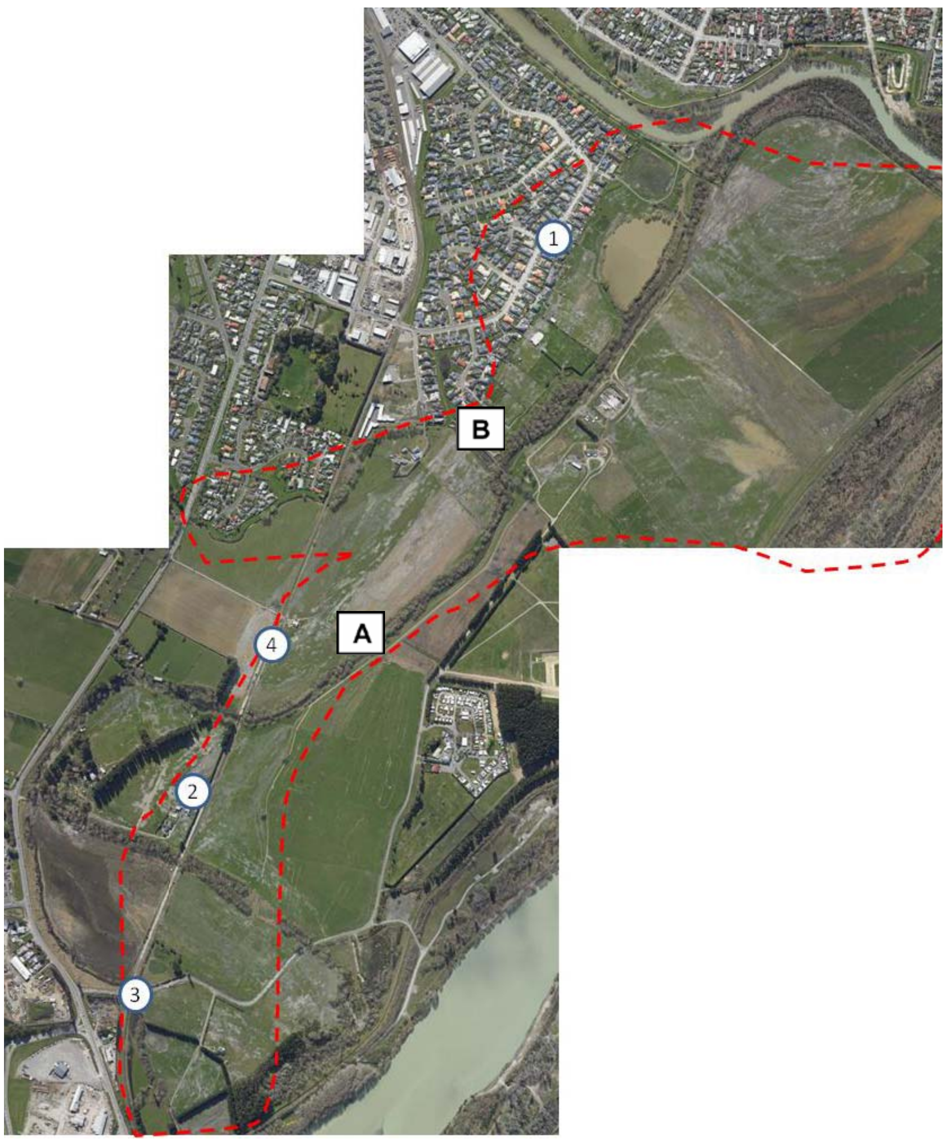


Figure 4.30 Aerial view of the lateral spreading area at South Kaiapoi.

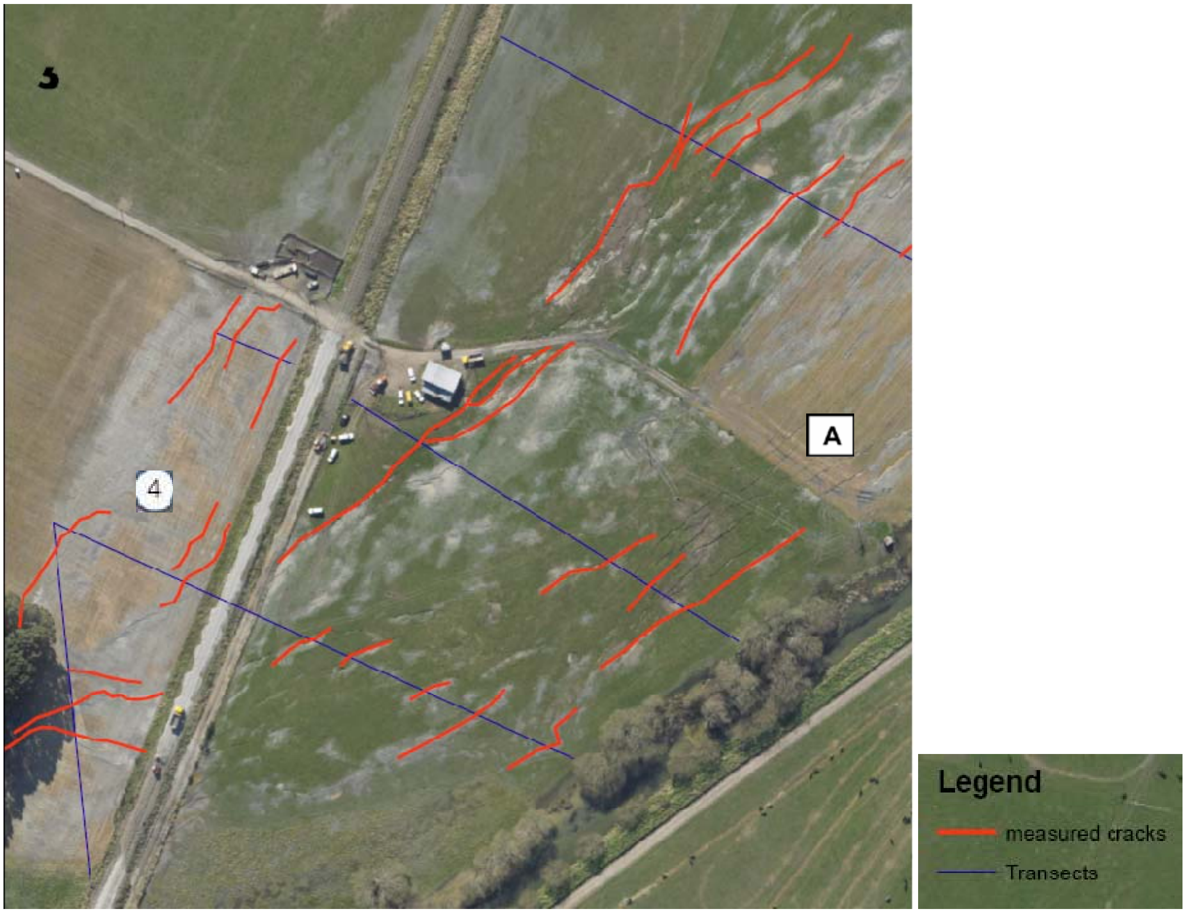


Figure 4.31 Aerial view of the lateral spreading area at position A at South Kaiapoi showing four transects of detailed ground surveys.

Further south near the train tracks at position 2 (Figure 4.30), large sand boils formed (Figure 4.32). At position 3 (Figure 4.33), liquefaction resulted in damage to the train tracks. The photo in Figure 4.33 was taken from a position on Doubleday's Rd in a NNE direction along the tracks, indicating ground deformation and track movement. Moving north along the train tracks to positions 4 and A (Figure 4.30), Figure 4.31 provides a more detailed aerial view of liquefaction and lateral spreading crossing the tracks just south of Kaiapoi. Using the vehicles in the photo for scale gives a good indication of the significant size of these cracks and the volume of ejecta.

Figure 4.32 Sand boils in fields. (Position 2; -43.4026º, 172.6503º)

Figure 4.33 Damage to train tracks due to ground movement. (Position 3; -43.4068º, 172.6489º)

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, single story and two story houses suffered very severe damage due to large lateral ground movements including large tilt, loss of foundation support, tension cracks in foundations and slabs (Figure 4.34). 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. The reconnaissance team visited the area and conducted detailed inspections and measurements of the distorted houses on several occasions. 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 neighboring 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.

An SASW test, DCPT and SWS test were performed at a home along Courtenay Dr. The results are presented in Figure 4.35.

(a)

(b)

Figure 4.34 Lateral spreading at Courtenay Dr, South Kaiapoi: (a) Sand boils and lateral spread cracks; and (b) effects of lateral spreading in residential area.

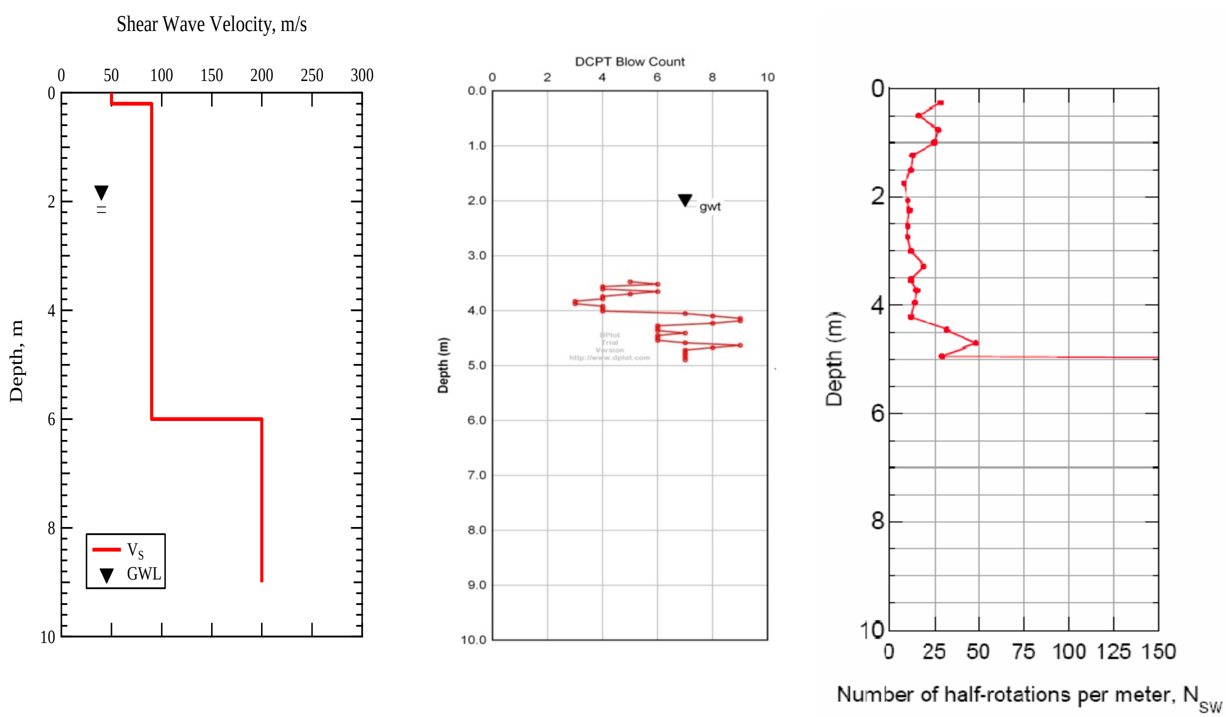


Figure 4.35 Results of SAWS test, DCPT and SWS test performed at a residential property along Courtenay Dr.

Liquefaction associated with ejected gravel

Selwyn River near Greendale

The Selwyn River traverses the Canterbury Plains flowing in a roughly south-easterly direction to the south of Christchurch and discharging into Lake Ellesmere.

At the evening meeting of Sunday, 12 September 2010, Pilar Villamor of GNS reported to the Team that she had seen liquefaction in a farm paddock at the Greendale end of the fault trace. The paddock was on the Selwyn Forks property which is accessed from the Hororata - Dunsandel Rd on the southern side of the Hororata and Selwyn rivers. The locations of the liquefaction are shown in Figure 4.36.

The GEER-NZ Team visited the area on Monday, 13 September 2010. On the evening of Sunday, 12 September 2010, there had been heavy rain in the area, so on Monday the river channels were running high and the Hororata River was flowing in new areas because of the levee damage during the earthquake. The Team first looked at end of Gillanders Rd, on the Darfield side, and found an area with ground damage off the end of the track, close to one of the river channels (Figure 4.37).

A short distance from here at the end of Gillanders Rd, the team found damage to the unsealed pavement and in the grass verge nearby. Evidence of liquefaction was seen (Figure 4.38). Notable here was the fine gravel on the surface of the sand. Also note that rain had fallen the previous evening so the surface of the ejected material would have been altered somewhat.

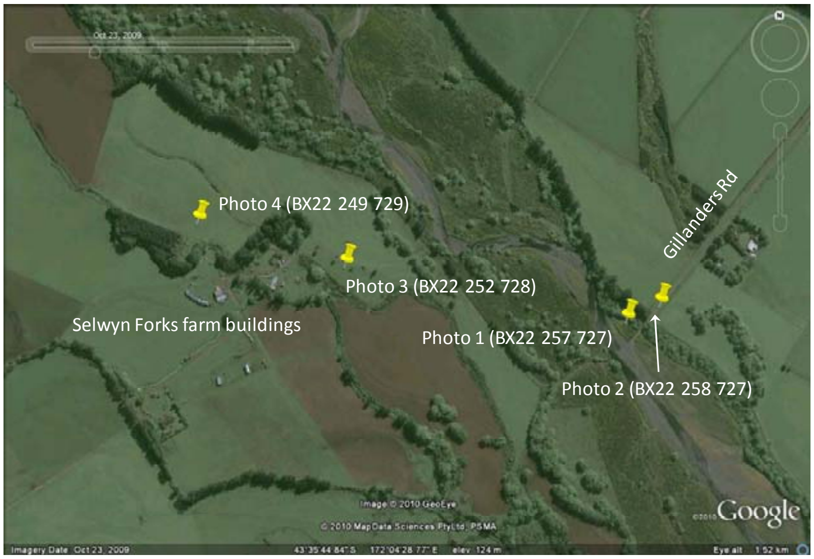


Figure 4.36 Location of the liquefaction along the Selwyn River in the Greendale region. (Date of Google image 23 October 2009)

Figure 4.37 Ground damage adjacent to the bank of the Selwyn tributary near the end of Gillanders Rd (Darfield side). (Position marked as Photo 1 in Fig. 4.36; -43.596667°, 172.080000°)

Figure 4.38 Liquefaction on the grass verge adjacent to the end of Gillanders Rd (Darfield side). Note the fine gravel particles on the surface and the fissure towards the top right hand side - it was possible to push the sampling spoon to a depth of about 300 mm into the fissure. (Position marked as Photo 2 in Fig. 4.36)

The liquefaction was located on the Selwyn Forks property (map reference BX22 250727). Access was a little difficult because a farm creek was being fed from an errant tributary of the Hororata River. The liquefaction was distributed across several fields. Material was ejected from fissures in the ground, which are likely to be lateral spreads given the stream channels nearby. The ejected material was topped off with a layer of coarse gravel (Figure 4.39). Figure 4.40 shows not only sand and gravel but also clods of topsoil. It is not clear if the gravel was part of the liquefied layer or was carried to the surface with the ejected sand. When questioned, Mr Ridgen suggested that the ground profile consisted of topsoil, gravel and then sand. If this profile is confirmed then the gravel was probably carried to the surface by the liquefied sand coming from below.

Further liquefaction has been reported up the Selwyn beyond the Selwyn Forks property. The Team has not been able to confirm this by their own inspection.

Figure 4.39 Material ejected from a fissure on the Selwyn Forks farm (front paddock). Note the gravel overlying the brown colored sand. This is what was visible after a night of rain. (Position marked as Photo 3 in Fig. 4.36.)

Figure 4.40 Ejected material on another paddock of the Selwyn Forks farm (Sheepyard paddock). As well as sand and gravel the ejecta contain clods of topsoil. (Position marked as Photo 4 in Fig. 4.36.)

Selwyn River near Irwell

Further liquefaction adjacent to the Selwyn River, not far from the town of Leeston, was evident of the Willow Lea property near Irwell (Figure 4.41).

Figure 4.42 shows the material ejected at the position labeled Photo 5 in Figure 4.41 illustrating that the material ejected consisted of sand with some gravel. Comparison of photos in Figures 4.39, 4.40 ,and 4.42, shows that the materials ejected at Selwyn Forks and at Willow Lea were similar.

The farmer at Willow Lea, Mr Mark Fleming, reported that the fissures he observed were at least 2-m deep based on probing with a length of number 8 fencing wire. He also explained that the width of the fissures had increased gradually since the earthquake and that the prominence of the ejected sand had decreased with time (the photograph in Figure 4.42 was taken on 29 September 2010). More instances of liquefaction have been reported on other properties further down the Selwyn River, but the team has not confirmed this by site visits.

Near Clearwater

Liquefaction also occurred near the Clearwater development along Johns Road (-43.454433°, 172.595247°). Figure 4.43 shows that gravel was ejected in addition to sand. There were a number of other instances of liquefaction in the open ground adjacent to the location shown in Figure 4.43.

Figure 4.41 Location of the liquefaction along the Selwyn River in the Irwell region. (Date of Google image 13 July 2009)

Figure 4.42 Ejected sand and gravel at the Willow Lea property. (Position marked as Photo 5 in Fig. 4.41; -43.688056°, 172.353333°)

Figure 4.43 Ejected sand and gravel in the Clearwater area. (photo by Ian McCahon)

Most Distal liquefaction feature

The most distal sites from the epicenter and fault rupture where liquefaction was induced during the main shock are in Waikuku Beach, north of Kaiapoi along the coast, and in Akaroa, southeast of Christchurch on Banks Peninsula. The site-to-source distance to Akaroa is slightly more than to Waikuku Beach. The epicentral distance and closest distance to the fault rupture for the Akaroa site are ~54 and 44 km, respectively. These distances are plotted in Figure 4.44, along with data compiled by Ambraseys (1988) from global earthquakes. As may be observed from this figure, the epicentral distance falls well within the boundary for maximum distance of observed liquefaction formed by data from global earthquakes, but the closest distance to the fault rupture is close to the global earthquake data boundary.

In addition to the liquefaction induced by the main shock of the Darfield earthquake, the M5.0 aftershock that occurred on 19 October 2010 re-liquefied soils at a few locations. The epicenter for this aftershock was south of Christchurch (-43.63˚, 172.56˚) and the known most distal location where liquefaction was re-induced was in Hoon Hay, ~8 km north of the epicenter. This point plots ~5.5 km to the right of the boundary formed by data from global shallow to intermediate depth earthquakes (i.e., focal depths < 50 km) and is the only point that plots this far to the right of the boundary.

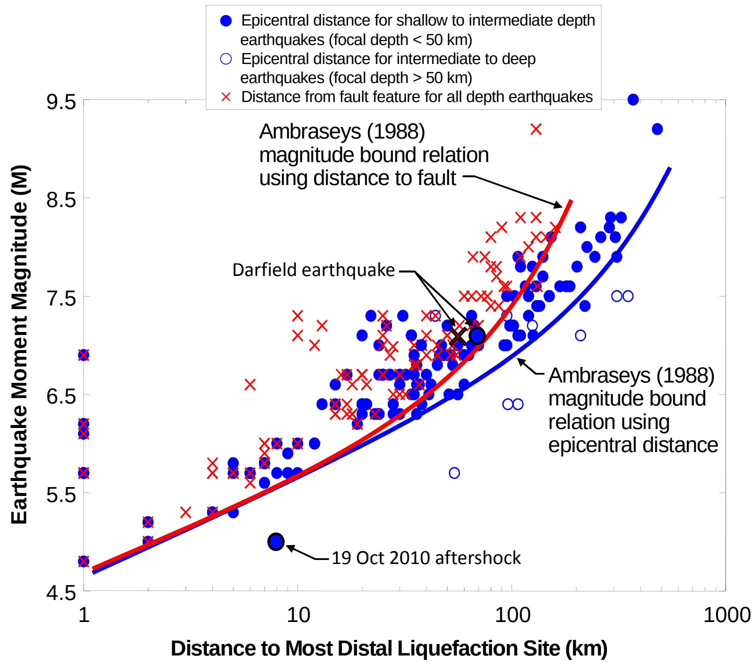


Figure 4.44. Comparison of the most distal liquefaction feature from the Darfield Earthquake with worldwide earthquake data collected by Ambraseys (1988) (Adapted from Rathje et al., 2010).

References

Andrus, R.D., and Stokoe, II, K.H. (2000). Liquefaction resistance of soils from shear wave velocity, Journal of Geotechnical and Geoenvironmental Engineering, 126(11): 1015-1025.

Ambraseys, N.N. (1988). Engineering Seismology, Earthquake Engineering and Structural Dynamics, 17: 1-105.

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, 27(3): 178-189.

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

ECan (2004). Environment Canterbury, http://ecan.govt.nz/publications/General/solid-facts-christchurch-liquefaction.pdf

Google Inc. Google Earth, [map]. Generated by Liam Wotherspoon: using Google Earth. http://www.google.com/earth/index.html (generated October 5, 2010), 2010.

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

NZ Aerial Mapping (2010). Kaiapoi, [air photo]. Wellington, NZ: NZ Aerial Mapping, 2010.

Ward and Reeves (1865). Plan of portion of the plains of Canterbury, [map]. 1:126,720. Christchurch, NZ.

Rathje, E., Bachhuber, J., Cox, B., French, J., Green, R., Olson, S., Rix, G., Wells, D., Suncar, O. (2010). "Geotechnical Engineering Reconnaissance of the 2010 Haiti Earthquake", GEER Association http://www.geerassociation.org/GEER_Post%20EQ%20Reports/Haiti_2010/Cover_Haiti10.html , Report No. GEER-021.

Shell New Zealand (1935). Christchurch and area, [map]. 1:63,360. Wellington, NZ: Shell Company of New Zealand.

Stokoe, II, K.H., Wright, S.G., Bay, J.A., and Roesset, J.M. (1994). Characterization of geotechnical sites by SASW method, Geophysical characterization of sites (R.D. Woods, ed.), IBH Oxford Press, New Delhi, 1-24.

Waimakariri District Council (2010). Personal Communication, 29 September 2010.

Youd, T. L., I. M. Idriss, R. D. Andrus, I. Arango, G. Castro, J. T. Christian, R. Dobry, W. D. L. Finn, L. F. Harder, Jr., M. E. Hynes, K. Ishihara, J. P. Koester, S. S. C. Liao, W. F. Marcuson, III, G. R. Martin, J. K. Mitchell, Y. Moriwaki, M. S. Power, P. K. Robertson, R. B. Seed and K. H. Stokoe, II (2001). Liquefaction resistance of soils; summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils, Journal of Geotechnical and Geoenvironmental Engineering**,** 127(10): 817-833.