Earthquake News

Geotechnical Damage due to the 2011 Christchurch, New Zealand

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INTRODUCTION

On 22 February 2011, a magnitude Mw 6.3 earthquake occurred with an epicenter located near Lyttelton at about 10km from Christchurch in Canterbury region on the South Island of New Zealand (Figure 1). Since this earthquake occurred in the midst of the aftershock activity which had continued since the 4 September 2010 Darfield Earthquake occurrence, it was considered to be an aftershock of the initial earthquake. Because of the short distance to the city and the shallower depth of the epicenter, this earthquake caused more significant damage to pipelines, traffic facilities, residential houses/properties and multi-story buildings in the central business district than the September 2010 Darfield Earthquake in spite of its smaller earthquake magnitude. Unfortunately, this earthquake resulted in significant number of casualties due to the collapse of multi-story buildings and unreinforced masonry structures in the city center of Christchurch. As of 4 April, 172 casualties were reported and the final death toll is expected to be 181. While it is extremely regrettable that Christchurch suffered a terrible number of victims, civil and geotechnical engineers have this hard-to-find opportunity to learn the response of real ground from two gigantic earthquakes which occurred in less than six months from each other. From geotechnical engineering point of view, it is interesting to discuss the widespread liquefaction in natural sediments, repeated liquefaction within short period and further damage to earth structures which have been damaged in the previous earthquake. Following the earthquake, an intensive geotechnical reconnaissance was conducted to capture evidence and perishable data from this event. The team included the following members: Misko Cubrinovski (University of Canterbury, NZ, Team Leader), Susumu Yasuda (Tokyo Denki University, Japan, JGS Team Leader), Rolando Orense (University of Auckland, NZ), Kohji Tokimatsu (Tokyo Institute of Technology, Japan), Ryosuke Uzuoka (Tokushima University, Japan), Takashi Kiyota (University of Tokyo, Japan), Yasuyo Hosono (Toyohashi University of Technology, Japan) and Suguru Yamada (University of Tokyo, Japan)

GEOLOGICAL AND TECTONIC SETTING

The Canterbury Plains, about 180 km long and of varying width, are New Zealand's largest areas of flat land. They have been formed by the overlapping fans of glacier-fed rivers issuing from the Southern Alps, the mountain range of the South Island. The plains are often described as fertile, but the soils are variable. Most are derived from the greywacke of the mountains or from loess (fine sediment blown from riverbeds). In addition, clay and volcanic rock are present near Christchurch from the Port Hills slopes of Banks Peninsula. The city of Christchurch is located at the coast of the Canterbury Plains adjacent to an extinct volcanic complex forming Banks Peninsula. Most of the city was mainly swamp, behind beach dune sand, and estuaries and lagoons, which have now been drained (Brown et al., 1995). The simplified geographical and geological information are shown in Figures 1, 2 and 3.

Canterbury has abundant water, in the rivers which carry mountain rainfall to the coast, and in aquifers. Beneath the plains, layers of porous gravels are interspersed with impermeable finer sediments. Near Ashburton, bedrock is at a depth of 1,600 meters (Wilson, 2009). Unlike most urban water supplies, Christchurch's water comes from aquifers beneath the city. The aquifers are recharged by rainfall and by river seepage. They have been tapped to irrigate farmland and for town water supplies.

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The two main rivers, Avon and Heathcote, which originate from springs in western Christchurch, meander through the city and act as main drainage system. The Waimakariri River with its catchment in the Southern Alps, regularly flooded Christchurch prior to stopbank construction and river realignment, which began shortly after the city was established in 1850. Variable foundation conditions as a consequence of a high water table and lateral changes from river floodplain, swamp, and estuarine lagoonal environments, impose constraints on building design and construction (Brown et al., 1995).

According to studies by Brown et al. (1995), the geology, tectonic setting, and active seismicity of the Christchurch area indicate that future large earthquakes will occur which will have major impact on the city. Based on historical records, the north Canterbury Earthquake of 1888, centered on Amuri, damaged many buildings and caused the top of the spire on Christchurch Cathedral to collapse. In addition, the 1901 earthquake centered near Cheviot caused minor damage in the city while the Arthur's Pass earthquake of 1929 caused significant rockslides in the mountains. Moreover, as already reported, the 4 September 2010 earthquake centered in the town of Darfield about 40km west of Christchurch, caused widespread liquefaction in the eastern suburbs of Christchurch and in Kaiapoi.

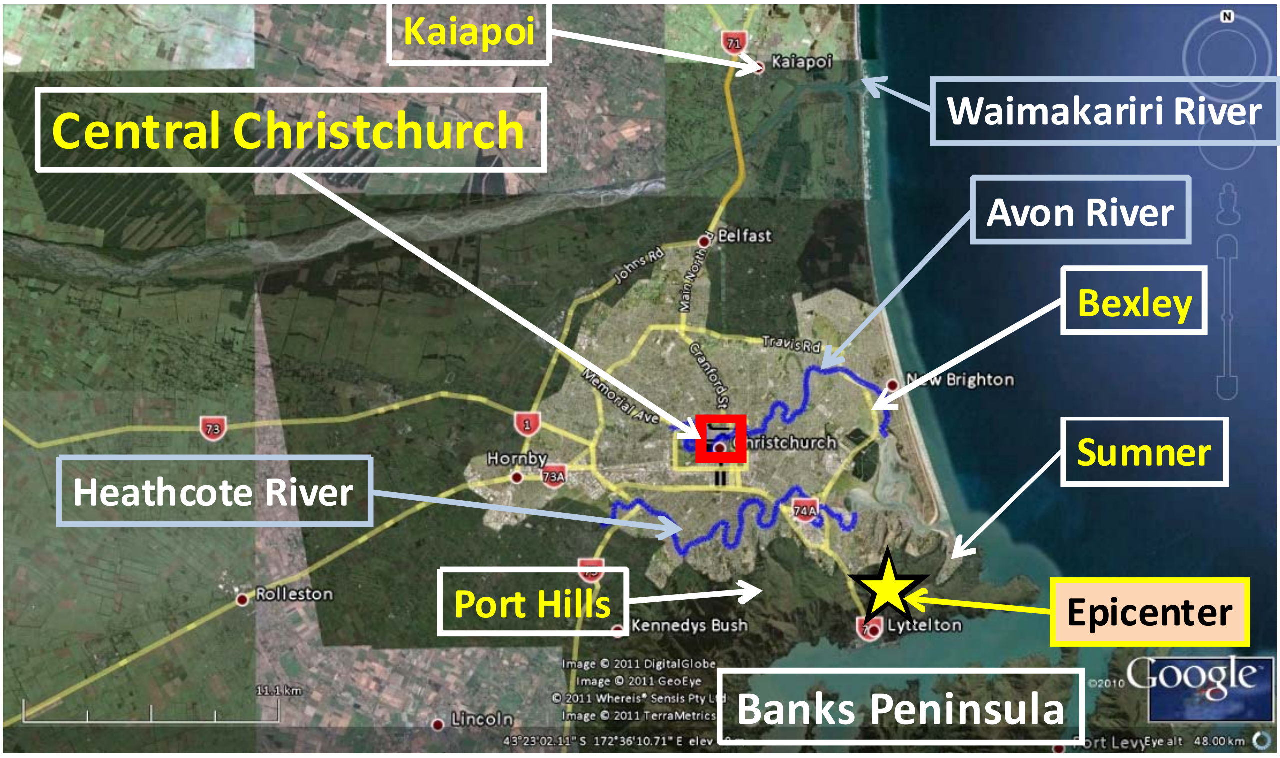

Figure 1. Geographical information in Christchurch region.

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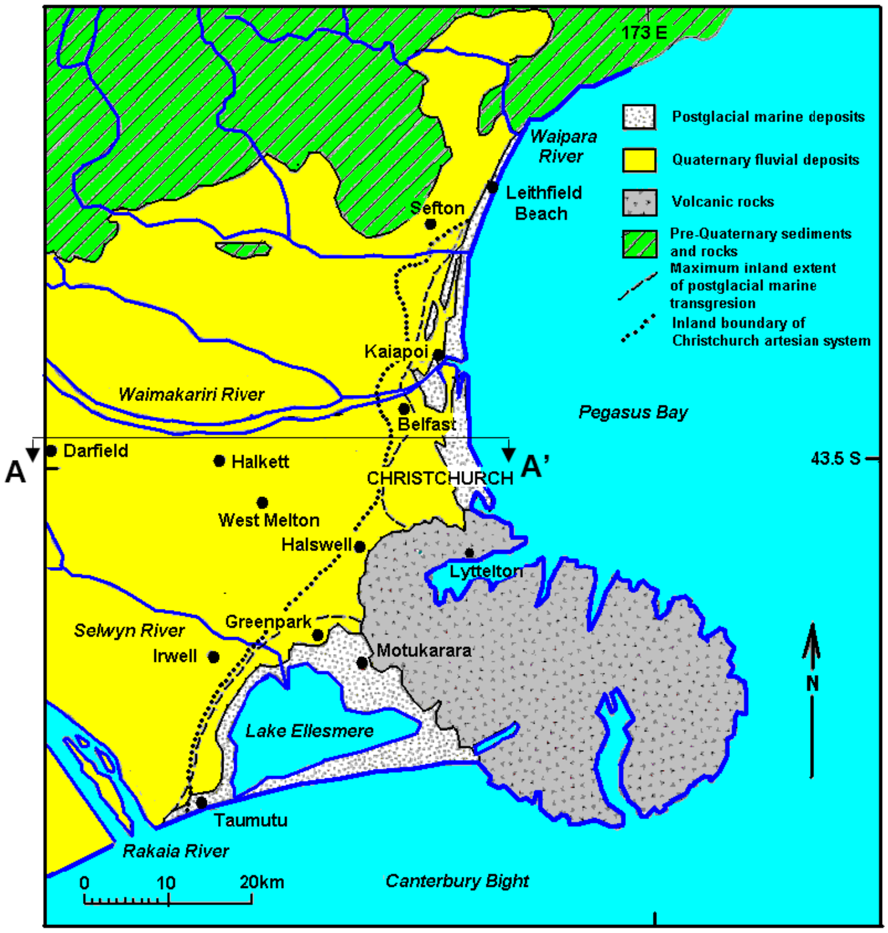

Figure 2. Simplified geology of Christchurch region. (Modified from Brown and Weeber, 1992).

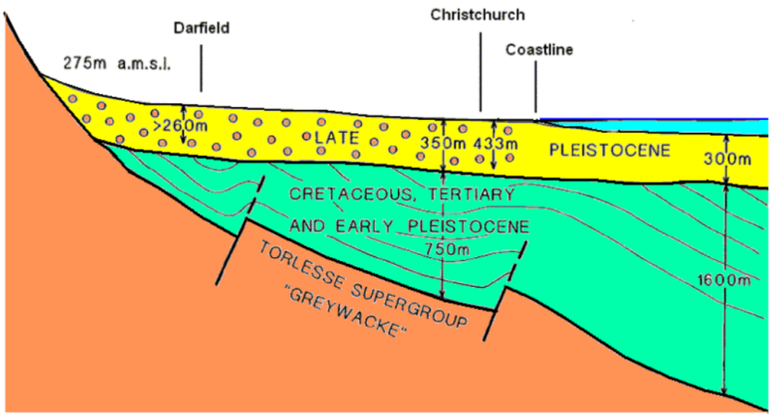

Figure 3. Simplified soil strata along a cross-section A-A' indicated in Figure 2. (Modified from Brown and Weeber, 1992).

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THE 2011 CHRISTCHURCH EARTHQUAKE

An earthquake of magnitude Mw 6.3 occurred at 12:51 pm local time, on 22 February 2011 with an epicenter located at Port Hills, near Lyttelton, about 10 km south-east of the city of Christchurch. The earthquake has a focal depth of 5 km and the maximum intensity felt was 8 based on MMI scale (GNS, 2011). The 2011 Christchurch Earthquake occurred more than 5 months after the 2010 Darfield Earthquake (4 September 2010), with the epicenter 50 km away from the last one. This earthquake is considered to be an aftershock of the earthquake that occurred on 4 September 2010 in spite of the long interval between the events and the large distance between the epicenters. The epicenter of this earthquake is located on a different fault from the Greendale Fault which was the source of the 2010 earthquake. However, it is considered that the earthquake was caused by a fault rupture within the zone of aftershocks that followed the earthquake on 4 September 2010 (NHRP, 2011).

NHRP (2011) described the aftershock activity as follows: "*At first the aftershocks were clustered largely along the east-west fault line across the Canterbury Plains, but they soon spread well beyond the visible ends of the Greendale Fault. Over many months a cloud of aftershocks has developed, indicating a network of subsurface faults. One cloud of aftershocks extended both north-northeast and south-southwest from the eastern end of the Greendale Fault. At the south end of the zone was another line of aftershocks, roughly parallel to the Greendale Fault but many kilometres further southeast. It extended eastward into southern Christchurch and beneath the Port Hills area.*"

Figure 4 the shows locations of the main shock, aftershocks with magnitude above 3, and fault ruptures in Canterbury. It is clearly understood that large number of aftershocks occurred in the south-west part of the fault that includes the epicenter of the February 2011 earthquake.

During the 2011 Christchurch earthquake, a series of strong motion accelerographs were triggered and motions recorded at several stations. The distribution of maximum accelerations is shown in Figure 5. The values indicated in the figure correspond to the maximum of the three components recorded. It can be seen that the maximum recorded acceleration was in the order of 2.2 g near the earthquake epicenter, a number of rock falls were caused by significant shaking in this area. The accelerometers around the CBD showed maximum acceleration ranging from 0.57 g to 0.80 g in this earthquake, more than three times of those recorded during the September 2010 event. Due to much stronger shaking, many multi-story buildings suffered severe structural damage in the CBD.

Figure 6 shows time histories of acceleration recorded on 4 September 2010 and 11 February 2011 at Christchurch Hospital which is locating at south-west edge of CBD. The waves colored in black and red shown in the figure correspond to the 4 September 2010 and 11 February 2011 earthquakes, respectively. Because of the short distance to the epicenter, the acceleration records in this earthquake indicate higher frequency and shorter duration time as well as larger amplitude in comparison with the ones recorded in 4 September 2010.

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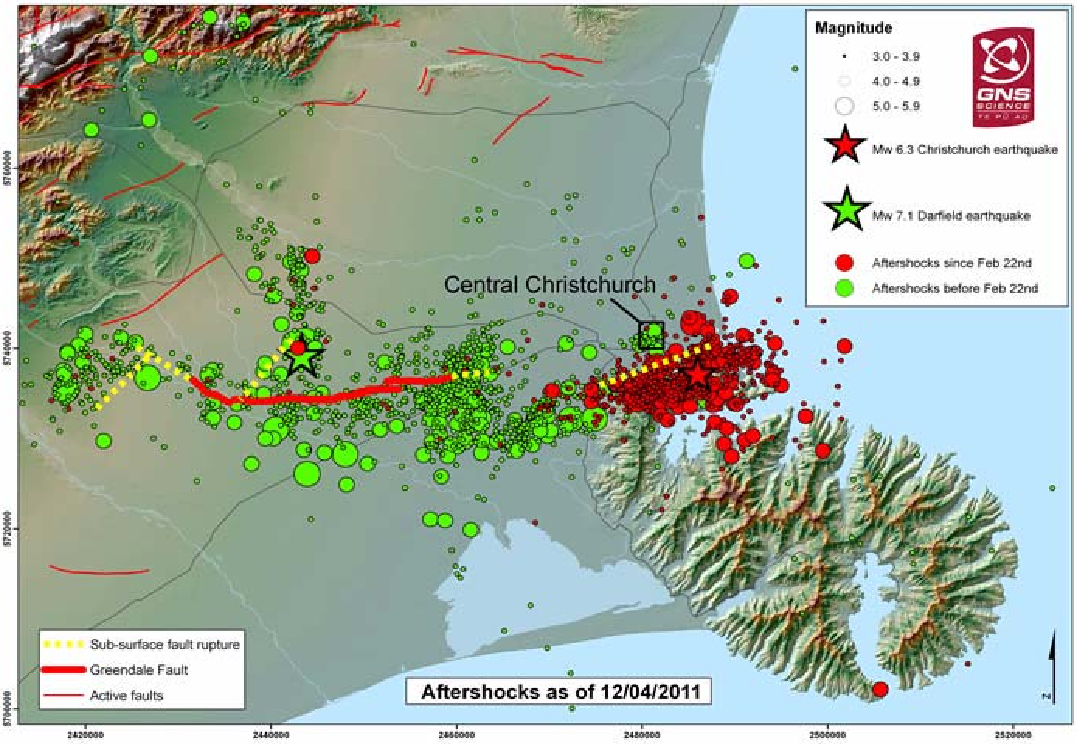

Figure 4. Location of main shock, aftershocks above magnitude 3, and fault ruptures in Canterbury. (Graphic by GNS Science, http://www.gns.cri.nz/) (as of 12 April 2011).

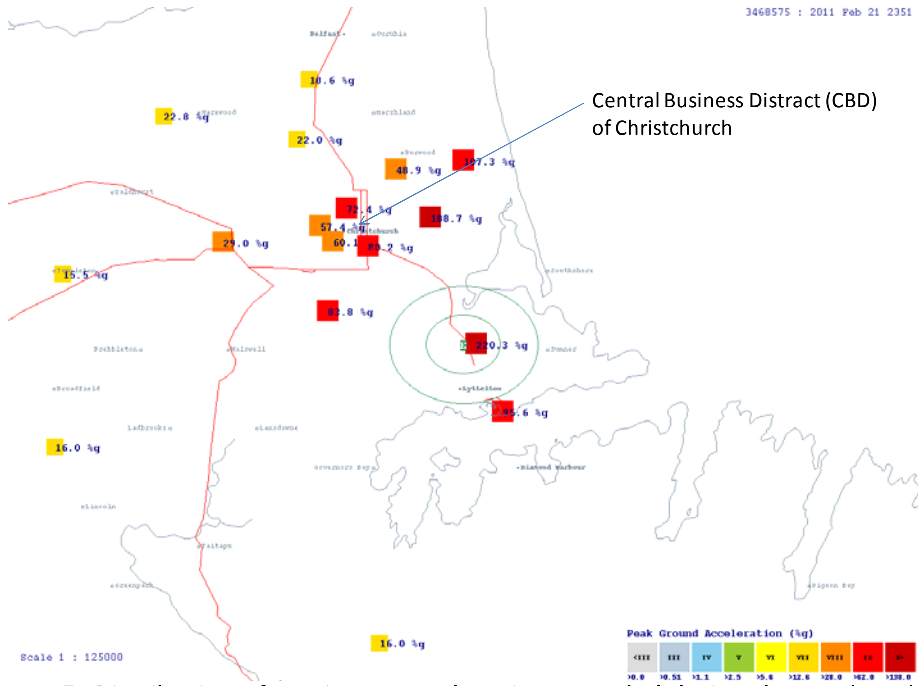

Figure 5. Distribution of maximum acceleration recorded during the earthquake. (Graphic by GNS Science, http://www.gns.cri.nz/).

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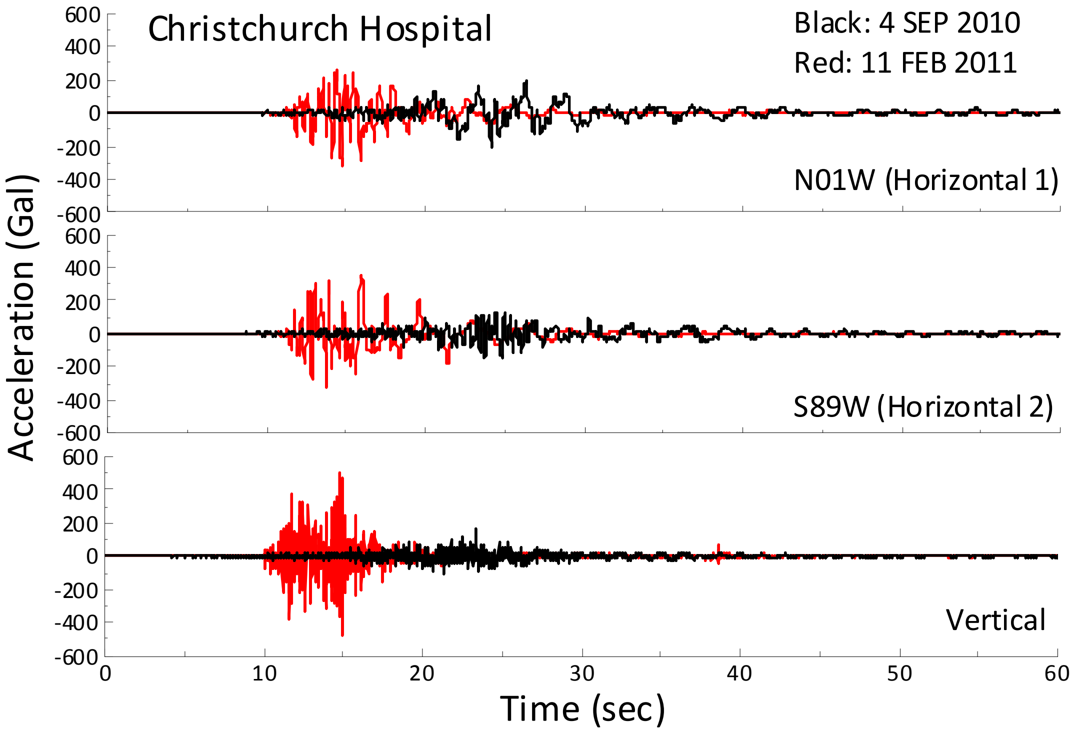

Figure 6. Acceleration records of the 2010 Darfield Earthquake and 2011 Christchurch earthquake at the Christchurch Hospital.

EFFECTS OF LIQUEFACTION

Because of the short distance to the city and the shallower depth of the epicenter, this earthquake caused more significant damage in Christchurch city than the September 2010 Darfield Earthquake in spite of its smaller earthquake magnitude (energy). The earthquake caused widespread damage to residential buildings, lifeline facilities and transportation infrastructure due to soil liquefaction and the associated ground deformations. Repeated liquefaction was observed in many places where liquefaction occurred in September 2010, such as in the eastern suburbs of Christchurch and in Kaiapoi town.

(1) Christchurch

The earthquake caused widespread liquefaction in the eastern suburbs of Christchurch city as well as in Central Business District (CBD). The liquefaction-affected area in Christchurch during this earthquake was much wider than the one in September 2010. While major liquefied sites in the September 2010 earthquake were distributed along the Avon River (northeast of CBD), liquefaction was observed in the 2011 earthquake across a wide areas in suburbs north to south of Christchurch city. Figures 7 and 8 show the areas of observed liquefaction in urban area of Christchurch after the 2010 Darfield earthquake and 2011 Christchurch earthquake, respectively. These two maps were based on surface manifestation of liquefaction visible in aerial photographs and initial observations from ground surveying. The survey to understand areas of liquefaction caused by each quake was conducted immediately after the earthquake occurrence by a reconnaissance team of the University of Canterbury.

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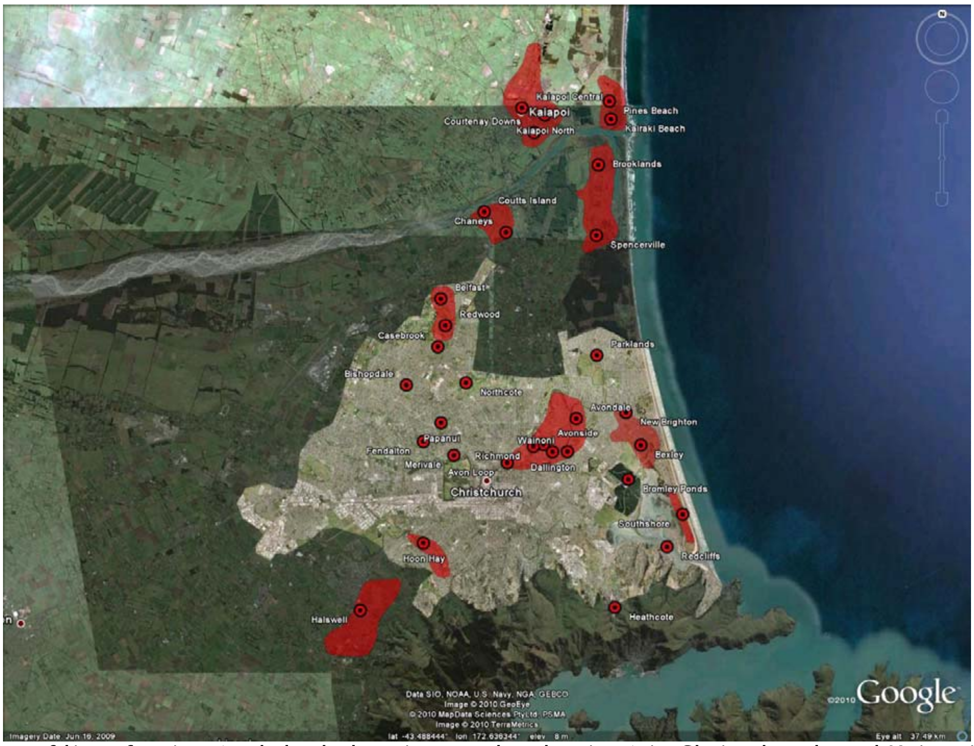

Figure 7. Areas of liquefaction (red shaded regions and red points) in Christchurch and Kaiapoi caused by the 2010 Darfield Earthquake (Cubrinovski et al, 2010).

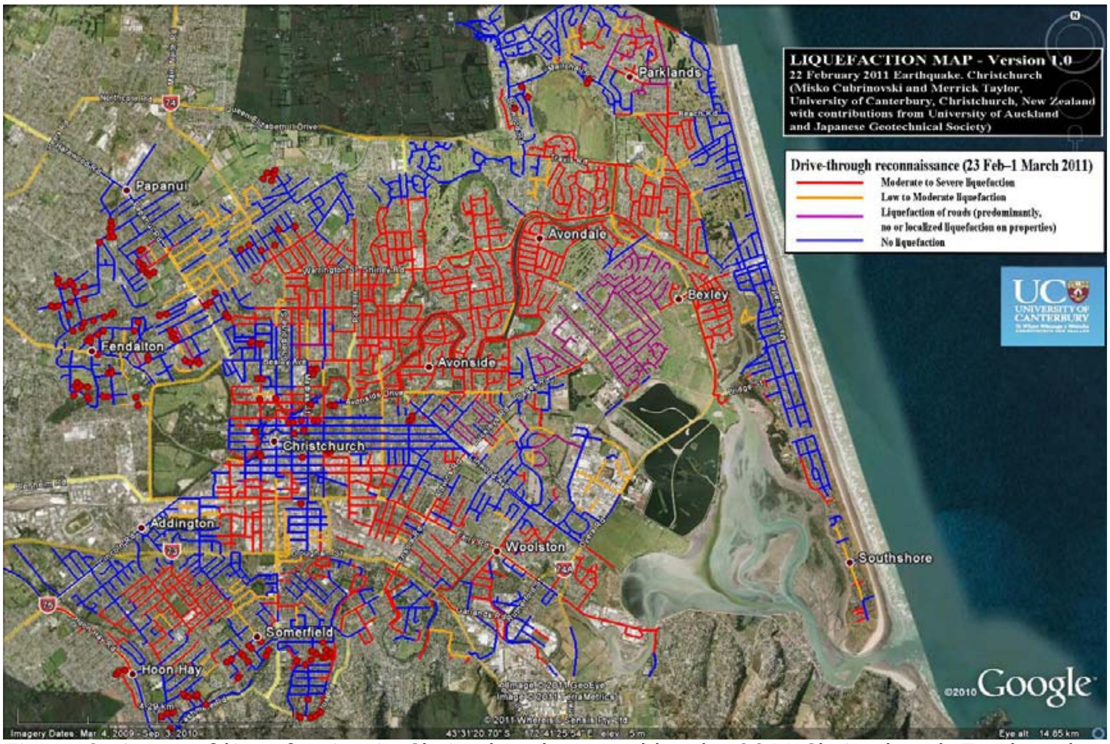

Figure 8. Areas of liquefaction in Christchurch caused by the 2011 Christchurch Earthquake. (Cubrinovski and Taylor, 2011, http://www.nzsee.org.nz/)

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After the 2010 Darfield earthquake, Swedish Weight Sounding (SWS) tests were performed by University of Canterbury at numerous locations affected by liquefaction and lateral spreading. 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). As a result of SWS test, the corresponding standard penetration test N-value (SPT-N) can be obtained through the following empirical equation (Inada, 1960);

$$N = 0.002W_{SW} + 0.067N_{SW}$$

where W_{SW} (kg) is the weight less than 100 kg and N_{SW} (/m) is the number of half-rotations for 1.0 m of penetration. W_{SW} is counted when penetration occurs with dead-load less than 100 kg. Note that this equation is applicable for gravel, sand and sandy soils.

Typical results of SWS tests in Christchurch are shown in Figure 9. It can be understood from the figures that there are strata of very loose (N < 5) silt/sand, at about 5 m or deeper below the ground water table.

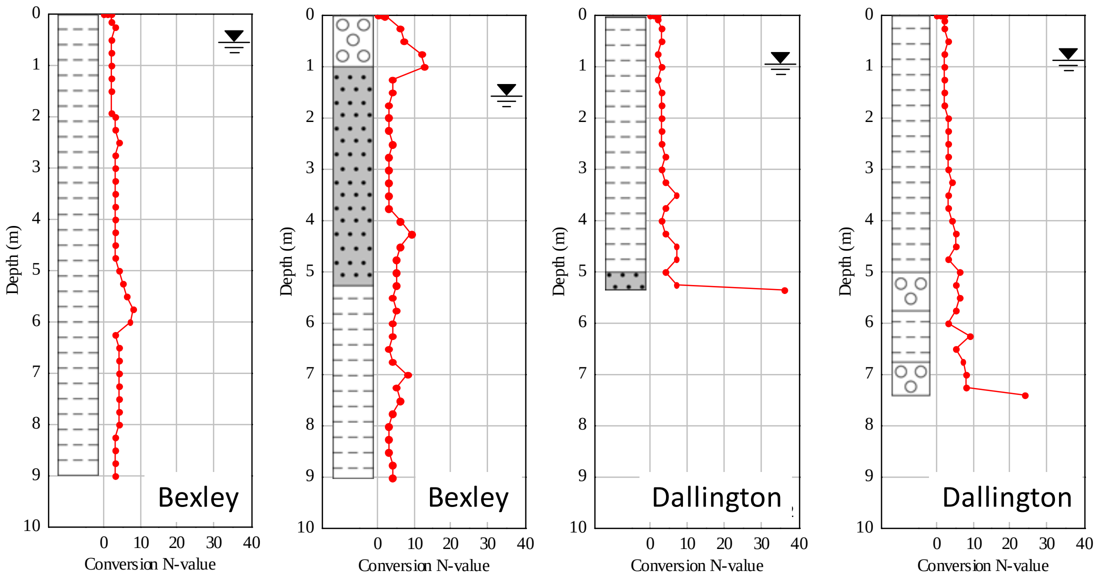

Figure 9. Converted N-Value profile in Bexley and Dallington. Ground survey was conducted by University of Canterbury and JGS Reconnaissance teams in September 2010 (JGS, 2010).

The ejecta from sand boils found at liquefied areas in Christchurch were generally similar and had distinctive features, like presence of non-plastic fine sand and silty sand with grey/blue color. Figures 10 (a) and (b) show the grain size distribution curves of sand ejecta collected at several sites in Christchurch after 2010 Darfield earthquake and 2011 Christchurch earthquake, respectively. In general, the sand ejected in both earthquakes had very similar grain size distributions.

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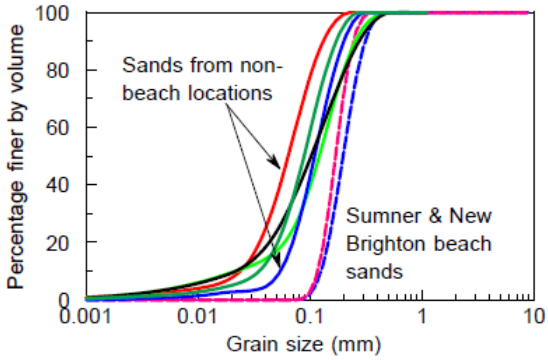
(a) 2010 Darfield earthquake using laser diffraction method (Cubrinovski et al., 2010)



(b) 2011 Christchurh earthquake using sieve analysis

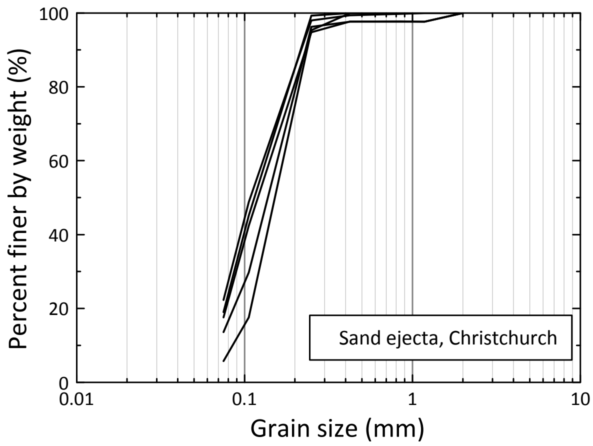


Figure 10. Grain size distribution curves of sand efecta collected in Christchurch city.

In the Central Business District (CBD), several buildings collapsed, while many of the buildings that survived suffered significant or some form of structural damage. Severe liquefaction was also observed in the CBD, such as along Kilmore Street (Figure 11a) and Armagh Street (Figure 11b). The relation between the building structural damages and liquefaction of the foundation ground is currently under investigation.

(a) along Kilmore Street (b) along Armagh Street

Figure 11. Liquefaction-induced damages in CBD.

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There are very few structures in the area where liquefaction countermeasures have been implemented in the foundation ground. One example is the AMI stadium located near CBD, where the ground under the east stand was stabilized with stone column. Minor liquefaction was observed near the east stand in spite of the severe liquefaction all around the stadium (Figure 12).

(a) Massive amount of sand ejecta in front of the west stand of AMI stadium.

(b) The ground in front of the east stand of AMI stadium. The green turf was not covered by sand boils.

Figure 12. Liquefaction adjacent to AMI stadium.

Because of short time interval between the two gigantic earthquake events, the earthquake caused additional damages to many facilities which suffered liquefaction-induced damage and had not been repaired. Figures 13 (a) and (b) are photos of a river embankment in Porritt Park (east bank of Avon River), after the 2010 earthquake and 2011 earthquake, respectively. The width of crack openings on the shoulder and settlement of the crown became larger due to repeated liquefaction of the foundation ground of the embankment. Extensive repeated liquefaction was observed in entire Porritt Park, where half of green grassy area was covered by sand boils again following the previous earthquake.

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(a) Damage in Porritt Park after 2010 Darfield Earthquake (JGS, 2010)

(b) Same area after the 2011 Christchurch Earthquake

Figure 13. Lateral spreading and the crown settlement of a stop bank near Porritt Park.

Extensive liquefaction was observed widely in residential areas along Avon River. The very shallow ground water table (1.0m to 1.5m) has been recognized in western suburb of Christchurch, particularly in areas close to the coastal line. Bexley is a newly constructed residential area developed by reclaiming the wetland near the mouth of Avon River. Figure 14 shows a broad panorama overlooking Bexley, taken from the South Brighton Bridge crossing the river mouth of Avon. It can be seen that residential houses are now located on an area where the ground elevation is almost the same as the water surface.

Figure 14. A photo overlooking the Bexley residential area.

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In Bexley, a large number of residential houses/properties suffered severe damage from liquefaction in September 2010 earthquake. After the 2011 earthquake, it was again one of the worst hit areas in terms of liquefaction-induced damage. Figures 15 (a) and (b) show damaged residences after the 2010 and 2011 earthquakes, at Seabreeze Close in Bexley. Massive amount of sands were ejected and deposited around the houses. Differential ground settlement was caused by severe sand boils, resulting in tilting in many houses.

(a) After the 2010 Darfield Earthquake (Cubrinovski and Orense, 2010) (b) after the 2011 Christchurch Earthquake

Figure 15. Damage to residential houses due to repeated liquefaction in Seabreeze Close, Bexley.

Damages in levees along Avon River were observed everywhere, spanning from inside the CBD to the river mouth. Many bridges crossing the Avon river suffered tilting in their abutments, as a result of lateral spreading and loss of bearing capacity due to liquefaction (Figure 16a). Damage to pipelines was also observed at the connections between bridge and backfill. In most cases, the settlement of the bridge abutment itself is smaller than that of the adjacent soil because the bridge is supported by pile foundations (Figure 16b).

(a) Tilt in abutment due to lateral spreading (b) Damage to pipeline installed in the bridge

Figure 16. Damage to bridge crossing the Avon River (Avondale Road).

Due to lateral spreading and heaving of the river bed, the cross-sectional area of the Avon River has become smaller than before the earthquake (Figure 17). Therefore, people living in areas adjacent to the river will now have to worry about flooding during the rainy season.

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(a) River dike moved laterally toward the river

(b) River bed appeared above water surface as lateral spreading pushed up the river bed

(c) High water level in Avon River

Figure 17. Ground distortions due to liquefaction along Avon River.

The South Brighton Bridge which crosses the mouth of Avon River was severely affected by liquefaction on ground basement. Observed damages near the bridge were lateral deformation and crown settlement in the bridge approach, large tilt of abutments, tension and compression cracks in pile foundations and failure of pipeline installed underneath bridge girder (Figure 18). The body of the embankment spread laterally, with the top settling down due to liquefaction of the ground underneath and causing large tilt of the abutments. The back side of the abutment settled down, the front side lifted up, and the pile foundation protruded to the ground surface. Tension and compression cracks were observed in the battered pile foundation; however no pile was broken. Thus, it can be considered that the loss of lateral bearing capacity of the pile foundation was induced by liquefaction below the abutment.

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(a) Damage to the body of the embankment (b) Tilted abutment and protruding battered pile foundation

Figure 18. Liquefaction-induced damage to South Brighton Bridge.

(2) Kaiapoi

Kaiapoi is located in the northeastern end of Canterbury Plains, about 20 km north of Christchurch (Figure 1). The Kaiapoi River, which cuts through the centre of the town, joins the Waimakariri River on the eastern edge of town and flows to the sea.

Extensive lateral spreading occurred in the areas close to Waimakariri and Kaiapoi Rivers during the 2010 Darfield earthquake. A large number of residential houses/properties, commercial facilities and stop banks suffered severe structural and geotechnical damage due to lateral spreading and liquefaction. Although repeated liquefaction was observed in Kaiapoi during this earthquake, the impact of liquefaction was minor than that in 2010 Darfield earthquake.

Figure 19 shows two photos of a residential house which suffered severe damage due to lateral spreading in 4 September 2010 earthquake. This residence is standing on a ground that moved toward Waimakariri River, resulting in tilting of the house and formation of 1.6 m wide crack. An investigation was carried out at the residential property shown in the figure on 4 March 2011. Sand boils were observed only in the crack, with the width of crack increasing to 1.9 m. It is unknown, however, whether the increase in crack opening was caused by this earthquake alone. Creep deformation in this area due to the aftershocks of 2010 Darfield earthquake has been reported (Cubrinovski and Orense, 2010). Therefore, there is a possibility that the width of the crack was more than 1.6 m before the February 2011 earthquake and the impact of the recent earthquake to this area was minor. No other remarkable additional damage to residential house/properties was observed in South Kaiapoi.

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Figure 19. Minor additional damage to a residential house which underwent foundation failure due to lateral spreading and liquefaction in 2010 Darfield Earthquake. (South Kaiapoi)

In areas close to the waterways, most of sand boils were observed at existing/repaired cracks caused by the 2010 earthquake. Aside from the lower intensity of ground shaking in Kaiapoi, it is possible that the excess pore water pressure generated by the earthquake motion could have been dissipated easily through the existing cracks and therefore, significant ground distortion was not caused by this earthquake (Figure 20 and 21).

Figure 20. Repeated liquefaction at a park adjacent to Courtenay Lake (South Kaiapoi). Liquefied soil was ejected from existing cracks, but ground distortion was minor compared to the ones observed in September 2010 earthquake.

Figure 21. Damage to the stop bank along Kaiapoi river (North Kaiapoi). Sand boils were observed on restored cracks. The damage to the stop bank was minor and lots of small fissures were observed at restored cracks.

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On the other hand, a more pronounced liquefaction was observed in residential houses/properties in North Kaiapoi, although relatively minor compared to those after the 2010 Darfield earthquake. Two examples of damage to residential properties are described below.

Figure 22 is comparative photos of settlement of a two-story house due to liquefaction. The slope in front of the garage was originally uphill, but it became a downhill after 2010 Darfield earthquake as a result of more than 50 cm of ground subsidence. This house suffered additional 15 cm of subsidence from the 2011 earthquake. The narrowing gap between the roof and the head of a member of the research team can be recognized from the figure. Although the investigators appearing in the photos are actually different, their heights are almost the same.

Figure 22. Further subsidence in two-story house neighboring the stop bank. (North Kaiapoi)

Massive amount of sand ejecta, about 400 mm in thickness, was observed in a property following the September 2010 event (Figure 23). The ejected sand covered a deck in front of the entrance, with thickness of about 10 cm. The observed thickness of sand ejecta after the 2011 earthquake was around 20 cm.

Figure 23. Repeated liquefaction in a residential property in North Kaiapoi.

As mentioned above, liquefaction-induced damage comparable to September 2010 was observed at few residential properties in North Kaiapoi. However, the areas affected by liquefaction in this earthquake were more localized than during the previous one. The areas where evidence of liquefaction were observed during the 2011 earthquake are indicated as red colored areas in the liquefaction map of 2010 Darfield earthquake (Figure 24; Cubrinovski et al., 2010). Note that liquefied area shown in the figure is based on the view observation conducted on 27 February and 4 March 2011. The indicated area may be extended as a result of further investigations.

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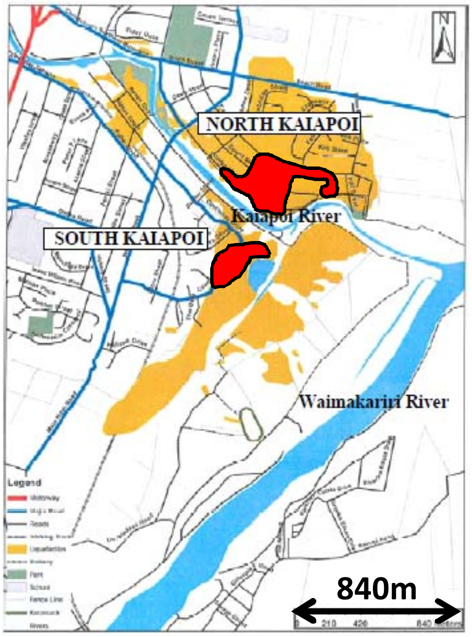

Figure 24. Comparison of liquefied area in Kaiapoi between 2010 Darfield and 2011 Christchurch earthquakes (Modified from Cubrinovski et al., 2010).

After the 2010 Darfield earthquake, SWS tests were conducted at a residential property shown in Figure 23 (Cubrinovski et al., 2010 and JGS, 2010). The profiles of converted N-value from SWS tests are shown in Figure 25. The upper portion of the ground consists of very loose sand, with depth more than 7 m and the ground water table was very shallow. Figure 26 shows the grain size distribution curves of sand ejecta collected in Kaiapoi. The solid curve with red color in the figure indicates the grain size distribution of soil collected after this earthquake, while the other dashed curves correspond to soils taken after the 2010 Darfield earthquake. The sands ejected in both earthquakes have generally similar grain size distribution. Moreover, they have similar grain size distributions as the sand ejecta in Christchurch, which are shown in Figure 10.

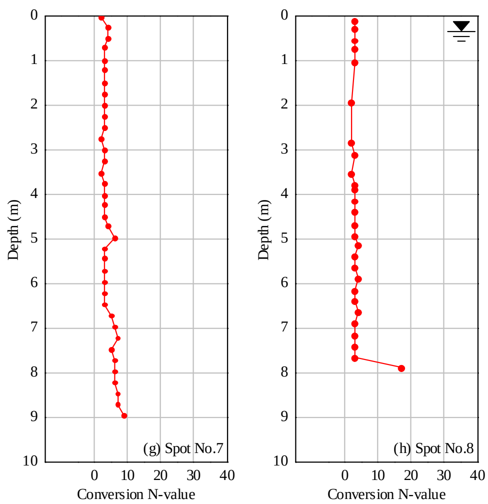

Figure 25. Converted SPT N-value profile in North Kaiapoi. Ground survey was conducted by University of Canterbury and JGS Reconnaissance team on September 2010 (JGS, 2010).

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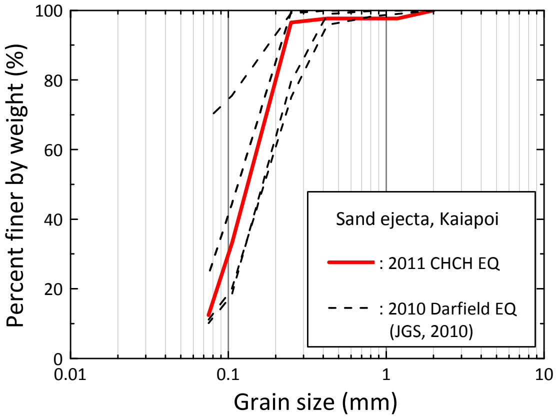

Figure 26. Grain size distribution curves of sand ejecta collected at Kaiapoi.

EFFECT ON SLOPE (CLIFF) STABILITY

During the Christchurch earthquake, numerous slopes and cliffs suffered shallow land slides and rock falls. One of the most severe damages to a cliff was observed in Sumner, located at the north end of Port Hills in the Banks Peninsula, about 12 km south-east of Christchurch. The cliffs in this area were formed by slope erosion of an ancient volcano. Residential houses were constructed on the cliffs as well as on the flat ground underneath. Many residential houses were built at the edge of the cliff.

Figure 27 shows a landscape of the affected cliff located at the west side of Wakefield Avenue in Sumner. This cliff is approximately 70 m high and 500 m long in north-south direction. The cliff surface was previously covered with vegetation, but became bare due to earthquake disturbance.

Figure 28 shows a rock fall near a building. The fallen rock is about 4.8 m wide, 6.6 m high and 15.8 m long. Numerous rock falls occurred in other hilly areas adjacent to the epicenter and residential houses and traffic were severely affected.

Figure 27. Panoramic view of a disturbed cliff (Sumner).

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Figure 28. Huge rock fall adjacent to a building (Sumner).

CONCLUDING REMARKS

Although the collapse of many commercial buildings led to the greatest casualties in the M 6.3 Christchurch earthquake, by far the most significant damage to residential buildings and lifelines was the result of liquefaction and associated ground deformations. Although the M 7.1 Darfield earthquake caused liquefaction in Christchurch and adjacent areas, the M 6.3 Christchurch earthquake induced more widespread liquefaction and caused more serious damage to infrastructure. Experiences from case histories all over the world have highlighted the effect of liquefaction to buildings and buried structures, but the scale of damage experienced in Christchurch following the 2011 event was unprecedented and may be the greatest ever observed in an urban area. Moreover, the short time interval between two large events has presented a very rare opportunity to investigate liquefaction in natural deposits.

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