LIQUEFACTION-INDUCED DAMAGE CAUSED BY THE 2010 DARFIELD EARTHQUAKE, NEW ZEALAND

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ABSTRACT: On September 4, 2010, the Darfield Earthquake hit around the Canterbury region, New Zealand. This report summarizes results from field investigations in Christchurch city and Kaiapoi city which were conducted a week after the earthquake. The earthquake-induced liquefaction caused severe damage to residences, buried lifelines and river dikes. High ratio of occurrence of liquefaction was reported in areas which may be linked to the soft subsurface ground, lowland areas, former river channels and reclaimed lands that were constructed on the swamps. Swedish weight sounding tests were conducted at several sites where liquefaction occurred in Christchurch city.

Key Words: Darfield earthquake, Liquefaction, Field reconnaissance, Swedish weight sounding test

INTRODUCTION

The Darfield earthquake measuring the moment magnitude Mw of 7.1 (USGS, 2010) hit the South Island of New Zealand at 4:35 local time on Saturday, September 4, 2010 with a focal depth of about 10 km. The epicenter was about 40 km west of Christchurch and Kaiapoi which were most affected cities due to the earthquake (Fig. 1). Fortunately, there are no reports of casualties by this earthquake.

Figure 2 shows the peak ground accelerations that were recorded in the Canterbury region during the earthquake. The ground motion shaking as a result of the main shock was widely felt in the Canterbury region as shown in Fig. 2.

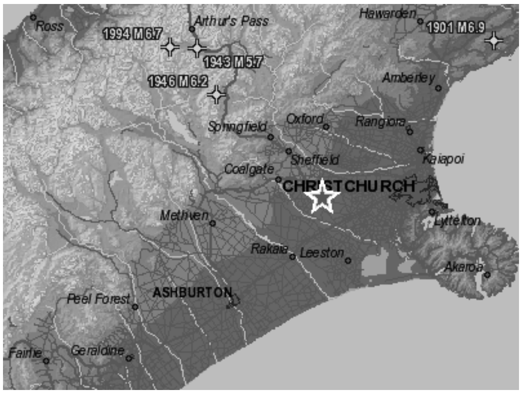

Figure 1 Location of epicenter of Darfield earthquake (GeoNet, 2010)

After the earthquake, the authors visited Christchurch and Kaiapoi in order to conduct a geotechnical investigation from September 11 to 16. During the survey, Swedish weight sounding

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(SWS) tests were carried out at several sites. This report summarizes results from the above investigations, focusing on the liquefaction-induced damages, in Christchurch city and Kaiapoi city.

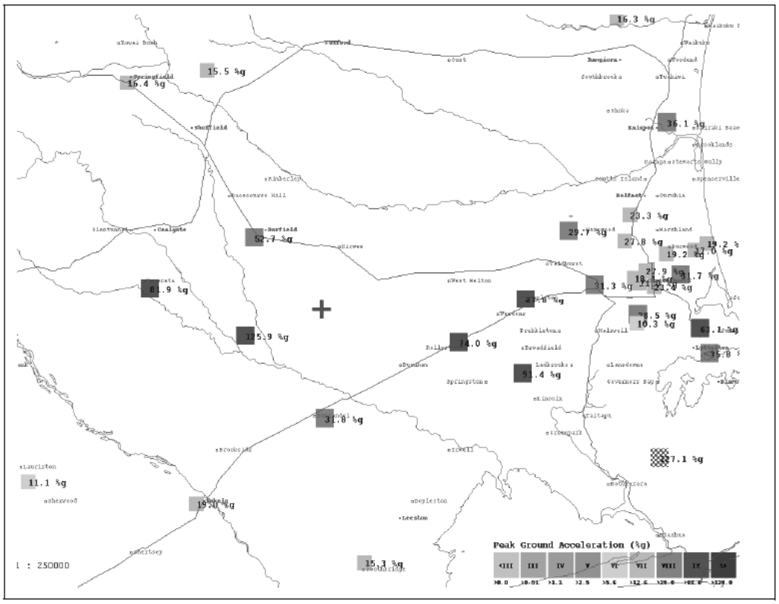

Figure 2 Peak ground accelerations in the Canterbury region during Darfield earthquake (after GeoNet, 2010)

LIQUEFACTION-INDUCED DAMAGE IN CHRISTCHURCH CITY

The business area of Christchurch city is located about 8.5 km west of the coast line as shown in Fig. 3. A meandering stream, Avon-river, flows through center part of Christchurch city. Based on the damage aspects due to liquefaction found in this survey, Christchurch city can be divided into three areas, business area, Dallington area and Bexley area. The results of the field survey are summarized below for each area.

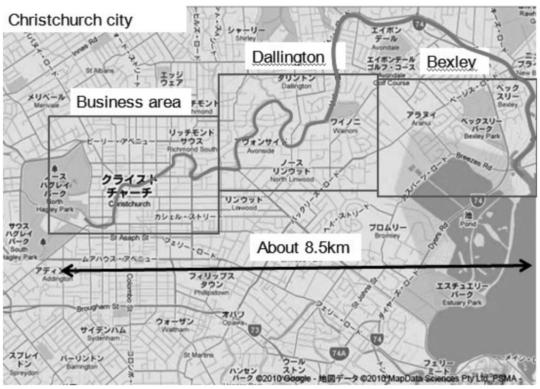

Figure 3 Map of Christchurch city

Business area

Figure 4 shows the map of the business area. At site 1 in the park, sand boiling occurred as shown in Photo 1. This suggests that soil deposits in the park have been liquefied. However, in this park, the occurrence of liquefaction was very limited. Although some old buildings suffered damage from ground shaking, no sand boiling could be observed at the center of business area (e.g., sites 25, 50 in Fig. 4).

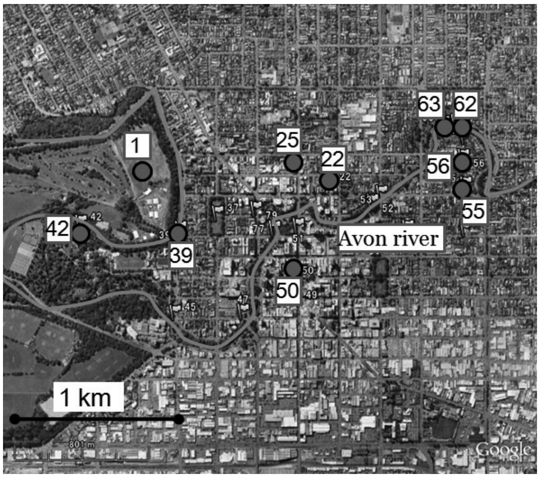

Figure 4 Survey map of business area in Christchurch city

Photo 1 Trace of sand boiling in the park of business area (Site 1 in Fig. 4)

At sites 56 (Photo 2), where the Avon river shows meandering shape, sand boiling was found in residential which clearly indicates occurrence of liquefaction. At sites 63 and 62, as shown in Photo 3 and 4 respectively, roads and levees along Avon-river suffered from ground deformation, which may be caused by liquefaction of subsoil deposits. On the other hand, at site 55 about 300 m from the Avon river channel, the traces of liquefaction were not observed.

Figure 5 shows grain size curves of boiled sands that were retrieved from the Business area. Most of their fines contents were less than 30 %, while the one from site 22 was higher than 60 % without plasticity.

Photo 2 Sand boiling occurred at residential district in Business area (Site 56 in Fig. 4)

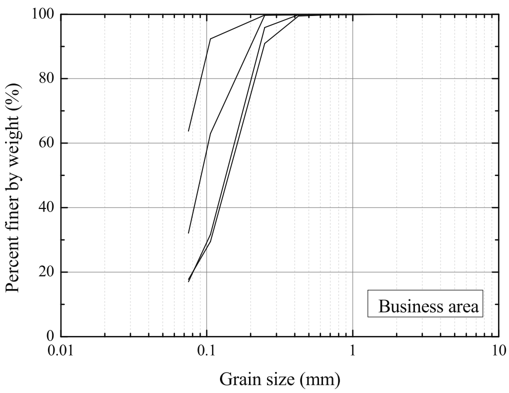

Figure 5 Grain size curves of boiled sands in Business area

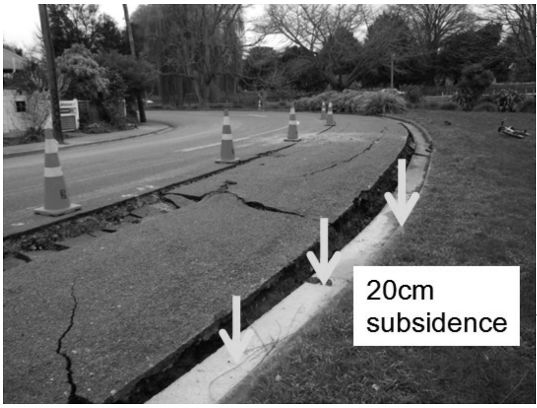

Photo 3　Road on river dike suffered from settlement and cracking (Site 63 in Fig. 4)

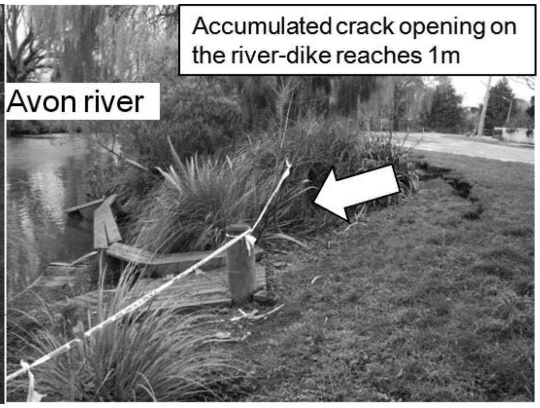

Photo 4　River dike along Avon-river suffered from large crack and lateral deformation (Site 62 in Fig. 4)

Dallington Area

The survey map of Dallington area is shown in Fig. 6. Yasuda (2010) reported that the Dallington area suffered extensive damage due to liquefaction. At the time of the earthquake, the areas along Avon-river were reportedly inundated with boiled sand and ground water.

However, at the time of survey that was conducted in a week after the earthquake, no water could be observed on the street, and the boiled sand was placed at the side of the street (Photo 5).

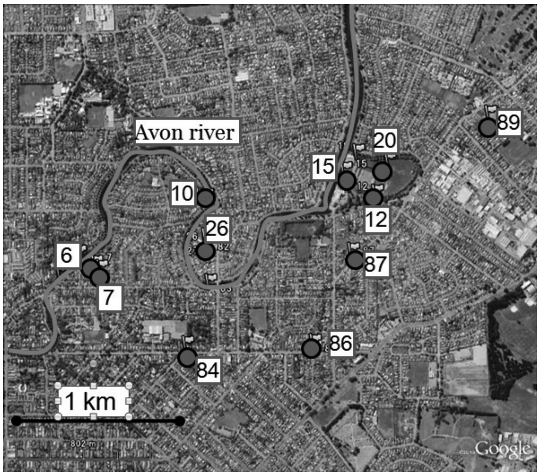

Figure 6　Survey map of Dallington area in Christchurch city

Photo 5　Boiled sand was placed at side of the street. (Site 6 in Fig. 6)

At site 7, significant liquefaction occurred in the residential district. A large amount of boiled sand could be observed at their backyards (Photo 6). The boiled sand covered ground surface with a thickness of 30 cm as shown in Photo 7. A number of housing floors suffered from cracking that was caused by uneven settlement of the ground after liquefaction.

Photo 6 Boiled sand (Site 7 in Fig. 6)

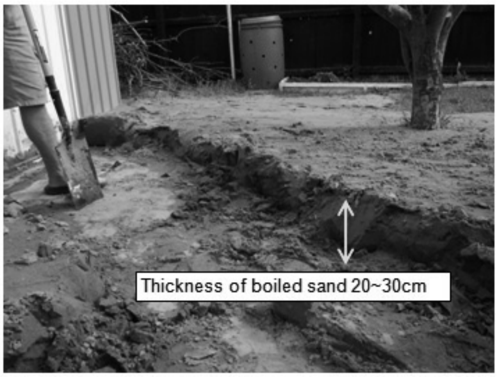

Photo 7 Boiled sand (Site 7 in Fig. 6)

In order to investigate the subsurface soil properties, Swedish weight sounding (SWS) test was carried out at site 7. SWS test results is shown in Fig. 7. Photo 8 shows the implementation of SWS test at site 7. Herein, the measured values of W_{SW} and N_{SW} has been converted into equivalent SPT-N value, N_{SPT}, by using the equation as follows (JIS A 1221).

$$N_{SPT} = 0.002W_{\mathrm{SW}} + 0.067N_{\mathrm{SW}} \qquad (1)$$

where Wsw is the minimum load required for penetration with 1000 N or less than 1000 N after starting penetration and N_{SW} is the value of static penetration resistance, which is the number of half rotations per penetration amount of 1m with the load of Wsw=1000 N.

As shown in Fig. 7, the ground water table was shallower than 1m from the ground surface, below which soft soil deposits with N_{SPT} values less than 5 could be found for a thickness of about 5 m. It clearly indicates occurrence of liquefaction with this soft layer. The boiled sand that was retrieved at the same location as SWS test was fine sand with D_{50} of 0.12 mm and fines content of 18%.

Photo 8 SWS test (Site 7 in Fig. 5). Behind of experimenters, there is house suffered from cracking.

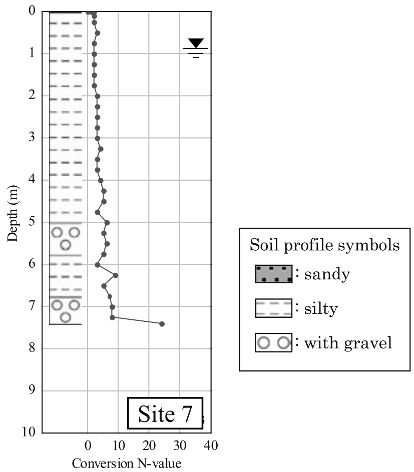

Figure 7 SWS test results (Site 7 in Fig. 6)

At site 26, St. Paul's Church that is located near the Avon-river suffered from uneven settlement. As shown in Figure 8, the settlements over 30 cm were measured at each side of cracking at the center part of the church, and the maximum settlement of 109 cm was measured at the tall structure. In addition, the pavement of parking lot around the building also suffered from cracking for a maximum differential settlement of about 50 cm as shown in Photo 9. These damages may have been caused by liquefaction because the extensive sand boiling occurred around the church.

SWS test was conducted at an open space in the same area of the church. As shown in Fig. 9, the ground water level was 1 m from the ground surface, below which soft soil deposits with N_{SPT} values less than 7 could be found for a thickness of about 4 m. The boiled sand that was retrieved around the church was fine sand with D_{50} of 0.11mm and fines content of 28% (PI= NP).

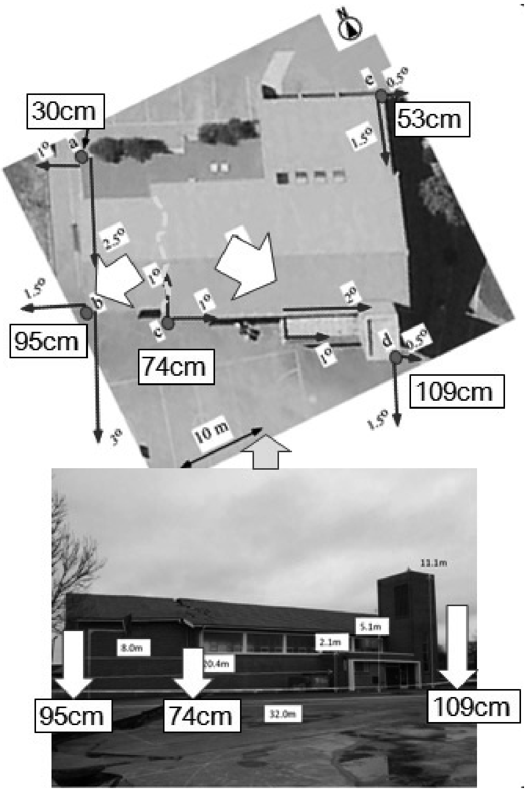

Figure 8 St Paul's church (built in 1956) suffered uneven settlement due to liquefaction (Site 26 in Fig. 6)

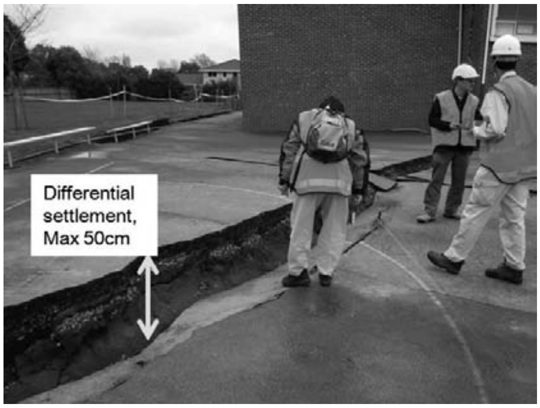

Photo 9 Pavement around St Paul's church suffered from large cracking and settlement (Site 26 in Fig. 6)

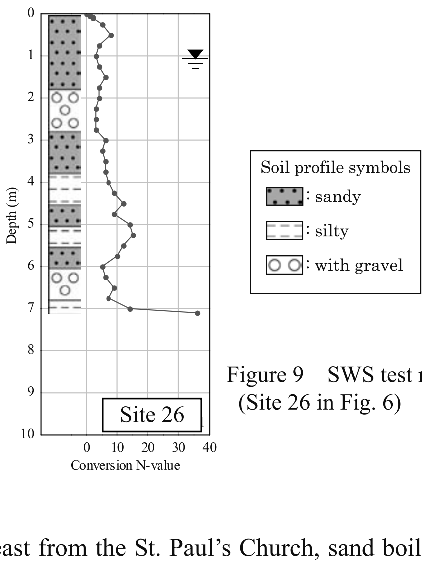

Figure 9 SWS test results (Site 26 in Fig. 6)

At site 20 at Porritt Park that is located about 1 km east from the St. Paul's Church, sand boiling occurred throughout the park. Numerous cracks having a maximum opening width of 70 cm occurred on ground surface (Photo 10). These cracks were caused by liquefaction because almost all crack openings were filled with boiled sand.

In the adjacent area (site 15), as show in Photo 11, river levee suffered from lateral spreading, and significant cracking could be observed on the ground surface, possibly caused by liquefaction of subsoil deposits.

Figure 10 shows grain size curves of boiled sands that were retrieved from the Dallington area. Most of their fines contents were less than 20 %, while those in the Porritt Park (site 22) were higher than 30 %.

Photo 10 Number of cracking and boiled sand could be observed in Porritt Park (Site 20 in Fig. 6)

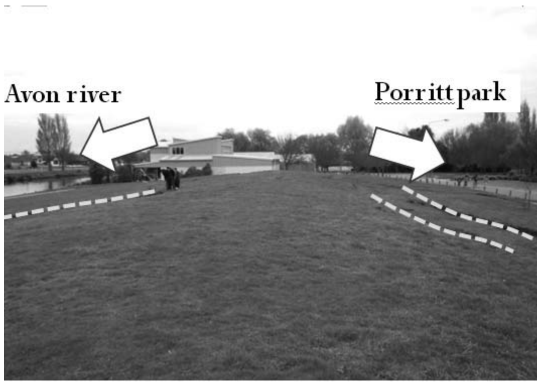

Photo 11 River levee was damaged due to settlement and cracking (Site 15 in Fig. 6)

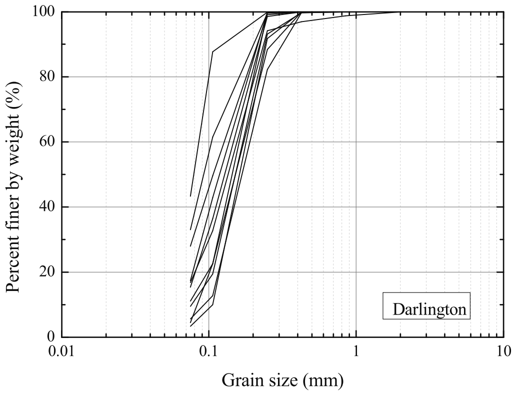

Figure 10 Grain size curves of boiled sands in Dallington area

Bexley Area

The survey map of Bexley area is shown in Fig. 11. At site 91, about 1 km west from Bexley area as well as Avon river, there was no damage by liquefaction. However, towards the Bexley area, the boiled sand came to be recognized on the street.

Reportedly, the residential area in Bexley had been elevated by soil filling about 5 years ago. Photo 12 shows a significant cracking which was found in the backyard of house along the margin of the landfill. Since the boiled sand could be found in the cracking, the filled material in this area was expected to be liquefied. In Bexley area, high damage ratio of houses was observed along the margins of landfill, and the slope of the filling was damaged due to excessive settlement and cracking.

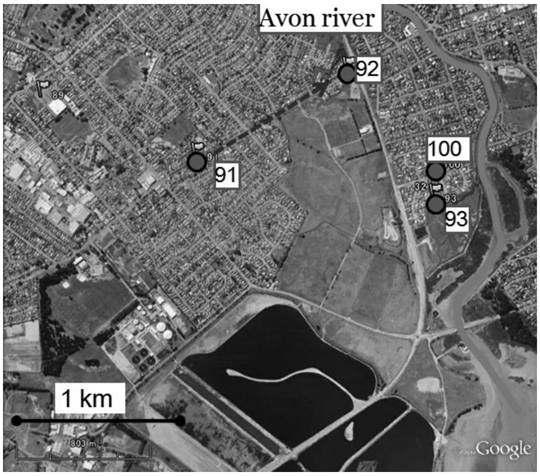

Figure 11 Survey map of Bexley area in Christchurch city

Photo 12 Foundation of house suffered from large cracking (Site 93 in Fig. 11)

Figure 12a) shows the result of SWS tests at site 93 that were conducted at the side of damaged house (Photo 12). The groundwater level was about 1.5m from the ground surface, below which very soft sandy soil deposits with N_{SPT} values less than 5 could be found for a thickness of about 4 m. This suggests that the compaction work had not been properly-conducted when the landfill was constructed. The boiled sand that was retrieved at the same location of SWS test was fine sand with D_{50} of 0.13mm and fines content of 12% as shown in Fig. 13.

Figure 12b) shows the result of SWS test that was conducted on the landfill at site 100, about 300 m from the margins of the landfill. The ground water level was shallower than 1.5 m from the ground surface, below which soil deposits with N_{SPT} values less than 10 could be found for a thickness of about 5 m. The N_{SPT} values at this point were slightly higher than those measured at the margin of landfill as shown in Fig. 12a). In fact, sand boiling around the site 100 was not significant as compare with the site 93.

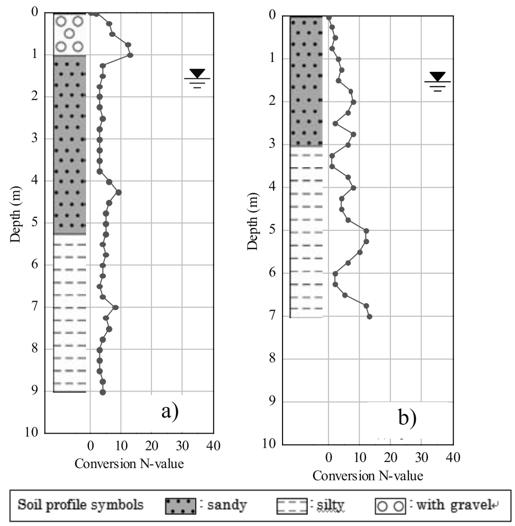

Figure 12 SWS test results (a) sites 93 and b) 100 in Fig. 11)

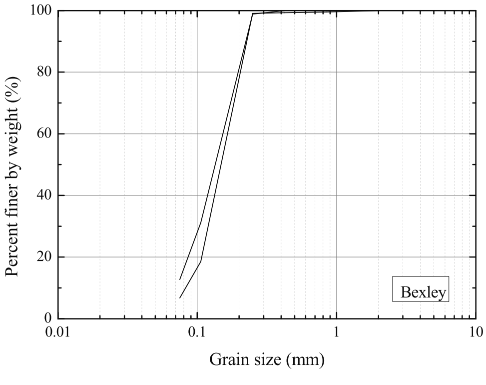

Figure 13 Grain size curves of boiled sands in Bexley area

Liquefaction map in Christchurch city
Based on the survey, the earthquake-induced damages in Christchurch city can be summarized in Fig. 14. The liquefaction-induced damage to the infrastructures including houses could be observed along Avon-river except for business area, while possibility of liquefaction occurrence seems to be limited at the sites that more than 300 m from the river. It should be noted that, the classification of damage in Fig. 14 has not been completed. Further wide-range of investigations is required.

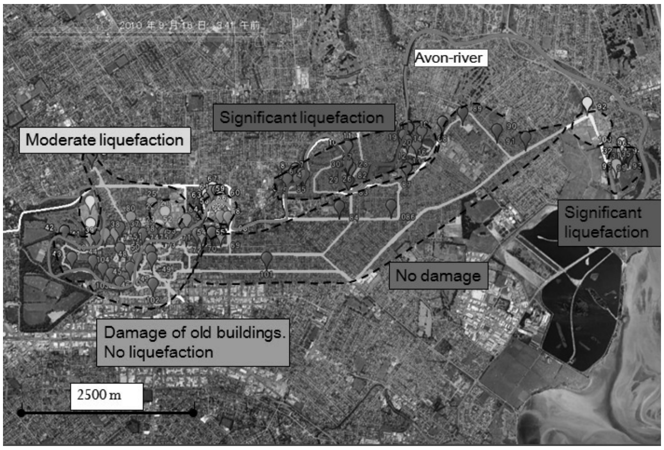

Figure 14 Earthquake-induced damage in Christchurch city on this survey

LIQUEFACTION-INDUCED DAMAGE IN KAIAPOI CITY

Kaiapoi city is located about 15 km north of Cristchurch city and about 4 km west of the coast line. As shown in Fig. 15, a tributary of Waimakariri-river flows through center part of Kaiapoi city. In this survey, significant damage due to liquefaction could be observed at both side of the tributary.

At site 109, a boathouse that is located on the levee suffered from uneven settlement as shown in Photo 13. At site 110, the ground surface of the levee suffered from significant cracking having the maximum opening of 1 m as shown in Photo 14. The groundwater could not be found in the large cracking, and the material of the levee was dense gravelly sandy soils that were not expected to be liquefied. Therefore, it can be considered that the liquefaction occurred in sandy layer beneath the levee and caused above damages. In fact, the sand boiling could be observed at the base of the levee, and the boiled sandy soil was different from the above gravelly soils. The boiled sand that was retrieved at the base of levee was fine sand with D_{50} of 0.15 mm and fines content of 20 % as shown in Fig. 16.

Reportedly, the residential area on the right side of the tributary had been elevated by soil filling about 5 years ago. High damage ratio of houses was observed along the margins of landfill as was seen in Bexley area. Typical damage of house due to liquefaction-induced ground deformation at the margin of filling in this area is shown in Photo 15. The house was caught up in the ground movement, and suffered from significant leaning to the slope side. The boiled sand that was retrieved at this house has fines content of 70 % as shown in Fig. 16. However, it could be liquefied because it has no plasticity.

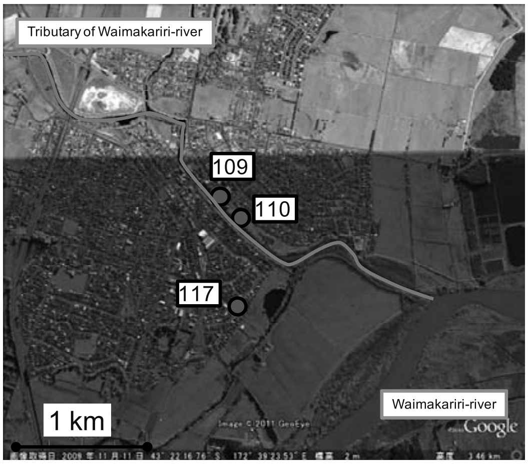

Figure 15　Survey map of Kaiapoi city

Photo 13　Boathouse suffered uneven settlement due to liquefaction (Site 109 in Fig. 15)


Photo 14　Significant cracking and boiled sand could be observed on the levee (Site 110 in Fig. 15)


Photo 15　Damaged house due to liquefaction-induced ground deformation (Site 117 in Fig. 15)

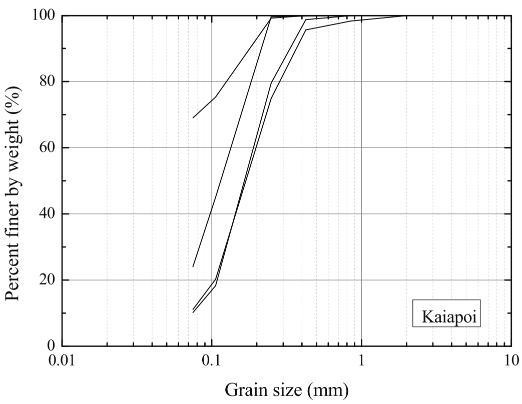

Figure 16　Grain size curves of boiled sands in Kaiapoi city

SUMMARY

The authors conducted damage survey after the 2010 Darfield Earthquake in Christchurch city and Kaiapoi city, New Zealand. The results from the survey can be summarized as follows:

Significant liquefaction occurred in Dallington and Bexley areas in Cristchurch city and Kaiapoi city. It caused severe damage to residences, roads and levees in Dallington area, while the landfill suffered from cracking and deformation in Bexley area in Christchurch city and Kaiapoi city.

By conducting Swedish weight sounding (SWS) tests, subsurface soil conditions with high groundwater table and soft soil deposits were investigated at several sites in Dallington and Bexley areas in Christchurch city.

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