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LIQUEFACTION IMPACTS IN RESIDENTIAL AREAS IN THE 2010-2011 CHRISTCHURCH EARTHQUAKES

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ABSTRACT: In 2010 and 2011, the city of Christchurch (New Zealand) was hit by a sequence of strong, local and devastating earthquakes. Widespread and very severe liquefaction affected many of the city suburbs and its central business district. This paper summarizes the characteristics of liquefaction and discusses its impacts on residential houses and buried pipe networks.

Key Words: Christchurch earthquake, earthquake damage, liquefaction, residential buildings, pipe networks

INTRODUCTION

In the period between September 2010 and December 2011, Christchurch (New Zealand) and its surroundings were hit by a series of strong earthquakes including six significant events, 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=5.8 and (M=5.9) earthquakes. As shown in Figure 1, 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. Christchurch is shown as a lighter colour area, and its Central Business District (CBD) is marked with a white square area in the figure. Note that the sequence of earthquakes started to the west of the city and then propagated to the south, south-east and east of the city through a set of separate but apparently interacting faults. Because of their strength and proximity to the city, the earthquakes caused tremendous physical damage and impacts on the people, natural and built environments of Christchurch. The 22 February 2011 earthquake was particularly devastating. The ground motions generated by this earthquake were intense and in many parts of Christchurch substantially above the ground motions used to design the buildings in Christchurch. The earthquake caused 182 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, which is the central heart of the city just east of Hagley Park, was practically lost with majority of its 3,000 buildings being damaged beyond repair. Widespread liquefaction in the suburbs of Christchurch, as well as rock falls and slope/cliff instabilities in the Port

Hills affected tens of thousands of residential buildings and properties, and shattered 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 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, lateral spreading displacements and their impacts on buildings and infrastructure. In addition, the ground motions produced 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 of the performance of ground and various types of structures during this unusual sequence of strong local earthquakes affecting a city.

This paper discusses the liquefaction in residential areas and focuses on its impacts on dwellings (residential houses) and potable water system in the Christchurch suburbs. The ground conditions of Christchurch including the depositional history of soils, their composition, age and groundwater regime are first discussed. Detailed liquefaction maps illustrating the extent and severity of liquefaction across Christchurch triggered by the sequence of earthquakes including multiple episodes of severe re-liquefaction are next presented. Characteristic liquefaction-induced damage to residential houses is then described focussing on the performance of typical house foundations in areas affected by liquefaction. Liquefaction impacts on the potable water system of Christchurch is also briefly summarized including correlation between the damage to the system, liquefaction severity, and the performance of different pipe materials. Finally, the characteristics of Christchurch liquefaction and its impacts on built environment are discussed in relation to the liquefaction-induced damage in Japan during the 11 March 2011 Great East Japan Earthquake.

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.

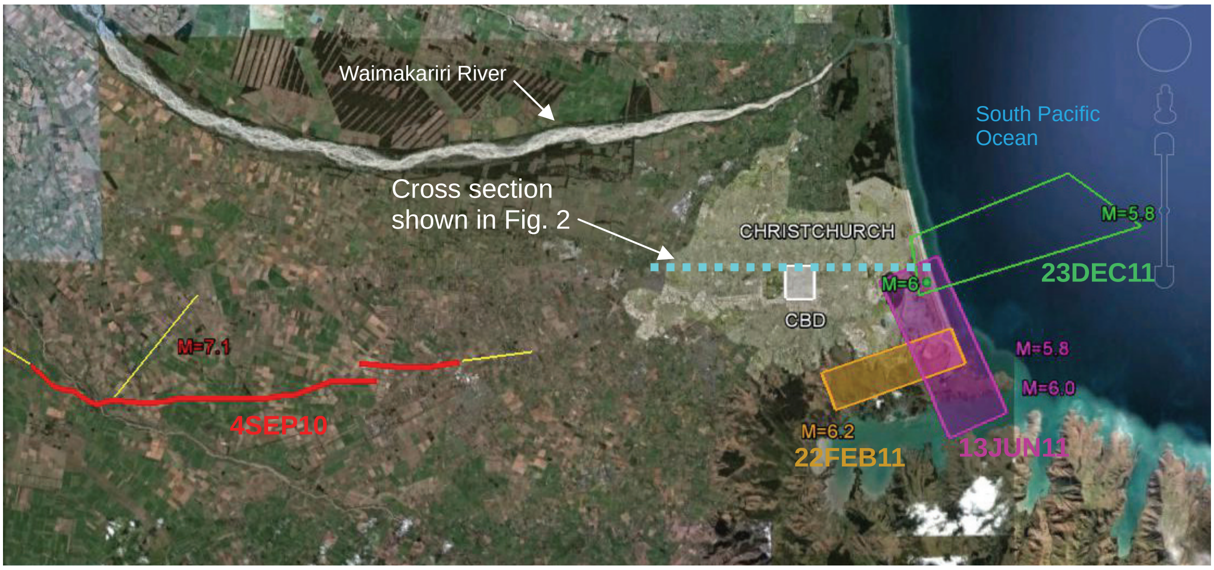

Fig. 1 Causative faults of the 2010-2011 Christchurch earthquakes (4 September 2010 earthquake, red line = trace of surface rupture, yellow lines = subsurface rupture; 22 February 2011 earthquake, orange area = fault area projection; 13 June 2011 earthquakes, magenta area = fault area projection; 23 December 2011 earthquake, green line = general source area); the Central Business District (CBD) of Christchurch is shown with the white square

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 Figure 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). 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 Figure 2 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 Figure 2. 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.

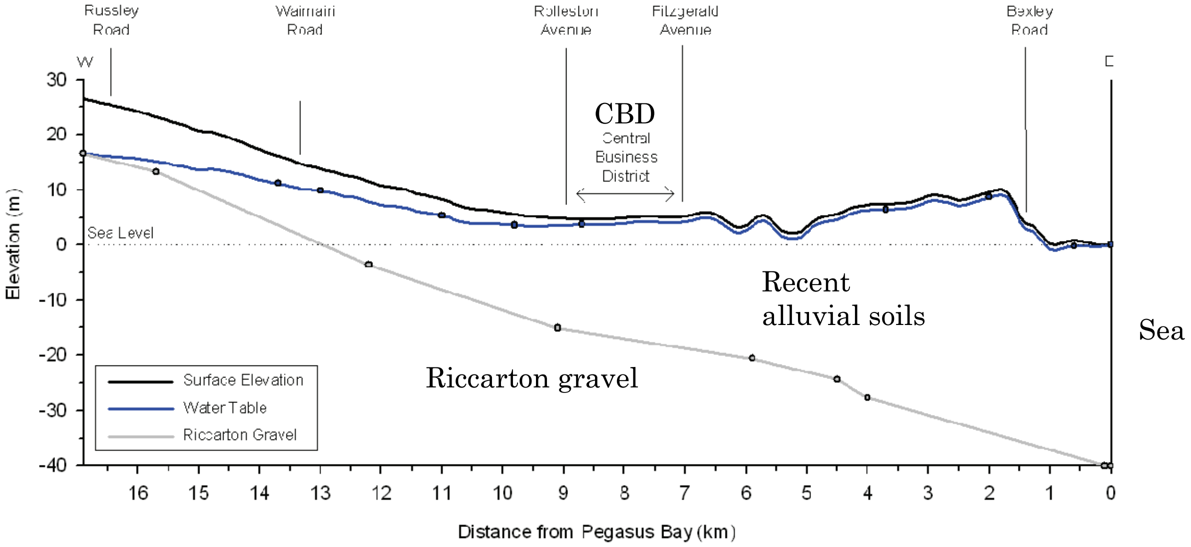

Fig. 2 General geologic profile of shallow Christchurch soils indicating thickness of recent alluvial soils and water table depth along an east-west cross section (indicated in Figure 1)

Data on age of the soils based on radiocarbon dating of samples from the Christchurch area presented by Brown and Weeber (1992) is plotted in Figure 3 correlating the depth of the soils beneath the ground surface and their age. The shallow soils within the top 10 metres are less than 4000 years old, and some are only few hundred years old, which makes them vulnerable to liquefaction.

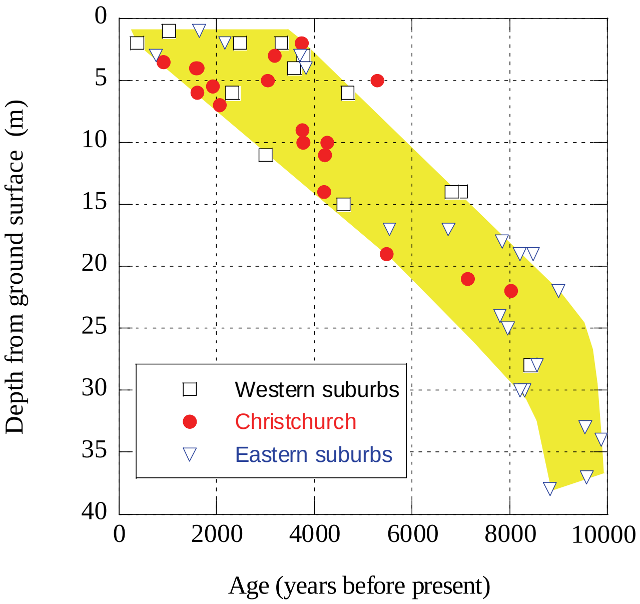

Fig. 3 Age of recent alluvial soils overlying the Riccarton Gravel expressed as a function of depth (based on radiocarbon ages of Christchurch soils samples reported by Brown and Weeber, 1992)

GROUND MOTIONS AND SEISMIC DEMAND SPECIFIC TO LIQUEFACTION

The 4 September 2010 M_w=7.1 Darfield earthquake was caused by a complex rupture of several fault segments, the largest and nearest to Christchurch being on the Greendale fault (red line in Figure 1) about 20 km west of the CBD. A maximum horizontal PGA of 0.24 g was recorded 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 was less than 10 km from the CBD along the southeastern perimeter of the city in the Port Hills (Figure 1). The close proximity of this event caused higher intensity shaking in the CBD as compared to the Darfield earthquake. Several of the recordings exhibited forward-directivity significant velocity pulses. In the CBD, horizontal PGAs of between 0.37 g and 0.52 g were recorded. The peak ground velocities produced by this earthquake were in the range between 30 cm/s and 70 cm/s. The recorded geometric mean peak ground accelerations (PGA) at two stations within the CBD (CBGS and REHS) and two in the northeast and east suburbs of the city (NNBS and PRPC) are summarized in Table 1 for six major earthquakes producing high accelerations (Bradley and Cubrinovski 2011). The data show that 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 five additional events.

For the shallow part of a deposit, the variation in the recorded PGA values corresponds closely with variations in the cyclic stress ratio (CSR, used in liquefaction evaluation). 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 ($CSR_{7.5}$) as summarized in Table 1. 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 earthquake, which were about 1.6 times the corresponding CSR-values from the

M_w=7.1, 4 September 2010, Darfield earthquake. At many sites in Christchurch liquefaction re-occurred during the subsequent earthquakes. In the CBD itself, only isolated areas liquefied during multiple events. Instead, widespread liquefaction occurred only in the CBD during the 22 February 2011 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 listed in Table 1. In order to compare the seismic demand specific to liquefaction between the Christchurch earthquakes and the 2011 Great East Japan Earthquake, the *PGA* and $CSR_{7.5}$ values recorded/computed at Urayasu are also listed in Table 1.

Table 1 Geometric mean horizontal Peak Ground Accelerations (PGA) and Cyclic Stress Ratios adjusted to 7.5 magnitude earthquake ($CSR_{7.5}$) from strong motion records in Christchurch (for six 2010-2011 earthquakes) and Urayasu (for the 2011 Great East Japan earthquake)

Earthquake	Magnitude	MSF	CBGS-CBD		REHS-CBD		PRPC		NNBS		Urayasu	
			PGA	$CSR_{7.5}$	PGA	$CSR_{7.5}$	PGA	$CSR_{7.5}$	PGA	$CSR_{7.5}$	PGA	$CSR_{7.5}$
4SEP10	7.1	1.15	0.16	0.09	0.25	0.14	0.21	0.12	0.21	0.12	-	-
22FEB11	**6.2**	**1.56**	**0.50**	**0.21**	**0.52**	**0.22**	**0.63**	**0.26**	**0.67**	**0.28**	-	-
13JUN11	5.3	2.40	0.18	0.05	0.19	0.05	0.30	0.08	0.24	0.06	-	-
13JUN11	6.0	1.77	0.16	0.06	0.26	0.10	0.34	0.12	0.20	0.07	-	-
23DEC11	5.8	1.93	0.16	0.05	0.20	0.07	0.29	0.10			-	-
23DEC11	5.9	1.85	0.21	0.07	0.25	0.09					-	-
11MAR11	**9.0**	**0.65**	-	-	-	-	-	-	-	-	**0.14**	**0.14**

PGA values as fraction of gravity (g); $MSF = 10^{2.24}/M^{2.56}$ (Youd and Idriss, 2011); $CSR_{7.5} = 0.65PGA/MSF$

SOIL LIQUEFACTION IN THE 2010-2011 EARTHQUAKES

The 2010 – 2011 earthquakes caused repeated liquefaction through the suburbs of Christchurch and its Central Business District. The liquefaction was very severe and widespread (covering nearly 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 earthquake (white contour/shaded area), 22 February 2011 earthquake (red = moderate to severe liquefaction; yellow = low to moderate liquefaction; magenta = moderate liquefaction predominantly on roads with some on properties; Cubrinovski and Taylor, 2011) and 13 June 2011 earthquakes (dark grey contours/shaded area; Cubrinovski and Hughes, 2011). The extent of liquefaction in the 23 December 2011 earthquake was similar to that in the June 2011 earthquake (the December event map is currently in preparation). 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 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. Nearly 6,000 residential properties will be abandoned in the “red zone” along the Avon River (New Zealand Government, 2011) because the damage is beyond economic repair, and it is estimated that an additional 15,000 properties were affected by liquefaction, the majority of which otherwise sustained only minor to moderate damage directly due to inertial loading from ground shaking.

The most severely affected by liquefaction were the suburbs along 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 top 5-6 m of the soils are often in a very loose state, with CPT cone tip resistance (q_c) of about 2-4 MPa (or an SPT blow count of 4-8). The cone resistance typically increases to 7-10 MPa (approximately 14-20 SPT blow counts) at depths between 6 m and 10 m, however lower resistances are often encountered in areas close to wetlands. Characteristic penetration resistance for these areas and those within CBD is shown in Figure 5. These areas are within the zone where very severe liquefaction occurred during multiple events.

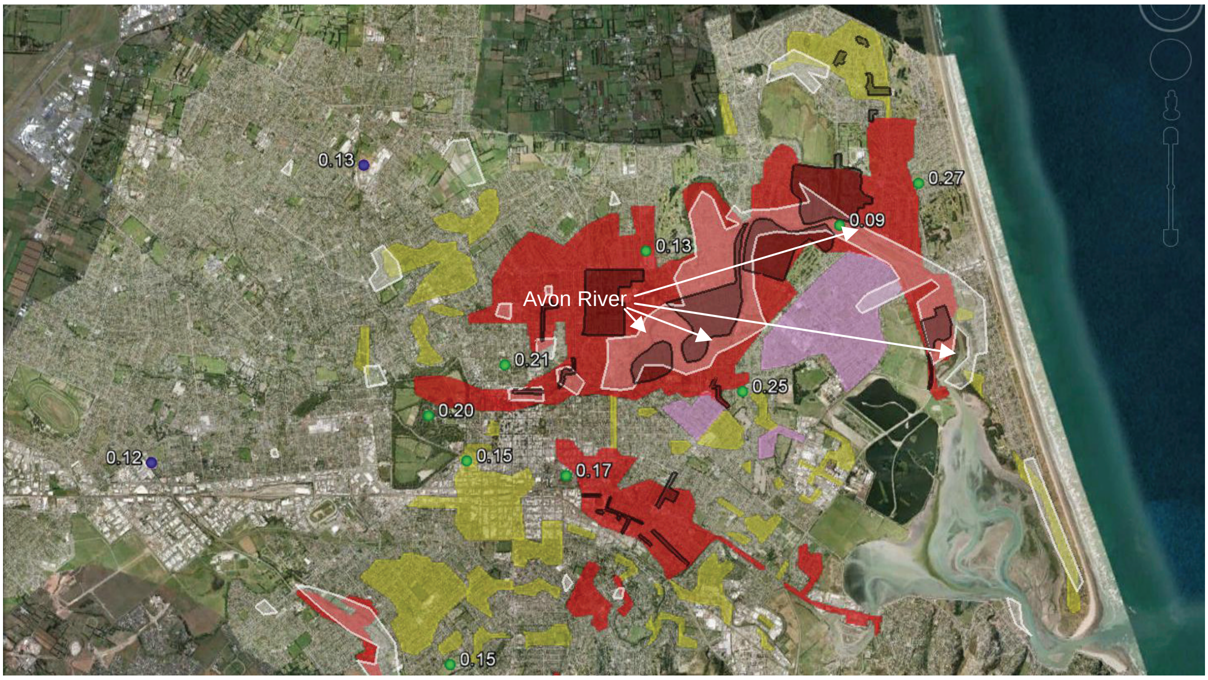

Fig. 4 Liquefaction maps indicating areas of observed liquefaction in the 4 September 2010 (white contours), 22 February 2011 (red, yellow, magenta areas), and 13 June 2011 (black contours) earthquakes; normalized cyclic stress ratios at water table depth, $CSR_{7.5(wt)}$, which were calculated using the recorded geometric mean peak ground accelerations and respective earthquake moment magnitude are also shown (green symbols indicate strong motion stations where the 22 February 2011 produced the highest $CSR_{7.5(wt)}$ value whereas the 4 September 2010 earthquake produced the highest $CSR_{7.5(wt)}$ value at the SMS depicted with blue symbols)

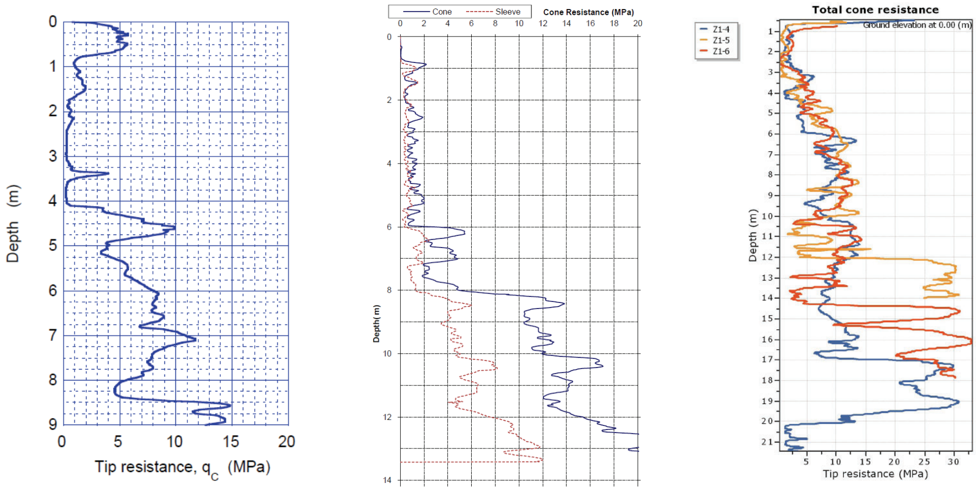

Fig. 5 Characteristic CPT resistance in areas of severe liquefaction (red area along Avon River and

CBD)

Figure 6 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 (Figure 6a), and massive in size sand boils (Figure 6b) indicated very severe (and often extreme) liquefaction of loose to very loose soils highly susceptible to liquefaction. In the worst affected areas, extreme liquefaction with mud and water flooding entire streets and adjacent properties and even larger neighborhoods encompassing several streets within a suburb. Following the 22 February 2011 earthquake, over 400 000 t of silt/sand ejecta was 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 in most cases the most severe liquefaction, a complete flooding of streets and very severe liquefaction occurred in these areas also during other earthquakes, as illustrated in Figures 6c and 6d where substantial sand boils and effects of liquefaction are seen in Avonside and Avondale after the 13 June earthquakes.

Fig. 6 Severe liquefaction in residential areas (suburbs along Avon River in the abandoned “red zone”)

DAMAGE TO FOUNDATIONS OF RESIDENTIAL HOUSES

Christchurch has a population of about 350,000 (the second largest city in New Zealand) and an urban area that covers approximately 450 km^2. It is sparsely developed with approximately 150,000 dwellings, predominantly single-storey houses with a smaller number of two-storey houses spread evenly throughout the city. Typical residential houses in Christchurch are light timber-frame structure with weatherboard (older buildings), unreinforced brick veneer and stucco used as exterior cladding.

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 Figure 7) are the two prevalent foundation types covering probably over 70%-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 relatively 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 Figure 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.

Approximately 20,000 houses were seriously affected by liquefaction, out of which more than 6,000 have been damaged beyond economic repair (in the abandoned areas suffering extensive liquefaction). 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 often substantial damage beyond economic repair. Some typical damage patterns of house foundations are schematically illustrated in Figure 8 (DBH, 2011).

The liquefaction often led to large global and differential settlements. In the worst cases, the total (global) settlement exceeded 40-50 cm. Differential settlement resulting in permanent tilt of houses and often causing foundation and structural damage (Figure 9a) was the most common mode of deformation for both foundation types. Concrete slabs suffered serious damage including wide cracks (Figure 9b), and non-uniform deformation such as dishing (sagging) and hogging. Figure 9c shows a characteristic dishing of a newly constructed slab on grade which was affected by heavy liquefaction in the foundation soils. A number of different deformation modes could be identified for the perimeter

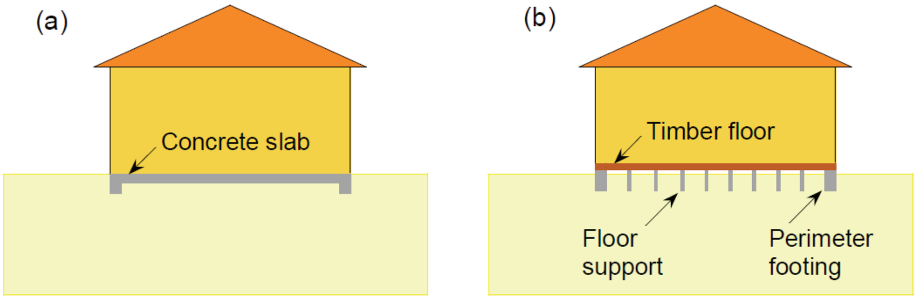

Fig. 7 Prevalent house foundation types in Christchurch: (a) concrete slab; (b) concrete perimeter footing

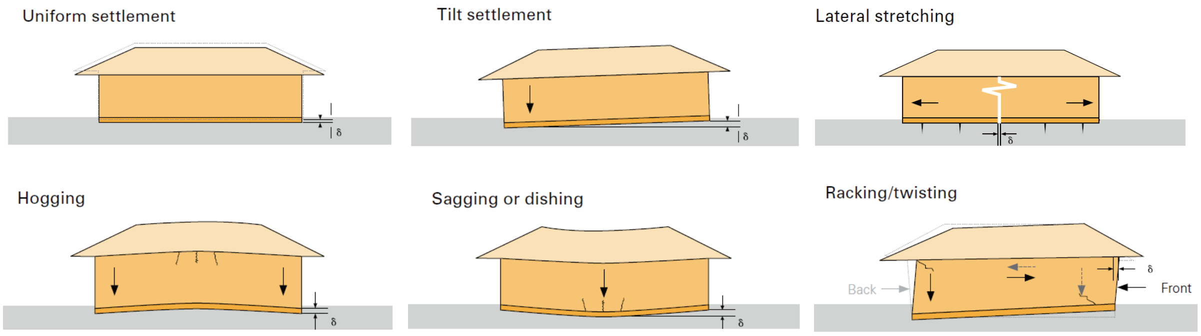

Fig. 8 Schematic plot of typical damage patterns for house foundations (DBH, 2011)

Fig. 9 Observed typical liquefaction-damage to house foundations: (a) differential settlement resulting in tilt and damage to house; (b) large crack in a concrete slab; (c) dishing of concrete slab on grade

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 for the slab on grade and perimeter footing foundations are summarized in Figures 10 and 11 respectively.

Correlation between the slope of concrete slab foundations (a proxy for the tilt as well) and liquefaction severity (0=none, 1=low, 2=moderate, 3=severe, 4=very severe, extreme liquefaction) is shown in Figure 10. Here, the maximum floor slope is shown based on approximately 15-20 floor elevation measurements across the footprint of the 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, as summarized in Table 2. The 1/200 slope is also indicated in Figure 10, as a reference ‘no-damage’ threshold. It is interesting to note that the new Japanese evaluation criteria for damage to houses (Yasuda et al., 2012) are defined as: partial damage (1/100 to 1/60), substantial damage (1/60 to 1/20) and severe destruction (over 1/20 slope). It is apparent from Figure 10, that the measured slope of concrete slabs was clearly related to the severity of liquefaction. In general, in areas of no/low liquefaction, the measured slope was within the construction tolerance or allowable slope. In areas of moderate and particularly severe liquefaction, however, the slope was often above the allowable threshold slope of 1/200. In several cases, the slope exceeded the partial damage limit of 1/100 specified in the Japanese assessment criteria.

Table 2 ‘No Damage’ DBH Criteria (if satisfied, no repair is required for the foundation)

Foundation type	Settlement	Lateral stretch	Crack width
Slab on grade and Perimeter footing	Differential settlement < 50 mm, and floor slope < 1/200 between any two points > 2 m apart	Total cracks width < 20 mm	Maximum crack width < 5 mm

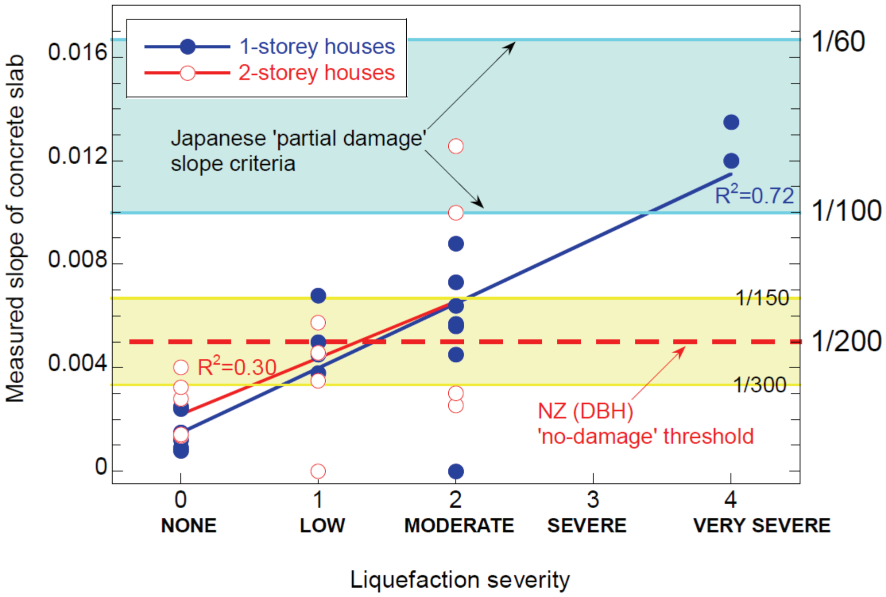

Fig. 10 Correlation between liquefaction severity and measured slope of concrete slab foundations for 32 houses in Christchurch with reference to recent New Zealand and Japanese damage criteria

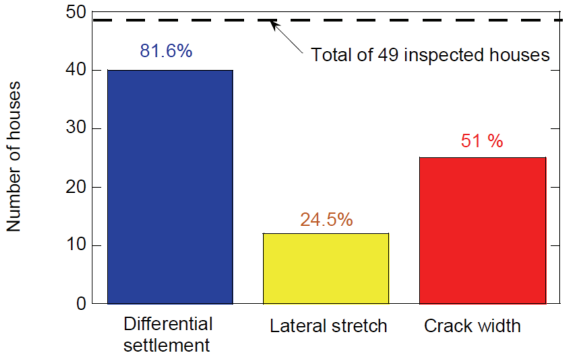

Fig. 11 Summary of damage to concrete perimeter foundations (49 inspected houses in Christchurch) indicating percentage of foundations exceeding the DBH no-damage criteria listed in Table 2

The 49 inspected perimeter footing foundations were scrutinized against the DBH damage criteria listed in Table 2. Since most of these foundations/houses were old (pre 1930, 1930-1959, 1960-1979) and of poor quality (often without any reinforcement), they suffered very high proportion of damage: 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 8 foundations showed damage greater than at least one of the criteria listed in Table 2 despite being located in areas of no liquefaction.

DAMAGE TO THE WATER SUPPLY NETWORK

Buried pipe networks suffered extensive liquefaction-induced damage in the 2010-2011 Christchurch earthquakes. The wastewater system of Christchurch was hit particularly hard resulting in numerous failures and reduction/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 two to three years to fully recover 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 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 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 12 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 19.3% in areas where no signs of liquefaction were observed.

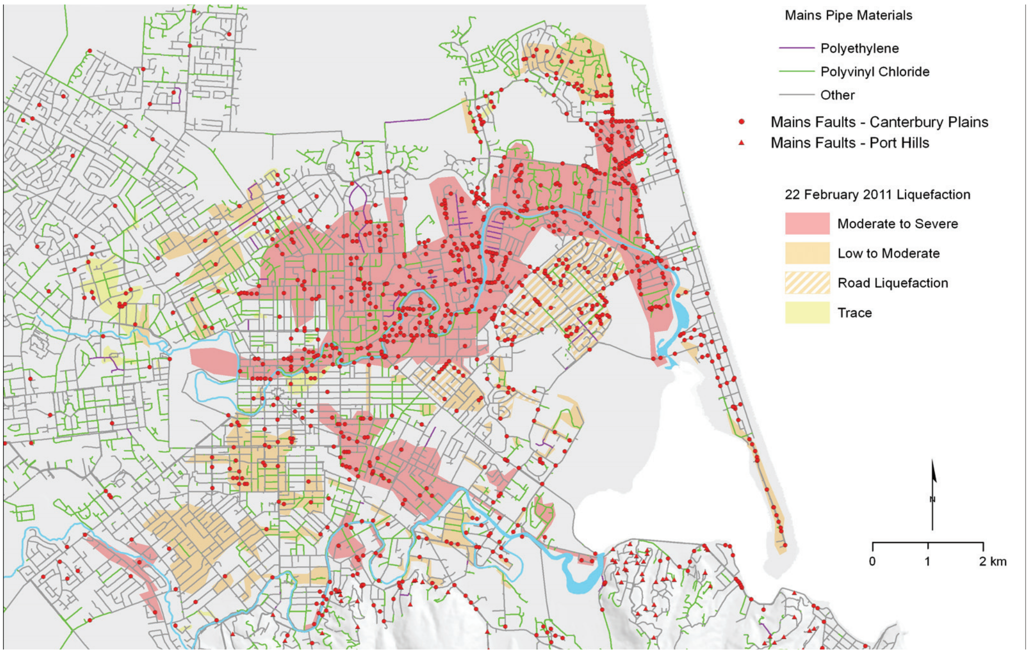

Fig. 12 Liquefaction map and locations of damage to the potable water network of mains (red symbols) of Christchurch due to the 22 February 2011 earthquake (Cubrinovski et al., 2011)

The analyses also revealed that PE pipes and PVC pipes suffered significantly less damage (three to five times less on average) than AC, steel, GI and other material pipes. Figure 13 summarizes the performance of different pipe materials (PVC, steel 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.

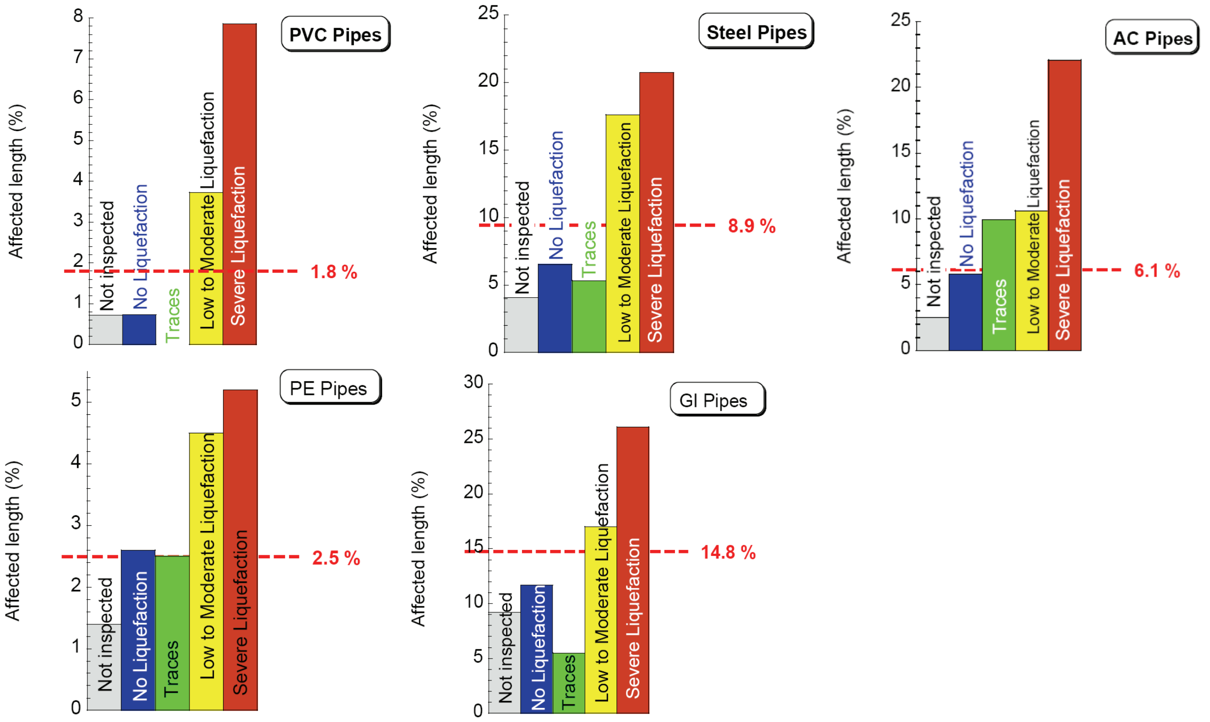

Fig. 13 Summary of damage to water pipes due to the 22 February 2011 earthquake indicating performance of different materials in relation to liquefaction severity: Water mains: (a) PVC, (b) Steel, (c) Asbestos Cement pipes; Submains: (d) PE, (e) Galvanized Iron pipes

DISCUSSION

There are many similarities but also important differences between the liquefaction and its impacts in the 2010-2011 Christchurch earthquakes and the 2011 Great East Japan Earthquake. From a seismic demand perspective both events are unusual in their own way. The Japan earthquake because of its very large magnitude and associated extreme duration of strong ground shaking including one very significant ‘aftershock’ following the main event, and in the Christchurch case, because of the sequence of at least six local earthquakes producing strong ground motions within the city boundaries. This feature is well depicted in Figure 14 where records at a strong motion station in Christchurch (CBGS) are comparatively shown with the records at Urayasu obtained during the 2011 Great East Japan Earthquake.

As shown in Table 1, when normalizing the seismic demand specific to liquefaction with respect to a reference magnitude 7.5 earthquake, the cyclic stress ratios at Urayasu of about 0.14, is well below the respective CSRs in Christchurch for the 22 February 2011 earthquake but is above the CSRs for the other Christchurch earthquakes. The key difference is however that in Urayasu reclaimed soils liquefied, whereas in Christchurch severe liquefaction was triggered in native soils in multiple events, including earthquakes producing CSRs lower than those in Urayasu. This suggests that the native soils in Christchurch have liquefaction resistance similar to that of reclaimed deposits despite being much older. It appears that at least several factors contributed to such low resistance of the Christchurch soils, with the low in-situ density, unfavorable soil composition and absence of aging effects being the most prominent factors. There is an interesting distinction in the time threshold for the aging effects, where soils 40 years or older showed greater resistance than more recent soils in Urayasu (Ishihara et al., 2011), whereas even several hundred years old deposits did not show an improved liquefaction resistance in the Christchurch environment. The potential role of the aquifers in the Christchurch liquefaction needs also further scrutiny.

The liquefaction impacts on residential houses and pipe networks were generally similar, but again different in details. Even for a single event and area (e.g. in Christchurch during the 22 February 2011 earthquake) there were significant differences in the manifestation and impacts of liquefaction due to specific ground conditions and build environment (construction details, materials, age of construction, etc), hence, such variability in impacts between different events is to be expected. Further studies are required to understand both the characteristics of liquefaction and details about its impacts on the performance of buildings and pipe networks in order to enhance our liquefaction assessment procedures and seismic design considerations.

CONCLUSIONS

Widespread and very severe liquefaction occurred in native soils in Christchurch during the sequence of 2010-2011 earthquakes. While the 22 February earthquake was the most damaging, in many areas along Avon River the soils liquefied in multiple events. The liquefied soils were loose to very loose

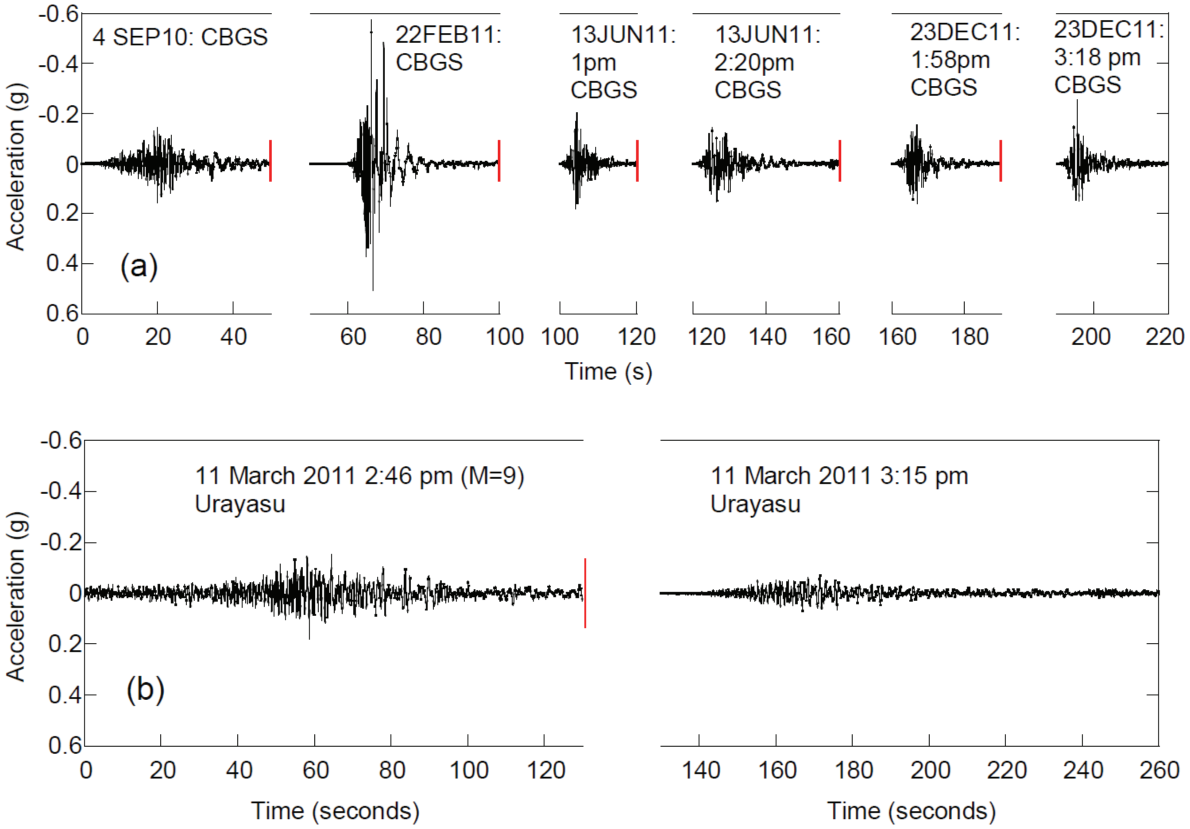

Fig. 14 Recorded acceleration time histories in Christchurch, New Zealand (records of 6 earthquakes at CBGS from 4 September 2010 to 23 December 2011) and Urayasu, Japan (records from the main shock and first larger aftershock in the 11 March 2011 earthquake)

fluvial deposits of clean sand and fines-containing sands (with non-plastic silts). The high water table and generated strong ground motions contributed to the extreme severity of the liquefaction and its impacts on buildings and infrastructure. The very intense ground water regime of Christchurch and supply of water through aquifers probably exacerbated the severity of liquefaction and its impacts on buildings and infrastructure.

Nearly 20,000 residential houses and properties were damaged by liquefaction, over 6,000 of which will be abandoned because they 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. There is a clear link between the severity of liquefaction and observed damage to the potable water network with nearly 80% of the damaged pipes being in liquefied areas, and 50% in areas of moderate to severe liquefaction. Also, a significant difference in the performance of different pipe materials was found, with the PE and PVC pipes showing much better performance than pipes of other materials. The Christchurch experience clearly shows that special considerations should be given to an improved design of the waste water system, which is more vulnerable to liquefaction and more difficult to recover/repair due its large depth of embedment.

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