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Liquefaction-Induced Damage in The2010-2011 Christchurch (New Zealand) Earthquakes

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LIQUEFACTION-INDUCED DAMAGE IN THE 2010-2011 CHRISTCHURCH (NEW ZEALAND) EARTHQUAKES

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ABSTRACT

A series of strong local earthquakes hit the city of Christchurch (New Zealand) in the period between September 2010 and December 2011. The earthquakes produced strong ground motions, and were very damaging. The magnitude 6.2 22 February 2011 earthquake was particularly devastating causing heavy damage to the city and 185 fatalities. The earthquake caused widespread and severe liquefaction over approximately one third of the city area which arguably was the most severe and extensive liquefaction in native soils on record. This paper presents an overview of the liquefaction-induced damage to the land, buildings and infrastructure caused by the 2010-2011 earthquakes.

INTRODUCTION

In the period between September 2010 and December 2011, Christchurch, the second largest city in New Zealand, and its surroundings were hit by a series of strong local earthquakes (the Canterbury Earthquake Sequence). The causative faults of the earthquakes were very close to or within the city boundaries thus generating very strong ground motions and causing tremendous damage throughout the city. The 22 February 2011 earthquake (Christchurch earthquake) was particularly devastating. The earthquake caused 185 fatalities, collapse of two multi-storey reinforced concrete buildings, collapse or partial collapse of many unreinforced masonry structures including the historic Christchurch Cathedral. The Central Business District (CBD) of Christchurch was practically lost with majority of its 3,000 buildings being damaged beyond economic repair. Rock falls and slope/cliff instabilities in the Port Hills affected significant number of residential properties in the south-eastern part of the city, but the most prominent geotechnical feature of the earthquakes was the widespread and very severe liquefaction in the eastern suburbs of Christchurch. The liquefaction affected 60,000 residential buildings (properties), large number of CBD buildings, and the lifelines and infrastructure over approximately one third of the city area. The total economic loss caused by the 2010-2011 Christchurch earthquakes is currently estimated to be in the range between 25 and 30 billion NZ dollars (or about 15% to 18% of New Zealand's GDP).

After each major earthquake, comprehensive field investigations and inspections were conducted to document the liquefaction-induced land damage and lateral spreads, and their impacts on buildings and infrastructure. In addition, the ground motions generated by the earthquakes were recorded by approximately 15 strong motion stations within (close to) the city boundaries providing and impressive wealth of data, records and observations on the performance of ground and various structures during this unusual sequence of strong local earthquakes repeatedly jolting the city and testing the resilience of both its built environment and residents.

This paper provides an overview of the liquefaction-induced damage to buildings and infrastructure caused by the 2010-2011 earthquakes. A brief overview of the earthquakes and ground conditions of Christchurch are first given, followed by detailed liquefaction maps summarizing the observations on the extent and severity of liquefaction across Christchurch including multiple episodes of severe re-liquefaction. Liquefaction-induced damage to residential houses, CBD buildings, pipe networks of the potable water and waste water systems, and bridges is then described illustrating the key features of the damage and impacts of liquefaction.

CANTERBURY EARTHQUAKE SEQUENCE

Within a period of 16 months (September 2010 to December 2011), Christchurch was hit by six significant earthquakes all generated by local faults in proximity to the city: 4 September 2010 (M_w=7.1), 22 February 2011 (M_w=6.2), 13 June 2011 (M_w=5.3 and M_w=6.0) and 23 December 2011 (M_w=5.8 and (M_w=5.9) earthquakes. As indicated in Fig. 1, the causative faults (or source areas) of the earthquakes were very close to or within the city boundaries thus generating very strong ground motions and causing tremendous damage throughout the city. The first earthquake (4 September 2010, Darfield earthquake) occurred in the Canterbury plains, on a system of faults located approximately 20-30 km west of Christchurch. The sequence of earthquakes then propagated to the south, south-east and east of the city through a system of separate but apparently interacting local faults within the city boundaries. The second in the series was the 22 February 2011 earthquake (Christchurch earthquake), which was the most devastating earthquake, and the only one in the sequence causing fatalities. Note that on 13 June 2011 actually two earthquakes occurred within 80 minutes interval, and exactly the same scenario of two earthquakes occurring 80 minutes apart was repeated on 23 December 2011. While such sequence of events within a source zone is not unusual from a seismological perspective, the Canterbury earthquake sequence was unusual in a sense that it repeatedly subjected the built environment and residents of a major city to damaging earthquakes and severe ground shaking. In addition to the huge devastation caused by the Christchurch earthquake, the cumulative impacts of these earthquakes on the infrastructure and post-earthquake recovery of an urban center are of profound significance.

Figure 2 shows the recorded ground accelerations during these six earthquakes at a strong motion station in Hagley Park (CBGS), located just few hundred meters west of the CBD. While strong ground motions were generated in all six earthquakes, the ground motions generated by the 22 February 2011 (Christchurch) earthquake were particularly intense and in many parts of Christchurch substantially above the ground motions used to design the buildings in Christchurch (Bradley and Cubrinovski, 2011).

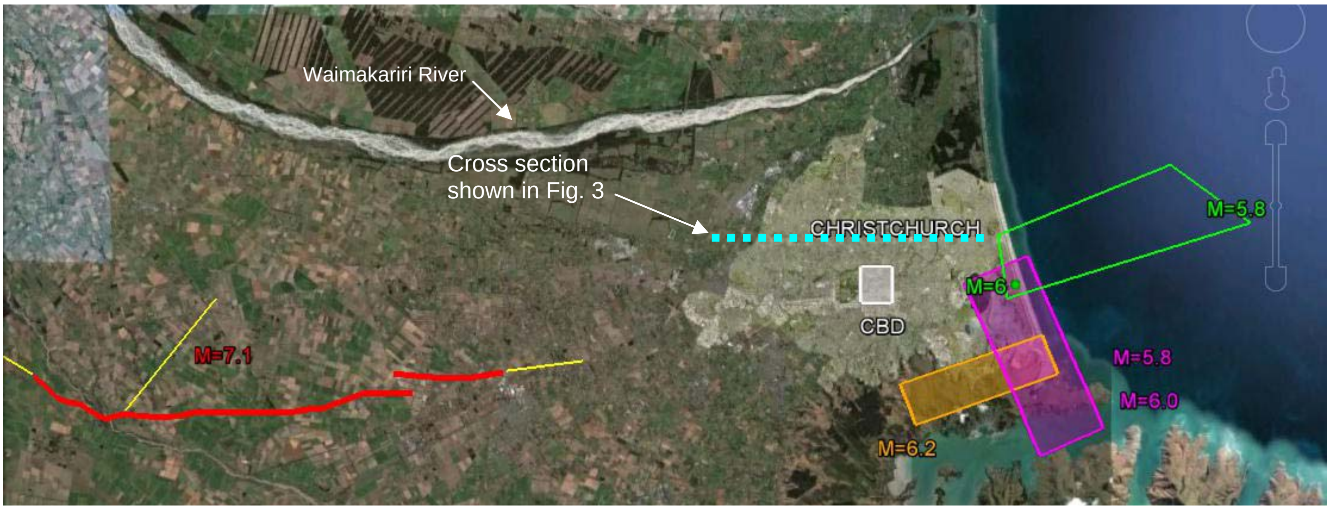

Fig. 1. Causative faults (source areas) and magnitudes of the 2010-2011 Christchurch earthquakes (4 SEP 2010 EQ: red line = trace of surface rupture; yellow lines = subsurface rupture; 22 FEB 2011 EQ: orange area = fault area projection; 13 June 2011 EQ: magenta area =fault area projection; 23 DEC EQ: green line = general source area; CBD =white square).

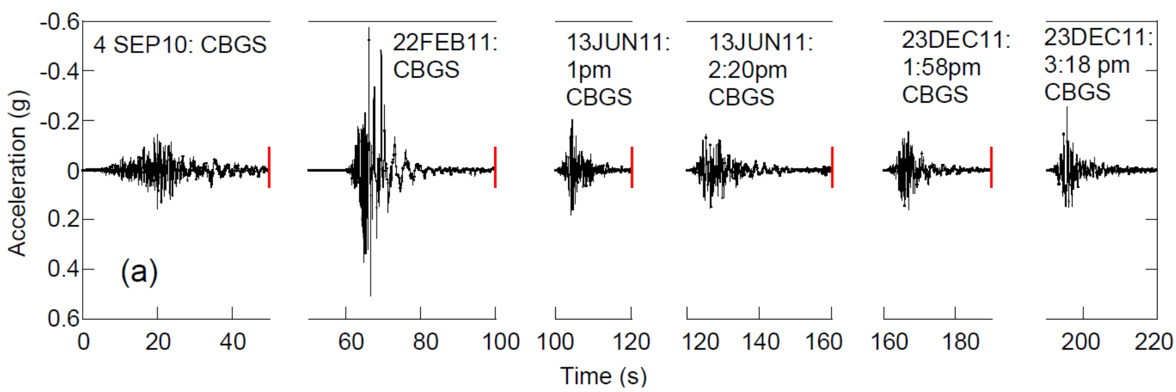

Fig. 2. Recorded accelerations at CBGS (a strong motion station just west of the CBD) during the six earthquakes

LOCAL GEOLOGY AND GROUND CONDITIONS

Christchurch is located on deep alluvial soils of the Canterbury Plains, except for its southern edge, which is located on the slopes of the Port Hills of Banks Peninsula. The plains are built of complex inter-layered soils deposited by eastward-flowing rivers from the Southern Alps into the Pacific ocean. The plains cover an area approximately 50 km wide by 160 km long, and consist of very thick soil deposits. At Christchurch, surface postglacial sediments have a thickness between 15m and 40m and overlie at least 300-500m thick sequence of gravel formations interbedded with sand, silt, clay and peat layers. These inter-layered formations of gravels and fine-grained soils form a system of gravel aquifers, with artesian (elevated) groundwater pressures.

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 floodplain. Since European settlement in the 1850s, extensive drainage and infilling of swamps has been undertaken (Brown and Weeber, 1992). The Waimakariri River regularly flooded Christchurch prior to stopbank construction and river realignment. The location of present day Waimakariri River is indicated in Fig. 1.

Canterbury has an abundant water supply through rivers, streams and very active groundwater regime including rich aquifers. It is estimated that over 10,000 wells have been sunk within the Christchurch urban area since 1860s (Brown and Weeber, 1992). 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. Relatively recent but numerous episodes of flooding by the Waimakariri River, and reworking of soils by the spring fed waters of Avon River and Heathcote River until they were channelized, particularly influenced and characterized the present day surficial soils.

The shallow soils in Christchurch comprise alluvial gravels, sands and silts (in the western part of Christchurch) or estuarine, lagoon, beach, dune, and coastal swamp deposits of sand, silt, clay, and peat (in the eastern suburbs). Note that approximately 6,500 years before present, the coastline was located about 1 km west of CBD (Brown and Weeber, 1992). These surface soils overlie the Riccarton Gravel, which is the uppermost gravel of an older age (14,000 – 70,000 years old) and also the topmost aquifer with artesian pressures. The thickness of the surface soils or depth to the Riccarton Gravel is indicated in Fig. 3 along an east-west cross section through the city. The thickness of the surface alluvial soils is smallest at the west edge of the city (approximately 10 m thick) and increases towards the coast where the thickness of the Christchurch formation reaches about 40 m.

As a consequence of the abundant water supply through open channels, aquifers and low-lying land near the coastline, the groundwater level is relatively high across the city. The water table is about 5 m deep in the western suburbs, becoming progressively shallower eastwards, and approaching the ground surface near the coastline, as indicated in Fig. 3. To the east of CBD, generally the water table is within 1.0 m to 1.5 m of the ground surface. Seasonal fluctuations of the groundwater level are relatively small, within 0.5 m to 1.0 m. Data on age of the soils based on radiocarbon dating of samples from the Christchurch (Brown and Weeber, 1992) suggest that the shallow soils within the top 10 metres are less than 4000 years old, and some are only few hundred years old (Cubrinovski and McCahon, 2011), which makes them vulnerable to liquefaction.

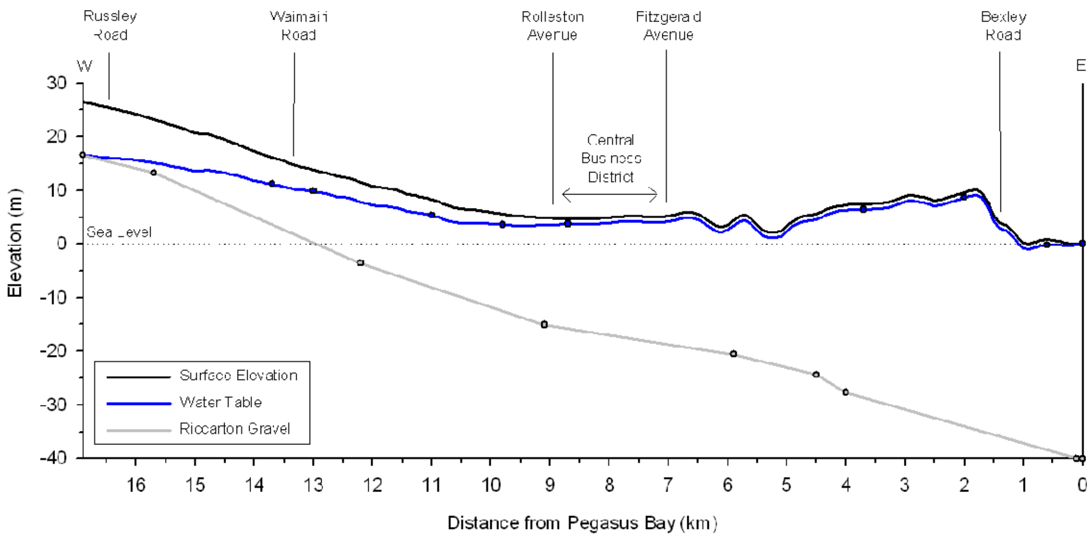

Fig. 3. General geologic profile of shallow Christchurch soils indicating thickness of recent alluvial soils (depth to Riccarton Gravel) and water table depth along an east-west cross section (indicated in Fig. 1)

OBSERVED SOIL LIQUEFACTION

The 4 September 2010 M_w=7.1 Darfield earthquake produced a maximum horizontal peak ground acceleration (PGA) of 0.24 g in the CBD, and the PGA decreased generally with distance downstream along the Avon River. The M_w=6.2, 22 February 2011 Christchurch earthquake which was about 4 km from the CBD along the southeastern perimeter of the city in the Port Hills (Fig. 1) generated much higher PGAs in the CBD, in the range between 0.37 g and 0.52 g. The peak ground velocities produced by this earthquake were in the range between 30 cm/s and 70 cm/s (Bradley and Cubrinovski 2011). In addition to the high PGAs during the 22 February 2011 earthquake (PGA = 0.37-0.52 g), the CBD buildings were subjected to significant PGAs in the range of 0.16-0.27 g in five additional events. In the eastern suburbs, the PGAs reached 0.63-0.67g in the February earthquake and 0.08-0.34g in the other five earthquakes.

For the shallow part of a deposit, the variation in the recorded PGAs correlate closely with the variation in the cyclic stress ratio (CSR), which is used as a proxy for the seismic demand in the simplified liquefaction evaluation (e.g. Youd et al., 2001). Magnitude scaling factors can then be applied to adjust each calculated CSR value (for each earthquake event) to an equivalent value for a reference M_w=7.5 earthquake ($CSR_{7.5}$). For the CBD strong motion stations, the highest adjusted $CSR_{7.5}$ values of 0.14-0.22 were obtained for the M_w=6.2, 22 February 2011 Christchurch earthquake, which were about 1.6 times the corresponding CSR-values from the M_w=7.1, 4 September 2010, Darfield earthquake. In the eastern suburbs where repeated liquefaction occurred during multiple events, the adjusted $CSR_{7.5}$ values at the water table were in the range of 0.26-0.28 for the February event and 0.06-0.12 for the other significant earthquakes.

The earthquakes caused repeated liquefaction through the suburbs of Christchurch and its Central Business District. The liquefaction was particularly severe and widespread during the 22 February event (covering approximately one third of the city area) causing extensive damage to residential houses/properties, commercial buildings, lifelines and infrastructure. Figure 4 indicates areas within Christchurch that liquefied during the 4 September 2010, 22 February 2011 (Cubrinovski and Taylor, 2011) and 13 June 2011 earthquakes (Cubrinovski and Hughes, 2011). The extent of liquefaction in the 23 December 2011 earthquake was similar to that of the June 2011 earthquake, though it was more pronounced in Parklands (north-east part of Christchurch) due to its proximity to the causative fault. The repeated liquefaction was often quite severe and some residents reported that the liquefaction severity increased in subsequent events.

The liquefaction was particularly extensive and damaging along the meandering loops of Avon River, from the CBD to the Avon-Heathcote Estuary, where multiple episodes of severe liquefaction occurred during the earthquakes. In areas close to waterways (rivers, streams), the liquefaction was often accompanied by lateral spreading. The liquefaction caused tremendous damage to properties and lifelines in the residential suburbs of Christchurch. Approximately 60,000 residential buildings and properties were affected by liquefaction; 20,000 of those were severely affected by liquefaction, out of which about 7,500 residential properties in the “red zone” along the Avon River were deemed uneconomic to repair and were abandoned (New Zealand Government, 2011). In the worst affected areas, combined effects of liquefaction and lateral spreading resulted in substantial ground subsidence and significant increase in the exposure to flooding hazards, which was found very difficult to deal with in a cost-effective way. More details on the characteristics and impacts of lateral spreading can be found in Cubrinovski et al. (2012).

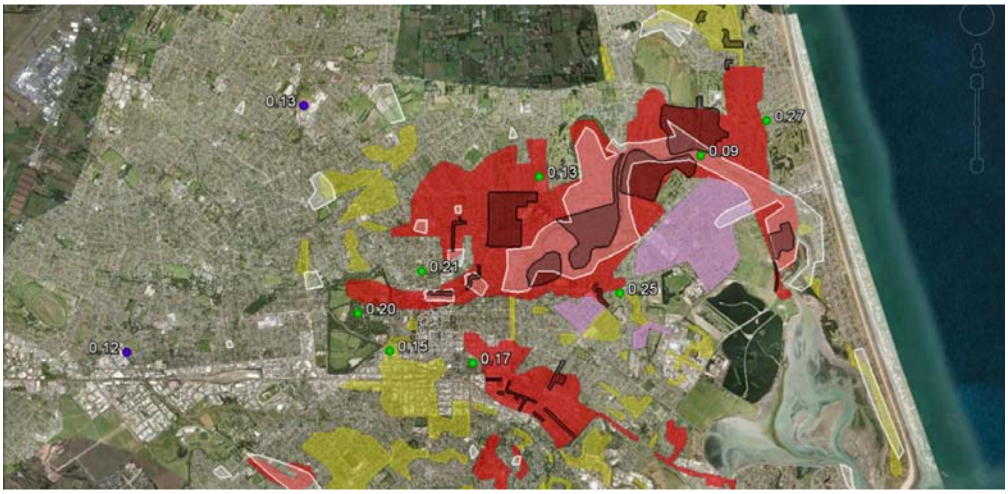

Fig. 4. Liquefaction maps indicating areas of observed liquefaction in the 4 September 2010 (white contours), 22 February 2011 (red = severe liquefaction, yellow = moderate, magenta areas = liquefaction predominantly on roads), and 13 June 2011 (black contours) earthquakes; normalized cyclic stress ratios at water table depth, $CSR_{7.5(wt)}$ are also shown at the locations of strong motion stations

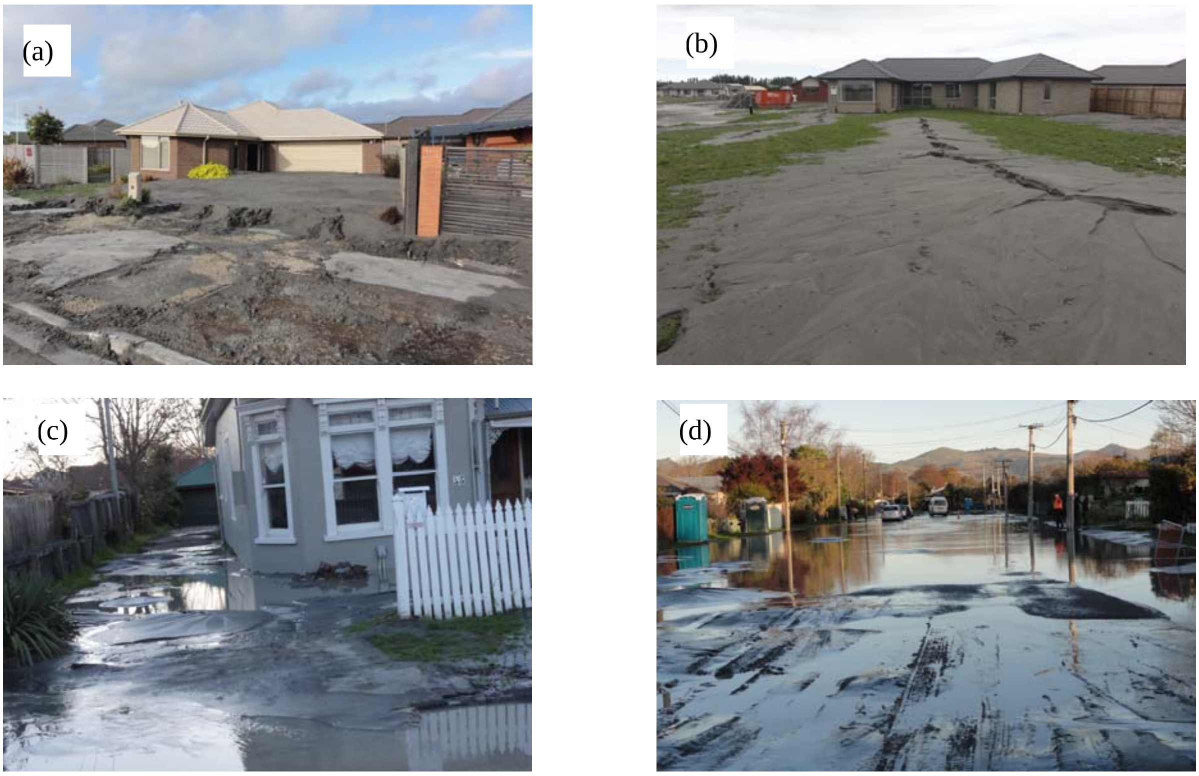

Fig. 5 Severe liquefaction in residential areas (suburbs along Avon River in the abandoned "red zone")

Figure 5 illustrates typical manifestation of severe liquefaction in the eastern suburbs of Christchurch. There was widespread and very large in volume (thickness) sand/silt ejecta covering the residential properties and streets in these suburbs. In numerous cases the entire area of the property was covered by 50-60 cm thick silt/sand ejecta (Fig. 5a), and massive in size sand boils (Fig. 5b) indicated very severe (and often extreme) liquefaction of loose to very loose soils. In the worst affected areas, extreme liquefaction occurred with mud and water covering entire streets and adjacent properties and even larger neighborhoods encompassing several streets within a suburb. Following the 22 February 2011 earthquake, over 400 000 tons of silt/sand ejecta were removed in the clean up of streets and properties which indicates both the extreme severity and extent of the liquefaction. While the 22 February event caused the most severe liquefaction, a complete flooding of streets and very severe liquefaction occurred in these areas also during other earthquakes, as illustrated in Figs. 5c and 5d where substantial sand boils and effects of liquefaction are seen in the suburbs of Avonside and Avondale after the 13 June earthquakes.

The most severely affected by liquefaction were the suburbs along the Avon River to the east of CBD (Avonside, Dallington, Avondale, Burwood and Bexley). The soils in these areas are predominantly loose fluvial deposits of liquefiable clean and fines-containing sands, with fines content predominantly in the range between 0% and 30%. Importantly, the fines are non-plastic silts. The soils in the top 5-6 m are often in a very loose state, with CPT cone tip resistance (q_c) of about 2-4 MPa. The cone resistance typically increases to 7-10 MPa at depths between 6 m and 10 m, however lower resistances are often encountered in areas close to wetlands. Characteristic CPT resistance for these areas is shown in Fig. 6. These areas are within the zone where severe liquefaction occurred during multiple events.

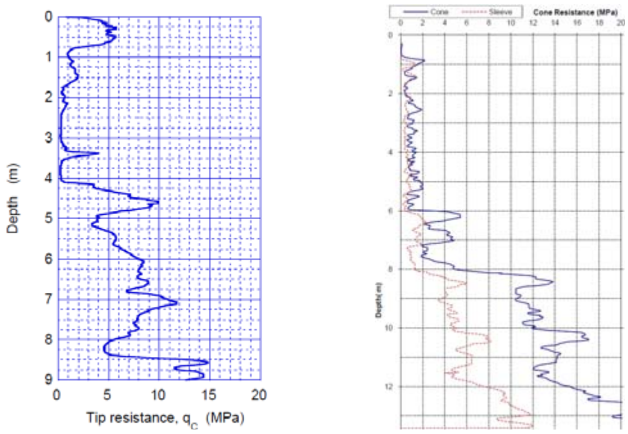

Fig. 6 CPT resistance in areas of severe liquefaction

LIQUEFACTION-INDUCED DAMAGE

Residential buildings

Christchurch has a population of about 390,000 (the second largest city in New Zealand) and an urban area that covers approximately 450 km^2. It is sparsely developed with approximately 150,000 dwellings, predominantly single-storey houses with a smaller number of two-storey houses spread evenly throughout the city. Typical houses in Christchurch are light timber-frame structure with weatherboard (older buildings), unreinforced brick veneer and stucco used as exterior cladding.

Approximately 60, 000 residential buildings were affected by liquefaction in these earthquakes. 20,000 of those were seriously affected by liquefaction, out of which about 8,000 houses have been damaged beyond economic repair (in the abandoned ‘red zone’ residential areas suffering extensive liquefaction, lateral spreading and/or subsidence). The worst damage to residential houses was inflicted in areas where severe lateral spreading occurred, however, liquefaction on its own, even in the absence of lateral spreading, caused extensive and substantial damage beyond economic repair.

Four different foundation types have been largely used in the Christchurch region for residential buildings, i.e. concrete slab on grade, timber floor with perimeter footing, piled foundations and more recently rib-raft or waffle slab with inverted beams. The concrete slab on grade and the perimeter footing (schematically shown in Fig. 7) are the two prevalent foundation types used in approximately 80 % of the housing stock in Christchurch. The slab on grade is unreinforced (except for the thickened perimeter beam) approximately 100 mm thick concrete slab for one-storey houses, and it is reinforced by a low capacity wire-mesh for two-storey houses. The slab rests on un-compacted or poorly compacted gravel bed. The concrete perimeter foundations range from unreinforced concrete filled with loose bricks (old construction) to (continuous) reinforced concrete foundations (newer construction). As shown in Fig. 7, the timber floor, which is elevated above the ground, is supported along its edges by the perimeter footing and by uniformly spaced concrete/timber supports (‘piers’) across the floor area.

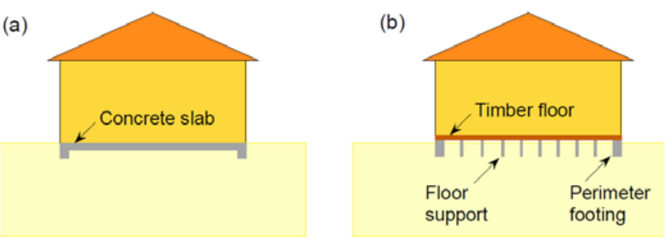

Fig. 7 Prevalent house foundation types in Christchurch: (a) concrete slab; (b) concrete perimeter footing

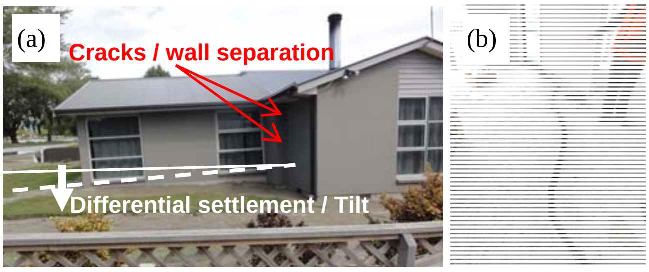

Fig. 8 Characteristic liquefaction-damage to house foundations: (a) differential settlement resulting in tilt and damage to house; (b) large crack in a concrete slab

The liquefaction often led to large global and differential settlements of the buildings. In the worst cases, the total settlement exceeded 40-50 cm. Differential settlement resulted in permanent tilt of houses, and often caused foundation and structural damage (Fig. 8a) because of the inadequate stiffness and strength of the foundation. Concrete slabs suffered serious damage including wide cracks (Fig. 8b), and non-uniform deformation such as dishing (sagging) and hogging. A number of different deformation modes could be identified for the perimeter footing foundations including humping of floors (often in individual rooms) due to larger settlement beneath the heavier walls, dishing caused by heavy brick chimneys founded on isolated footings in the interior of the floor plan, and racking/twisting of the superstructure caused by differential settlement/movement of corners/parts of the foundation due to its inadequate stiffness.

In order to examine the performance of different foundation types, 160 house foundations were inspected in detail (approximately 40 for each of the four foundation types distributed in areas of different liquefaction severity: none, low, moderate, severe and very severe liquefaction). In the inspections, land damage (liquefaction and lateral spreading severity in multiple earthquake events), foundations damage (where detectable in visual inspections), estimates of differential settlements, tilt (based on measured floor elevations using precision altimeter with ± 1 mm accuracy and local tilt measurements) and structural damage were documented. Some preliminary results from these investigations for the slab on grade and perimeter footing foundations are summarized in Figs. 9 and 10 respectively.

Correlation between the residual slope of concrete slab foundations (a proxy for the tilt as well) and observed liquefaction severity (0=none, 1=low, 2=moderate, 3=severe, 4=very severe, extreme liquefaction) is shown in Fig. 9. Here, the maximum floor slope is shown based on approximately 15-20 floor elevation measurements across the footprint of a building. The plot also indicates several recently developed damage criteria in New Zealand (DBH, 2011) and Japanese practices (Yasuda et al., 2012) based on experiences from the 2010-2011 Christchurch earthquakes and 2011 Great East Japan earthquake respectively. The shaded (yellow) area

(1/300 to 1/150 slope) indicate the typical range of slope found in newly constructed concrete floor slabs (the average slope between two points 2m apart), (DBH, 2011). In the DBH guidelines for repairing and rebuilding of houses affected by the Christchurch earthquakes, differential settlement (floor slope) and cracks width have been adopted as criteria to evaluate whether the foundation damage requires repair or not. The 1/200 slope is indicated in Fig. 9, as a reference 'no-damage' threshold. It is apparent in Fig. 9 that the measured slope of concrete slabs shown with the symbols was clearly related to the severity of liquefaction. In general, in areas of no or low liquefaction manifestation, the measured slope was within the construction tolerance or allowable slope. In areas of moderate and particularly severe liquefaction, however, the residual slope of concrete slabs was often above the allowable threshold slope of 1/200.

The 49 inspected perimeter footing foundations were scrutinized against the abovementioned DBH damage criteria. Since most of the foundations/houses in the inspected area were old (pre 1930, 1930-1959, 1960-1979) and of poor quality (often without any reinforcement), they suffered very high proportion of damage (as summarized in Fig. 10): 82% had tilts exceeding 1/200, 25% had total width of cracks exceeding 20mm and 51% max width of a single crack over 5mm. The damage for these foundations was poorly related to the liquefaction severity, and eight foundations showed damage greater than at least one of the no-damage thresholds despite being located in areas where liquefaction was not manifested on the ground surface.

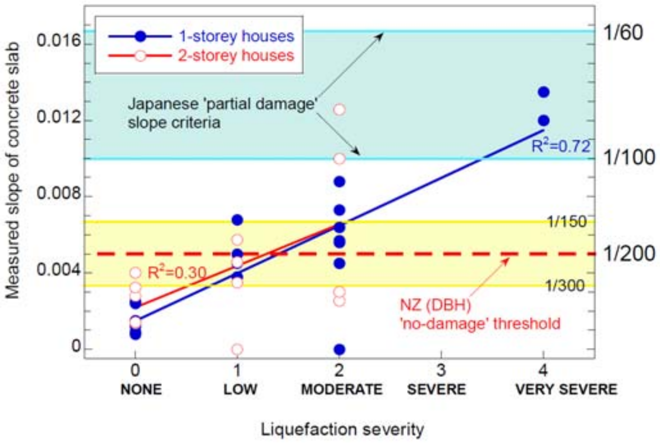

Fig. 9 Correlation between liquefaction severity and residual slope of slab foundations for 32 houses in Christchurch

CBD buildings

The earthquakes produced strong ground motions within the Central Business District (CBD) of Christchurch with the 22 February earthquake being the most damaging. Soil liquefaction in a substantial part of the CBD adversely affected the performance of many buildings resulting in total and differential settlements, lateral movement of foundations, tilt of buildings, and bearing failures. There were about 3,000 buildings within the CBD boundaries before the 2010-2011 earthquakes. Latest estimates indicate that over 1,500 of these buildings will be demolished because of excessive earthquake damage. In this subsection, a brief overview of the characteristic liquefaction-induced damage of CBD building foundations is presented, while further details can be found in Cubrinovski et al. (2011a) and Bray et al. (2014).

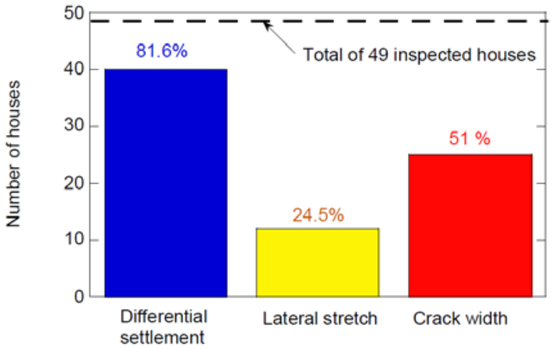

Fig. 10 Damage to concrete perimeter foundations (49 inspected houses) indicating percentage of foundations exceeding the DBH no-damage thresholds

Figure 11 shows the observed liquefaction in the CBD as documented after the Christchurch earthquake. The principal zone of liquefaction (red color area) stretches west to east through the CBD, from Hagley Park to the west, along the Avon River to the northeast boundary of the CBD at the Fitzgerald Avenue Bridge. This zone is of particular interest because many high-rise buildings on shallow foundations and deep foundations were affected by moderate to severe liquefaction in different ways. Note that this zone consists mostly of sandy soils and largely coincides with the path of the Avon River and network of old streams. The solid black lines (area) indicate zones of pronounced ground distress (cracking and slumping) caused by liquefaction. Also shown in the figure are the predominant soils in the top 7-8 m of the CBD deposits, indicating the significant variability of the soils across the CBD.

Many buildings on shallow foundations were affected by severe liquefaction resulting in substantial total and differential settlements or lateral movements. An example of significant differential settlement of a 6 storey reinforced concrete building is shown in Figure 12. Part of the shallow foundations of the building (the corner where the maximum settlement occurred) was affected by very severe liquefaction which was manifested with extensive surface cracks, fissures, depression of the ground surface, and water and sand ejecta in a well-defined narrow zone approximately 50 m wide. The differential settlement was about 30 cm, with consequent tilting of the building, and damage to the foundations and superstructure in addition to structural damage induced by the ground shaking itself; the building has been demolished because it was considered uneconomic to repair.

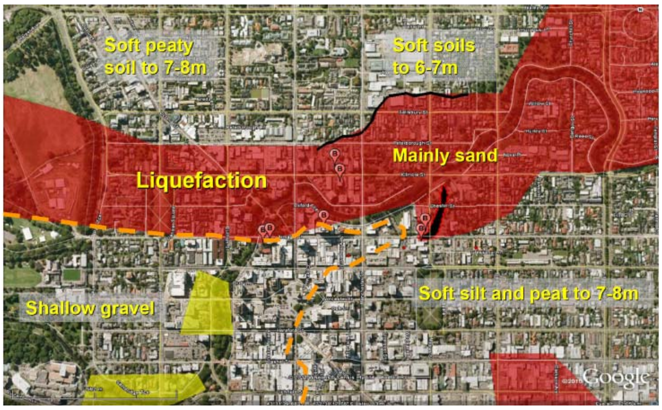

Fig. 11 Liquefaction map for the CBD (22 February 2011 earthquake) indicating zones of pronounced ground distress, and predominant soils in the top 7 m to 8 m of the deposits

Fig. 12 Liquefaction-induced differential settlement of a CBD building on shallow foundations

Several pile-supported buildings were located in the areas of severe liquefaction. Although significant ground failure occurred and the ground surrounding the structures settled, the buildings supported on piles typically suffered less damage, though substantial settlement of the ground relative to the building occurred. The building shown in Figure 13, was on pile foundations approximately 15 m to 16 m deep, and exhibited negligible settlement since the piles reached the underlying non-liquefied bearing strata. The surrounding soils, however, suffered severe liquefaction and consequent settlement of the ground of about 30 cm on the north side of the building and up to 17 cm on its south side during the Christchurch earthquake. The first storey structural frame of the building that was supported by the pile foundation with strong tie-beams did not show significant damage from these liquefaction-induced ground settlements. In the 13 June 2011 earthquakes, the settlement of the surrounding soil at the north side of the building further increased to about 50 cm. This building was also deemed uneconomic to repair and was demolished.

Across from this building to the north, is a seven-storey reinforced concrete building on shallow spread footing foundations that suffered damage to the columns at the ground level. This building tilted towards south-east as a result of approximately 10 cm differential settlement caused by the more severe and extensive liquefaction at the south, south-east part of the site. Hence, these two buildings provide invaluable information on the performance of shallow foundations and pile foundations in an area of moderate to severe liquefaction that induced uneven ground settlements. At this site, extensive field investigations were conducted including a dense array of CPTs (Bray et al. 2013) and Gel-Push sampling of undisturbed samples of sandy and silty soils from 2 m to 13 m depth (Taylor et al. 2012).

The effects of lateral spreading within the CBD were localized within relatively narrow zones along the Avon River. Ground surveying measurements conducted at ten locations within the

Fig. 13 Building on pile foundations in area of severe liquefaction showing large settlement of the surrounding soils relative to the foundation beams

CBD after the Christchurch earthqauke indicated maximum spreading displacements predominantly between 10 cm and 30 cm, except at several locations where the displacements reached 50-70 cm. The zone affected by spreading was relatively narrow and usually confined within a distance of 50 m from the Avon River. Even in the cases when the spreading displacements were larger and extended up to 150 m from the banks, the permanent lateral displacements beyond the distance of 50 m were less than 10 cm. Structures and foundations within the spreading zone were greatly impacted by the horizontal ground strains causing stretching of the ground, foundations and then the building itself. Typical stretching of the foundations resulting in damage of the structure (opening of expansion joints) is shown in Figure 14.

Fig. 14 Stretching of foundations due to lateral spreading resulting in opening of the expansion joints of a CBD building

Buried pipe networks

Buried pipe networks suffered extensive liquefaction-induced damage in the 2010-2011 Christchurch earthquakes over approximately one third of the city area. The wastewater system of Christchurch was hit particularly hard resulting in numerous failures and loss of service to large areas. Out of the 1766 km long wastewater pipe network, 142 km (8%) were out of service and 542 km (31%) were with limited service nearly one month after the February earthquake. A significant part of the network was still out of service even three months after the quake, and it is estimated that it will take at least three to five years to fully reinstate the system. Typical damage to the wastewater network included loss of grade in gravity pipes, breakage of pipes/joints and infiltration of liquefied silt into pipes (often accompanied by depression of carriageways, undulation of road surface and relative movement of manholes), and failure of joints and connections (particularly numerous failures of laterals). A number of pump stations were taken out of service and the wastewater treatment plant suffered serious damage and barely remained in operation though with significantly diminished capacity.

The potable water system was proven to be much more resilient. Even though a large number of breaks/repairs of the water pipes have been reported, the water supply service was quickly restored. The Christchurch water supply system is an integrated citywide network that sources high quality groundwater from confined aquifers, and pumps the water into a distribution pipe network consisting of approximately 1600 km of watermains and 2000 km of submains (CCC 2010). The water is supplied from approximately 150 wells at over 50 sites, 8 main storage reservoirs, 37 service reservoirs and 26 secondary pumping stations. Watermains and submains are located almost exclusively within legal roads, at shallow depths, usually at about 0.8m to 1.0m depth. About half of the watermains are asbestos cement (AC) pipes, while polyvinyl chloride (PVC) pipes dominate the remaining portion of the watermains. The submains network predominantly consists of polyethylene (PE) pipes (covering over 80% of the network) whereas Galvanized Iron (GI) pipes are dominant in the remaining 20% of the network.

Figure 15 shows the location of repairs/faults on the watermains network (red symbols) following the 22 February 2011 earthquake. Superimposed in the background of the figure (with red, orange and yellow colours) is the liquefaction map (Cubrinovski and Taylor, 2011) indicating the severity of liquefaction (and associated land damage) induced by this earthquake. Preliminary GIS analyses (Cubrinovski et al., 2011) using the pipe network damage data and liquefaction observation maps show a clear link between the damage to the pipe network and liquefaction severity. Approximately 58% of the damaged pipes were in areas of moderate to severe liquefaction, 20.2% were in areas of low to moderate liquefaction, 2.5% in areas where traces of liquefaction were observed and the remaining 19.3% in areas where no signs of liquefaction were observed.

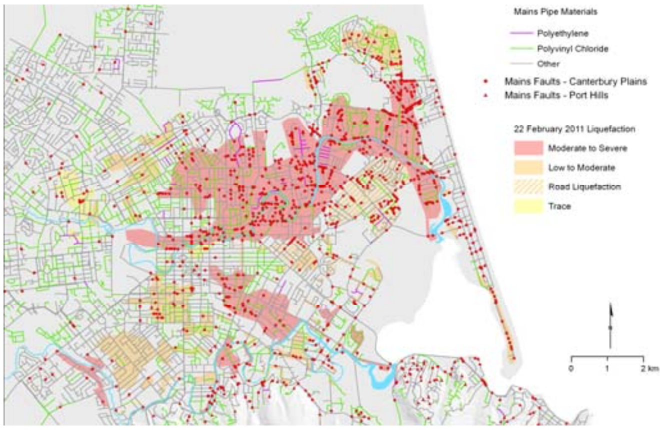

Fig. 15 Liquefaction map and locations of damage to the potable water network of mains (red symbols) of Christchurch due to the 22 February 2011 earthquake (Cubrinovski et al., 2011)

These analyses also revealed that more ductile PE pipes and PVC pipes suffered significantly less damage (three to five times less on average) than brittle AC, GI and other material pipes. Figure 16 summarizes the performance of different pipe materials (PVC and AC pipes for the watermains; PE and GI pipes for the submains) and clearly indicates the difference in the performance of different pipe materials and the increase in the pipe network damage with increasing liquefaction severity.

Bridges

There are over 800 road, rail and pedestrian bridges in the Christchurch region. Road bridges, are typically short- to moderate-length bridges (20 m to 70 m long) with short spans. Overall, in the 2010-2011 earthquakes road bridges performed relatively well compared to other engineering structures. They suffered low to moderate damage and were in service either immediately after the earthquakes or several days after each significant event, except for an overpass which was closed for an extended period of time.

Most of the damage to bridges was due to liquefaction in the foundation soils and lateral spreading of the river banks, with very few examples of serious damage on non-liquefiable sites. Practically all road bridges downstream on the Avon River, from the CBD to the Avon-Hethcote Estuary, were severely impacted by lateral spreading. The permanent spreading displacements of the river banks in the vicinity of the bridges were quite substantial and generally in the range between 1 m and 3m.

The short-span bridges have very stiff and strong superstructure (deck or deck-beam system) in the longitudinal direction which was a key factor in the development of a characteristic deformation mechanism of the bridges associated with lateral spreading (Fig. 17). It involves large spreading-induced lateral displacements of the river banks towards the river; this ground movement was resisted by the stiff bridge superstructure resulting in a deck-pinning and subsequent back-rotation of the abutments, because the abutment piles could not restrain the movement of the foundation soils. As indicated in the figure, this deformation mechanism caused substantial lateral displacement at the head of the abutment piles, bending of the piles and their subsequent damage. A pronounce slumping of the approaches also occurred due to liquefaction in the underlying soils which resulted in substantial settlements and vertical offsets between the approaches and the pile-supported deck of the bridge. This typical deformation pattern was observed both for more recently constructed bridges allowing relative movement between the deck and piers/abutments, and for older integral (jointless) bridges. More details on the spreading-induced damage to bridges may be found in Cubrinovski et al. (2013).

CONCLUSIONS

Widespread and very severe liquefaction occurred in native soils in Christchurch during the 2010-2011 earthquakes. While the 22 February earthquake was the most damaging, in many

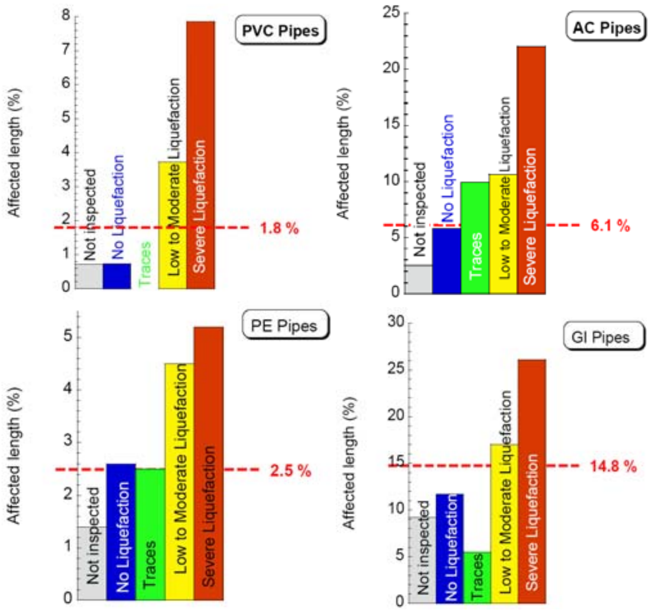

Fig. 16 Summary of damage to water pipes due to the 22 February 2011 earthquake indicating performance of different materials in relation to liquefaction severity

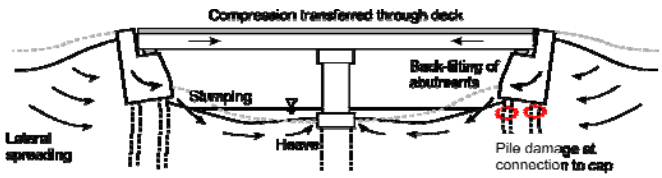

Fig. 17 Schematic illustration of characteristic spreading-induced damage mechanism for short-span bridges in Christchurch (Cubrinovski et al., 2013)

areas along the Avon River the soils severely liquefied in multiple events. The liquefaction resulted in large settlements of the ground, subsidence of wetland areas and substantial permanent ground displacements due to lateral spreading in a zone approximately 100-200 m wide along streams and the Avon River.

Nearly 20,000 residential buildings and properties were severely affected by liquefaction, and about 8,000 of those were damaged beyond economic repair. The liquefaction often led to large global and differential settlements, and damage to house foundations. Both concrete slab and particularly older perimeter foundations suffered substantial liquefaction-induced damage because of inadequate stiffness, strength and liquefaction considerations in their design. The damage to the foundations was clearly related to and increased with the liquefaction severity.

There is a clear link between the severity of liquefaction and observed damage to the buried pipe networks with nearly 80% of the damaged water pipes being in liquefied areas, and 50%

in areas of moderate to severe liquefaction. Ductile pipes (systems) such as PE and PVC pipes showed much better performance and suffered several times less damage than pipes of brittle materials or/and relatively rigid joints/connections.

The paper also summarizes characteristic liquefaction-induced damage to CBD buildings both on shallow and deep foundations, and illustrates the typical spreading-induced deformation mechanism for short-span bridges with stiff deck/superstructure involving deck-pinning, back-rotation of abutments and consequent damage to the abutment piles.

Further detailed research studies on liquefaction and lateral spreading characteristics in the 2010-2011 Christchurch earthquakes, and their effects on buildings and infrastructure are currently under way.

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