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COMPARISON OF LIQUEFACTION-INDUCED DAMAGE OBSERVED DURING THE 2011 CHRISTCHURCH (NEW ZEALAND) AND 1990 LUZON (PHILIPPINES) EARTHQUAKES

Rolando P. Orense, Dr. Eng, P.E.
Department of Civil & Environmental Engineering
University of Auckland
Auckland, New Zealand

ABSTRACT

Soil liquefaction and associated ground deformations caused extensive damage to residential buildings and lifeline facilities in many areas in Christchurch City (New Zealand) during the 2010 and 2011 Canterbury Earthquakes. Twenty years earlier, the 1990 Luzon (Philippines) earthquake also caused widespread in Dagupan City due to liquefaction. This paper compares the liquefaction-induced damage observed in both earthquakes, with emphasis on the characteristics of the sites affected by liquefaction, the extent of ground deformations observed and the influence of liquefaction-induced settlement and lateral spreading on the built environment. Moreover, cases of successive re-liquefaction observed in soil deposits in Christchurch over a span of nine months are discussed.

1. INTRODUCTION

On 22 February 2011, a magnitude 6.3 earthquake hit the Canterbury region on the South Island of New Zealand. The earthquake has epicentre located in Lyttelton, only 6 km to the southeast of the Christchurch central business district (CBD) with depth of 5 km. This quake, locally referred to as Christchurch Earthquake, occurred following a series of smaller aftershocks over a period of about six months brought about by the M7.1 main shock of 4 September 2010, which has an epicentre located 40 km west of the CBD at a depth of 10 km. In spite of its smaller magnitude, the February 2011 earthquake resulted in more damage to pipelines, transport facilities, residential houses/properties and multi-story buildings in the CBD than the main shock mainly because of the shorter distance to the city and the shallower depth. As of 1 June 2011, 181 casualties were reported (NZP, 2011). Widespread liquefaction and lateral spreading occurred in many areas adjacent to rivers and wetlands throughout the city of Christchurch (see Figure 1a). Liquefaction caused ground subsidence, tilting and settlement of residential houses while lateral spreading induced cracking of roads, footpaths, grounds and residential buildings.

Twenty years earlier, on 16 July 1990, a magnitude 7.8 earthquake was triggered by the movement of the Philippine Fault zone, inflicting damage over an area of about 20,000 km2 in Luzon, the Philippines' largest island. Over 1,600 people were killed and at least 3,000 people were seriously injured during this earthquake, officially called the Luzon Earthquake. Although located about 100 km from the epicentre (see Figure 1b), Dagupan City suffered the most damage due to the liquefaction of loose saturated sand deposit.

Correspondence to: **Rolando P. Orense, Dr. Eng, P.E.**, Department of Civil & Environmental Engineering, University of Auckland, Auckland, New Zealand

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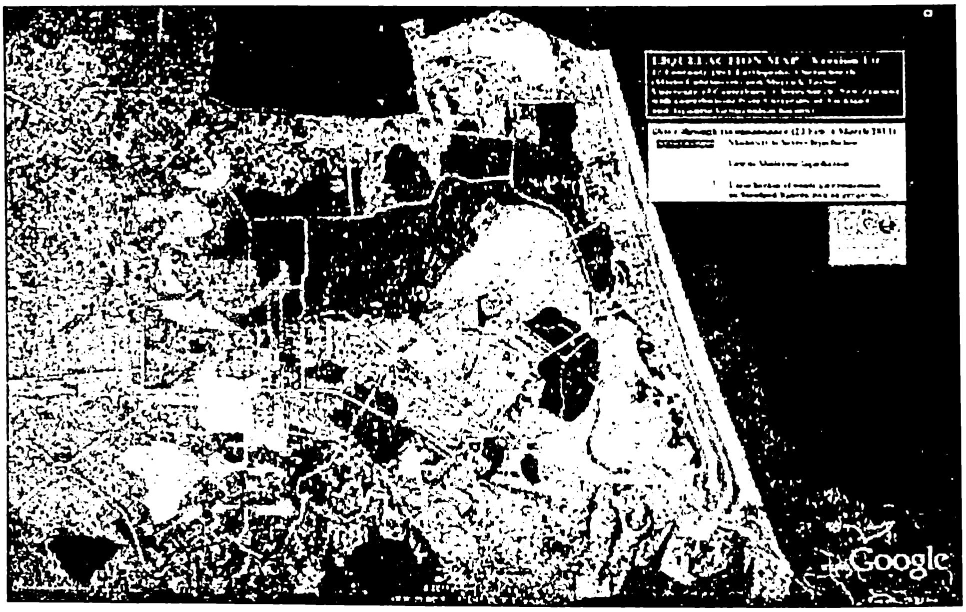
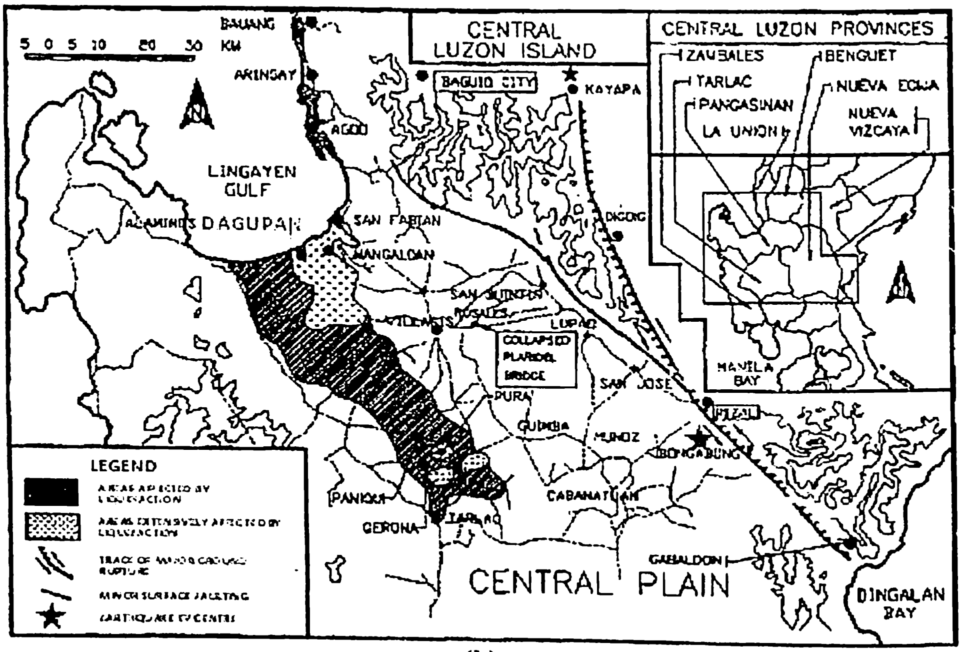


(a)



(b)

Figure 1. (a) Areas of liquefaction (shaded regions) in Christchurch caused by the 2011 Christchurch earthquake (map courtesy of University of Canterbury); (b) Locations where liquefaction was observed during the 1990 Luzon Earthquake (after Punongbayan and Umbal, 1990).

Following both earthquakes, the author performed post-earthquake reconnaissance works in the affected areas focusing on liquefaction-induced damage. A comparison of the liquefaction features observed in the aftermath of both earthquakes is presented in this paper, with emphasis on the characteristics of the sites affected by liquefaction, the extent of ground deformations observed and the influence of liquefaction-induced settlement and lateral spreading on the built environment. Moreover, the instances of re-liquefaction observed in Christchurch following the large aftershocks are described.

2. GEOMORPHOLOGY AND GROUND CONDITIONS

In terms of geologic setting, the cities of Christchurch (and adjacent areas) and Dagupan are not much different – both are located in flat terrain where extensive deposits of loose sand and gravels are present. The areas have many abandoned meanders, wetlands, and ponds, which are susceptible to liquefaction.

2.1 Christchurch City

Most of the city of Christchurch and the town of Kaiapoi (17 km north of Christchurch) are located on Holocene deposits of the Canterbury Plains, New Zealand's largest areas of flat land. The plains have been formed by the overlapping fans of glacier-fed rivers issuing from the Southern Alps, the mountain range of the South Island. 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 two main rivers, Avon and Heathcote, which originate from springs in western Christchurch, meander through the city and act as main drainage system. Figure 2 shows the locations of Avon River and other streams based on a 1850 map of the city superposed on the present map of Christchurch CBD. The meandering nature of the Avon is conspicuous as it flows from the west towards the east. Also, it can be seen that several wetlands and streams criscrossed the future city centre, some of which were later artificially reclaimed as the city grew. Variable foundation conditions as a consequence of a high water table (within 1.0-1.5m deep) and lateral changes from river floodplain, swamp, and estuarine-lagoonal environments, impose constraints on building design and construction (Brown et al., 1995).

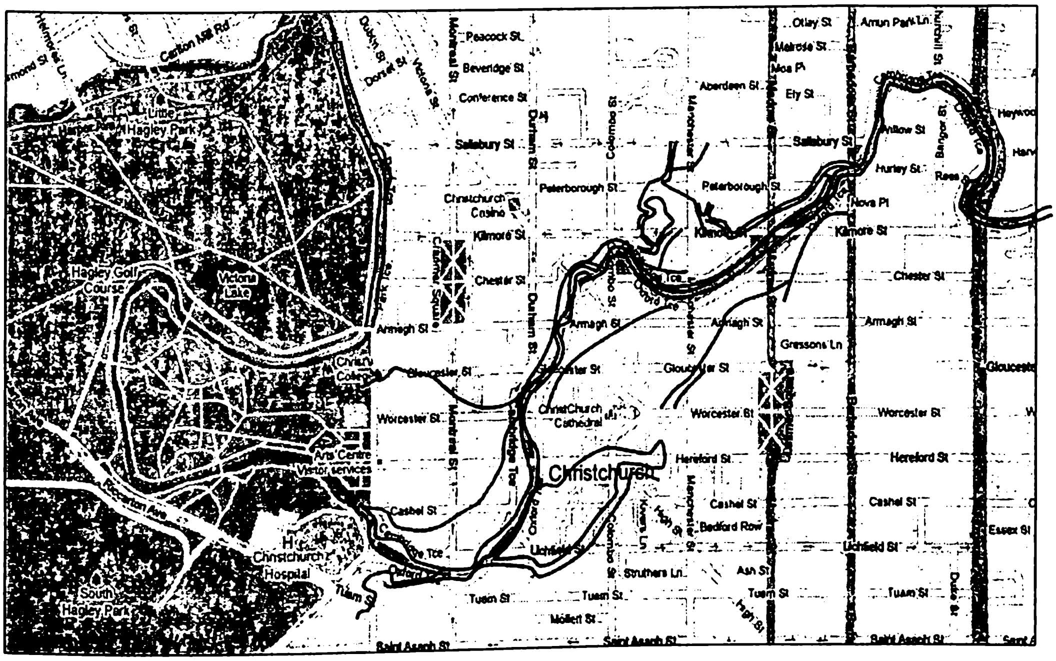


Figure 2. Location of Avon River as well as wetlands and streams in 1850 superposed to the present-day map of the Christchurch CBD.

2.2 Dagupan City

Dagupan City is located in the western coast of Luzon along the southern shores of Lingayen Gulf. Most of the city and adjacent areas facing the gulf are predominantly flat terrain and the soil in this region is made of loose quaternary deposit. Dagupan is situated in the eastern margin of the delta of Agno River, and is traversed by the Pantal River. Due to the meandering nature of Pantal River, the natural lateral shifting in its course resulted in channel abandonment in some areas. This natural land reclamation and the construction of artificial cut-offs account for the loose saturated sediments which make-up most of the city's soil formation. Subsequent soil investigations confirmed that loose deltaic deposits characterize the area, with the top 15~18m composed of silty sand overlying a thick layer of clay (Orense 2003). It was reported that prior to the 1900's, most of Dagupan City's land areas were fishponds and marshlands (see Figure 3). As the area developed and became a commercial centre, most of these swampy areas were reclaimed by filling on the flooded areas where shrimp and milkfish farms were located. The poorly compacted nature of such deposits accounts for the area's high susceptibility to liquefaction (Orense et al. 1991).

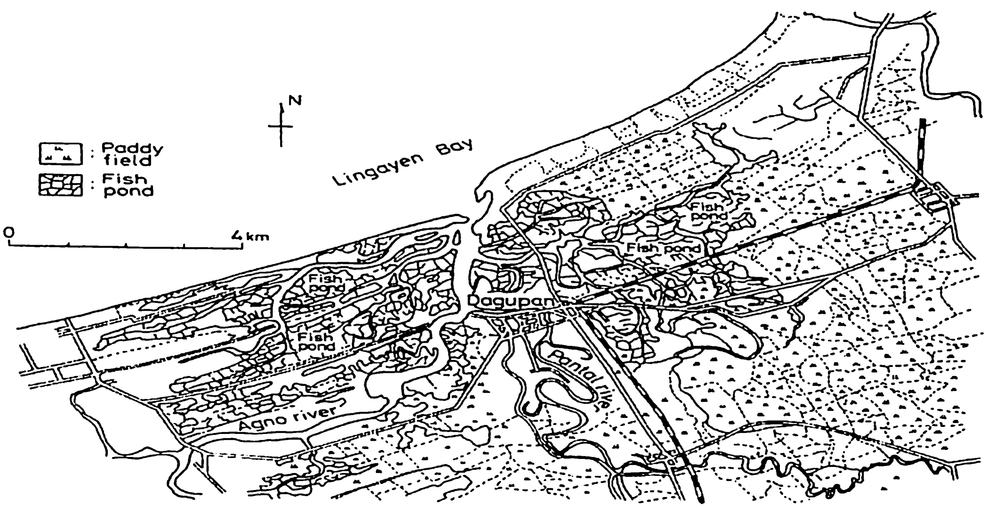


Figure 3. The area of Dagupan City near Lingayen Gulf (after Ishihara et al., 1993)

3. STRONG MOTION CHARACTERISTICS

During the 2011 Christchurch Earthquake, a series of strong motion accelerographs within the GeoNet system was triggered and motions recorded at several stations. The vertical peak ground acceleration (PGA) recorded was 2.2g at Heathcote Valley (about midway between the CBD and the epicentre) whilst in the CBD the PGA was 0.6g–0.8g, and in the eastern suburbs the maximum recorded vertical PGA was 1.9g (GeoNet, 2011). A feature of this earthquake was the very strong vertical component of PGA, which in general was greater than the horizontally components. Because of the shorter distance to the epicentre, the acceleration records in this earthquake have higher frequency and shorter duration time as well as larger amplitude in comparison with the ones recorded in 4 September 2010 (Yamada et al. 2011).

During the 1990 Luzon Earthquake, no strong motions were recorded. The reconnaissance team of the Japan Society of Civil Engineers roughly estimated the magnitudes of accelerations on the basis of observed performances of rigid objects such as concrete fences or benches. In Baguio City, where landslides and collapsed buildings occurred, the intensity of the main shaking was inferred to be in the order of 0.4g. Sato (1991) estimated the magnitude of acceleration in Dagupan City to be 0.2-0.3g.

4. FEATURES OF LIQUEFACTION-INDUCED DAMAGE

4.1 Christchurch City

Although structural failure of 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. Liquefaction occurred in areas which are known to have high potential to liquefy – former river channels, abandoned meanders, wetlands, and ponds. Immediately following some of the largest aftershocks from the M7.1 earthquake, liquefaction re-occurred in some of these areas. During the M6.3 earthquake, liquefaction was more widespread and vents continued to surge during the aftershocks immediately following this event. The impact of sand boils and cracks caused by lateral spreading was that parts of the eastern suburbs were inundated with sand and silt – in places there were layers of ejected soil that was many tens of centimetres thick.

Liquefaction and lateral spreading were extensive in areas adjacent to Avon River, which follows a meandering course through Christchurch from its source in the west through the CBD. Many buildings, such as the 5-storey Trade Centre Building in the CBD shown in Figure 4(a), sank and tilted as a result of the loss in bearing capacity of the foundation ground. Geotechnical investigations indicated that virtually all buildings in the central business district are on shallow foundations, with a several high-rise structures, such as the Forsyth Barr and Price Waterhouse buildings, are on of Colombo are on raft foundations (McCahon 2011). All this area is underlain with shallow gravel to 8 – 10m depth, over sand (dense to very dense) below 12 – 15m and then first gravel aquifer at 22 – 23m. Outside this area, the gravel disappears and many larger and more recent buildings are supported by pile foundations. Ground conditions are highly variable and there is shallow gravel in places with shallow foundations.

(a) (b)

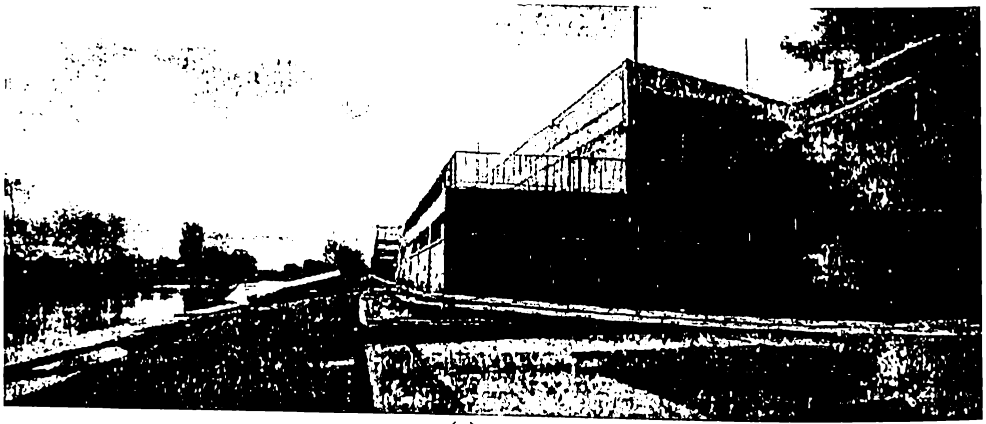
Figure 4. Settlement of reinforced concrete buildings:
(a) 2011 Christchurch Earthquake; and (b) 1990 Luzon Earthquake.

(a) (b)

Figure 5. Uneven settlement and tilting of structures:
(a) 2011 Christchurch Earthquake; and (b) 1990 Luzon Earthquake.

In the suburb of Bexley, located southeast of Christchurch CBD, many houses in the southern portion of the area underwent non-uniform settlement due to liquefaction (see Figure 5a). The area was formerly a swamp and formed part of the Bexley wetlands. It has been reclaimed in the late 1990s by filling the area and the subdivision was built over it. Interviews with homeowners indicate that the area was fairly new, with some houses built as recent as five years ago (Orense et al. 2011).

Lateral spreading associated with soil liquefaction resulted in large permanent lateral displacements in the order of 1-3.5 m in many areas, with large ground cracks of about 0.5-1.5 m wide running through residential properties. The Avon Rowing Club building, shown in Figure 6(a), underwent severe damage due to large lateral ground movements towards the river. Along Bassett Road, the abutment of a bridge tilted (Figure 7a) as a result of liquefaction-induced lateral spreading.



(a)

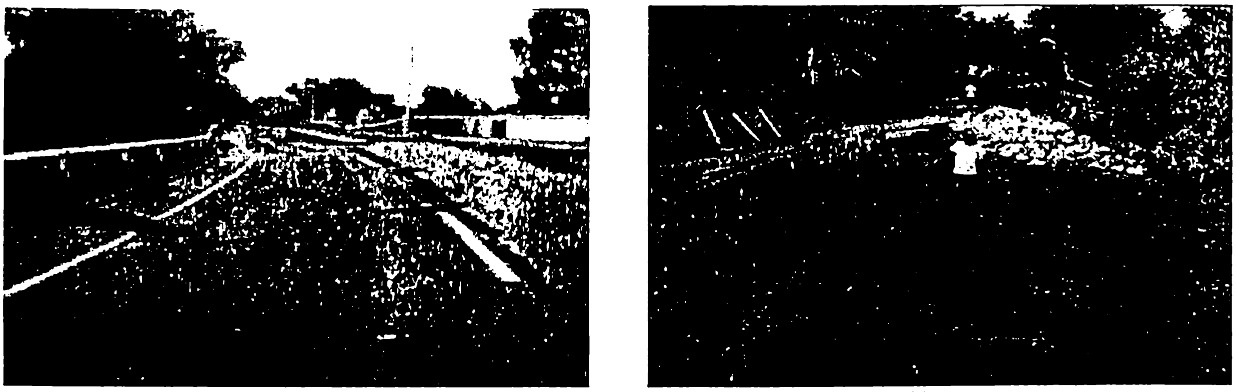
(b)

Figure 6. Damage to structures due to lateral spreading:
(a) 2011 Christchurch Earthquake; and (b) 1990 Luzon Earthquake.

Road collapse, especially adjacent to the waterways, was also a familiar sight after the earthquake. For example, a portion of Fitzgerald Avenue adjacent to the Avon River collapsed due to the liquefaction of the foundation ground (see Figure 8a). Other manifestations of soil liquefaction observed during the Christchurch Earthquake include uplift of buried structures such manholes and damage to pipelines. In addition, significant volume of sand ejecta was evident in the areas affected by liquefaction and lateral spreading.

(a) (b)

Figure 7. Damage to bridges due to lateral spreading:
(a) 2011 Christchurch Earthquake; and (b) 1990 Luzon Earthquake.



(a) (b)

Figure 8. Damage to roads:
(a) 2011 Christchurch Earthquake; and (b) 1990 Luzon Earthquake.

4.2 Dagupan City

In Dagupan City, close to around 500 buildings and residential houses underwent severe settlements (Figure 4b), as well as varying amounts of tilting (Figure 5b), as a result of the loss in strength of the underlying soil. Except for one, no building in the affected area was supported by piles, and therefore, no resistance was possible against subsidence after liquefaction. Ironically, earthquake shaking did not destroy buildings in the area nor caused any structural damage.

Lateral spreading in the order of about 3-5 m occurred along the banks of Pantal River. Large lateral displacements and flow failures of the riverbanks, as shown in Figure 6b), account for the damage to several buildings and other structures built near the river. Magsaysay Bridge collapsed as a result of the lateral movement of the opposing banks of Pantal River where the bridge was abutted (Figure 7b). At the same time, the bridge piers sank and tilted towards the centre of the river as a result of the liquefaction of the river bed. Several kilometers of roads became virtually impassable due to cracks in road pavements as a consequence of general subsidence and lateral displacements in the area (Figure 8b).

Several buried structures, such as gasoline tanks, septic tanks and buried pipes, were uplifted due to the buoyant force exerted by the liquefied soil. Immediately after the earthquake, the whole town was buried in dark-grey mud and water ejected from fissures in the ground.

5. SAND BOILS AND ZONES OF LIQUEFACTION

5.1 Properties of ejected sands

After both earthquakes, the affected areas were covered by ejected water and sand boils. In all places visited in Christchurch after the 2011 earthquake, the appearance of the ejected sands as a result of liquefaction were very similar, typically grey to dark grey in colour and consisting of very fine sands. Samples were taken at various locations and the grain size distributions were obtained by sieving. Figure 9 shows the grain size distribution curves of soil samples taken at AMI Stadium, Kaiapoi, Bexley, Porritt Park, Avonside and St Martins. It can be observed that the distributions of grain sizes were fairly similar, and they plot over a narrow range. The fines contents were low, ranging from 10-25%. Also indicated in the figure is the range of grain sizes obtained in Dagupan City, where the sand boils which erupted from cracks in the ground were generally black to dark grey in colour (Orense et al., 1991). It can be seen that the Dagupan sands are poorly graded with very few fines contents (<10%), when compared to Christchurch soils.

Also shown in the figure are the range of grain size distributions of sands which are deemed to have high possibility of liquefaction (A) and possibility of liquefaction (B). These ranges were obtained from past historical earthquakes in Japan and stipulated in the Japanese design code for port and harbour facilities (PHRI 1997). Note that there are problems associated with the use of compositional criteria as a measure of liquefaction susceptibility because there are no generally accepted criteria and the difference between natural and reclaimed deposits. Nevertheless, using these criteria, it can be seen that the ejected sands obtained at different locations in Christchurch and Dagupan can be said to have high potential to liquefy.

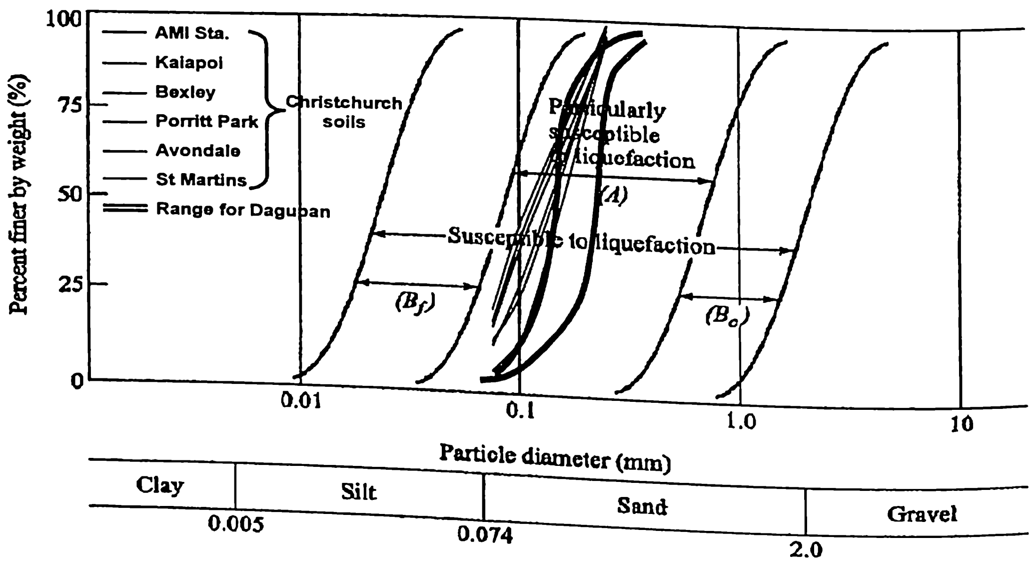


Figure 9. Grain size distribution curves of ejected sands from different sites in Christchurch and Dagupan.

5.2 Zones of liquefaction

5.2.1 Christchurch

Based on post-earthquake investigation, liquefaction-induced damages in Christchurch during the 2011 Christchurch Earthquake were centred in areas such as former river channels, abandoned meanders, wetlands, and ponds. In the CBD, liquefaction was extensive in alluvial fan sites adjacent to river channels, such as the Avon River. In Christchurch, many sites adjacent to the Avon River liquefied and underwent lateral spreading (see Figure 1a). Earthquake shaking also triggered liquefaction of the loose reclaimed subdivision in Bexley, and this resulted in ground settlement and lateral spreading.

After the earthquake, Swedish weight sounding (SWS) tests were performed at numerous locations in Christchurch and Kaiapoi. In SWS test, a screw-type tip called screw point is penetrated by increasing step-wise the static load, Wsw, until it reaches a total of 100 kg. Further penetration is carried out by manually rotating the screw rod while applying the 100 kg static weight and the number of half-revolutions required for one metre of penetration, Nsw, is obtained (JSA, 1995). Typical results of SWS tests conducted in Christchurch, expressed in terms of N_{sw}, are shown in Figure 10. It can be seen that zones where penetration is low (loose deposit, N_{sw}<100) consist of sandy to silty soil, with depths ranging from 5-7m.

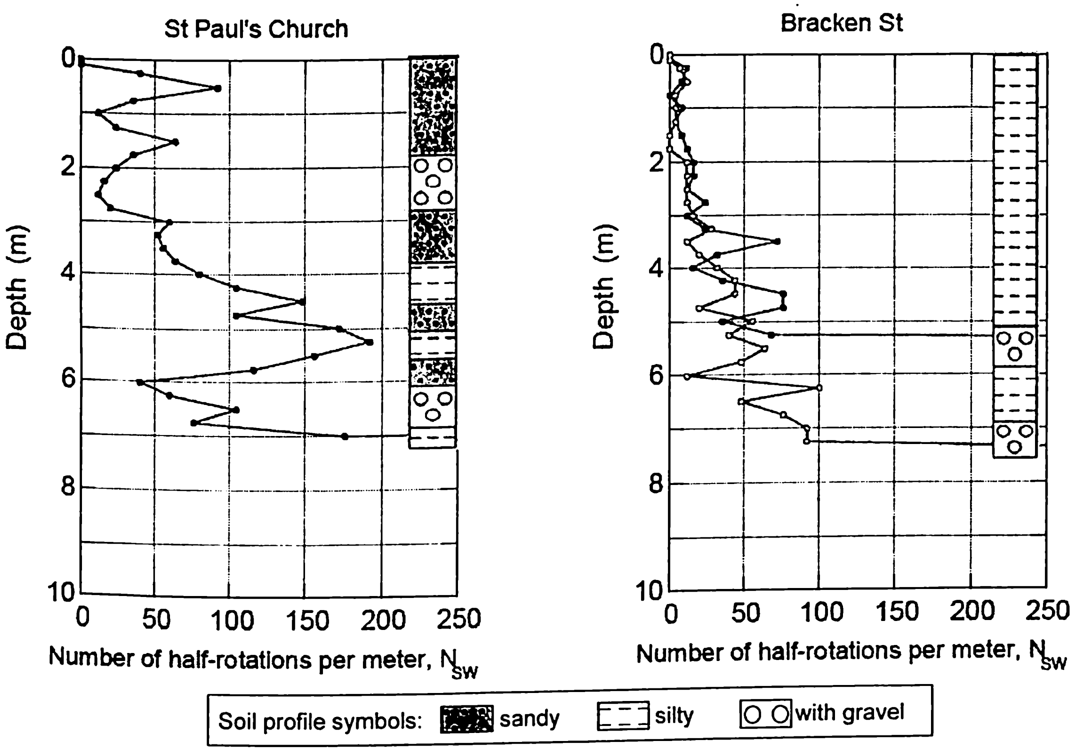
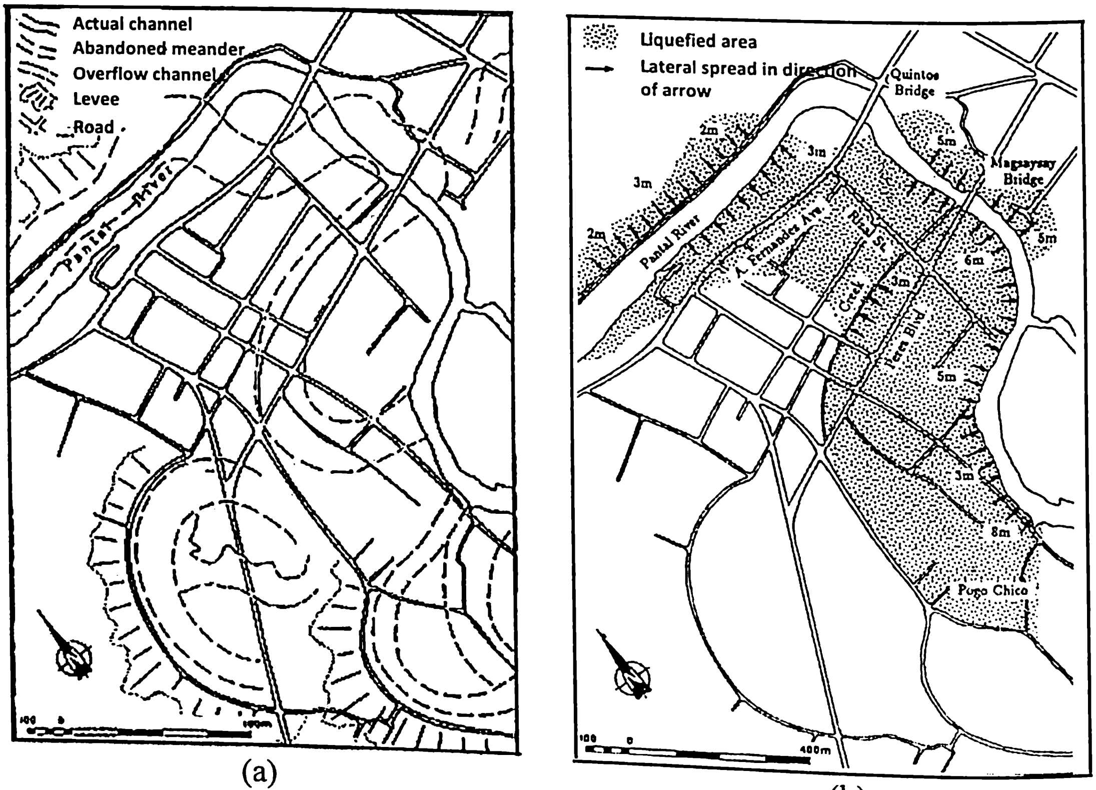


Figure 10. SWS test results in Dallington and Avonside following the Darfield Earthquake (after Cubrinovski and Orense, 2010).

5.2.2 *Dagupan City*

Liquefaction-induced damage observed in Dagupan City correlated very well with the geomorphology of the site. The locations of former river channels within the city are shown in Figure 11(a). The shift of the river courses took place for a long geologic era, and therefore the abandoned portions of the river channel are not man-made fills, but were created probably by transport of sediments during flooding and inundation (Orense, 2003). The area of old channels is composed of loose deposits of silts and sands, and thus susceptible to liquefaction during earthquakes. On the other hand, the locations where signs of liquefaction, such as sand boils and fissures, are shown in Figure 11(b). Note the strong correlation between the locations of reclaimed areas and the damage distribution.

SWS tests were also performed at damaged areas in Dagupan City after the event, and typical results are plotted in Figure 12. It can be seen that there exists a layer to a depth of about 6-7m where the resistance to penetration is low (N_{sw}<100), indicating loose deposits which are susceptible to liquefaction.



(a) (b)

Figure 11. (a) Locations of abandoned meanders in Dagupan (after Punongbayan and Torres, 1990); (b) areas where liquefaction-induced damage was observed (after Orense et al., 1991).

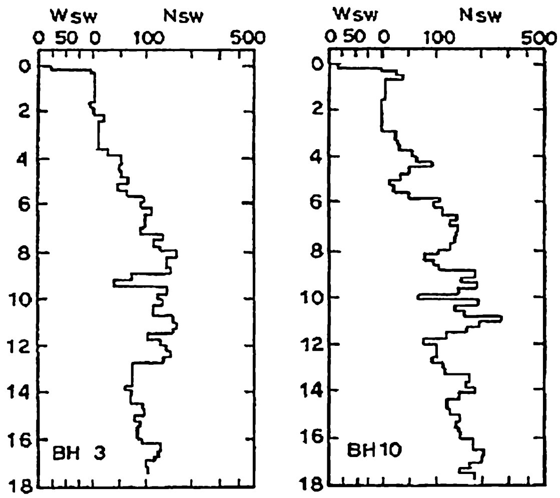


Figure 12. Typical results of SWS tests in Dagupan City (after Ishihara et al., 1993)

6. CASES OF RE-LIQUEFACTION IN CHRISTCHURCH

As mentioned earlier, liquefaction occurred in many areas in Christchurch and Kaiapoi following the 4 September 2010 main shock. More detailed description of damage is provided by Cubrinovski et al. (2010) and Orense et al. (2011). The areas most severely affected by liquefaction and lateral spreading were close to waterways (rivers, streams, swamps). Evidence of massive liquefaction and large surface distortion in areas adjacent to the Avon River were observed and sand boil ejecta covered many areas, about 30 cm thick in places. The potable water and sewer systems became out of service for quite some time. Widespread liquefaction occurred north of the Kaiapoi River affecting a large number of residential houses in the town of Kaiapoi, Some residents reported geysers appearing in their backyard following the earthquake, often forming a small pond near the houses that remained for several days after the event. The severe liquefaction also led to large settlement of houses, including differential settlement that resulted in structural and foundation damage. The large ground distortion, cracks and fissures in the ground also caused significant damage to buried lifelines. This area of Kaiapoi also liquefied during the 1901 Cheviot earthquake (Berrill et al., 1994).

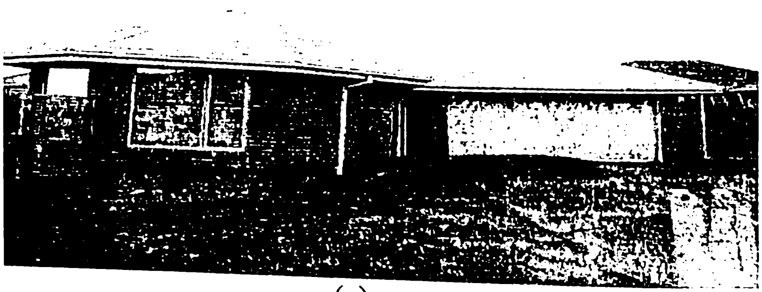
Some suburbs, such as Hoon Hay located southwest of the city, re-liquefied following the M5.0 aftershock in 19 October 2010 whose epicentral distance was about 8 km. As a result, large amount of sand ejecta were observed in several residential properties and in a park. Many residents in the area reported that houses suffered additional damage during the aftershock, including widening of the cracks in walls and foundations due to lateral movement of foundation soils (Cubrinovski and Orense 2010). This area of Hoon Hay heavily liquefied during the mainshock of the Darfield earthquake.

When the M6.3 aftershock occurred in 22 February 2011, liquefaction occurred again, this time more widespread than that observed following the main shock. It is worthy to note that while major liquefied sites in the September 2010 earthquake were concentrated along the Avon River, liquefaction was observed in the 2011 earthquake across a wider areas, i.e., not only in the eastern suburbs but in the north and in the CBD as well. In some areas where liquefaction was not observed during the 2010 earthquake, the ground shaking may have loosened the soil but did not cause sufficient pore pressure build-up to induce liquefaction; then, with such disturbance and with no enough time to reconsolidate, the ground may have been primed up for liquefaction to occur easily during the 2011 earthquake.

Then, in 13 June 2011, a series of aftershocks, the largest of which were M5.6 and M6.3 occurring 80 minutes apart , rattled the city. These aftershocks again caused extensive liquefaction in many parts of Christchurch. Streets were again flooded with water and ejected sands, reminiscent of what happened immediately after the February 2011 earthquake. Such re-occurrence of liquefaction indicates that the soil deposits in the area were still loose even after the intense shaking they have been subjected to over the last nine months.

(a)

(b)



(c)

Figure 13. Comparison of damage to a house in Bexley: (a) after 4 September 2010 earthquake; (b) after 22 February 2011 earthquake; and (c) after 13 June 2011 earthquake.

Figure 13(a) shows a house in Seabreeze close in Bexley, which was damaged following the September 2010 earthquake. Note the volume of ejected materials adjacent to the house, with thickness of about 20cm. Following the February 2011 earthquake, more sand boils were observed in the area (about 55cm thick), with the house undergoing more tilt as a result of uneven settlement, as shown in Figure 13(b). When the site was again visited following the 13 June aftershock, ejected sands were again observed in the vicinity of the house, with thickness of about 15cm (see Figure 13c).

Field measurements, such as standard penetration and cone penetration tests, have been performed in several sites in Christchurch following the September 2010 and February 2011 earthquake. Except for the change in the level of the ground surface, the strength-depth profiles were similar in many places (Van Ballegooy, 2011). This indicates that the February earthquake did not result in significant densification of the deposits.

Ten days following the 13 June aftershocks, the New Zealand government issued an announcement that all greater Christchurch land has been divided into four residential zones depending on the degree of damage and the rebuilding process involved (NZ Herald 2011). In areas classified as "red zone", i.e., zones where significant and extensive area-wide land damage occurred and where the repair would be disruptive and protracted for landowners, the government will offer to buy the properties off the owners at an estimated cost of up to NZ$635 million. The red zone, consisting of approximately 5,000 homes, coincides with the highly liquefiable regions adjacent to the Avon River. The orange zone, with about 10,000 residential houses, will require further investigation.

7. CONCLUDING REMARKS

Extensive liquefaction and lateral spreading were observed following the two major earthquake events – the sequence of Canterbury earthquakes in 2010-2011 and 1990 Luzon Earthquake. In both cases, liquefaction occurred in areas which are known to have high potential to liquefaction - former river channels, abandoned meanders, wetlands, and ponds. These areas are characterized by the presence of loose saturated sandy deposits, which are susceptible to liquefaction. In other words, liquefaction during these earthquakes occurred in sites which are expected to liquefy. As a result, liquefaction caused extensive damage to residential houses and other infrastructures through lateral spreading, ground subsidence, and differential settlements. Although Dagupan City has rebounded a few months after the catastrophe with the cessation of seismic activity, the re-liquefaction of many sites in Christchurch following continuous aftershocks has highlighted the high susceptibility of soil deposits to liquefaction. This has presented a very challenging problem not only to the local residents and government leaders but to the geotechnical engineering profession as well.

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