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Impacts of Liquefaction on the Potable Water System of Christchurch in the 2010-2011 Canterbury (NZ) Earthquakes

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Abstract
This paper explores the performance of the potable water system of Christchurch during the series of strong local earthquakes that hit Canterbury, new Zealand, in 2010-2011. Widespread soil liquefaction, and associated ground deformation (failures) and lateral spreading shattered the lifelines and infrastructure over approximately one third of the city area. The waste water system was hit particularly hard, whereas the potable water system showed much greater resilience. Even though a large number of breaks/repairs were reported, the potable water service was quickly restored. Preliminary analyses of the repair records show: (a) clear increase in the level of damage to the pipe network with increase in the severity of liquefaction (with nearly 80% of the damaged watermains being in liquefied areas), and that PVC and PE pipes suffered several times less damage than other material pipes (i.e. asbestos cement, galvanized iron and steel pipes). Lessons learned regarding the performance of the system including development of performance objectives and liquefaction zoning maps based on earthquake observations are summarized.

Keywords
Buried pipe networks, earthquake damage; liquefaction; potable water system

INTRODUCTION

In the period between September 2010 and December 2011, Christchurch, the second largest city of New Zealand (population: ~ 350,000; area: ~ 450 km^2), was hit by a sequence of strong earthquakes including four (six) significant events: 4 September 2010 (M_w=7.1), 22 February 2011 (M_w=6.2), 13 June 2011 (a couple of earthquakes: M_w=5.3 at 1pm and M_w=6.0 at 2:20pm) and 23 December 2011 (a couple of earthquakes: M_w=5.8 at 1:58pm and M_w=6.0 at 3:18pm) earthquakes. The causative faults of all these 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 was particularly devastating. It caused 185 fatalities, collapse of two multi-storey reinforced concrete buildings, and collapse or partial collapse of many unreinforced masonry structures including the historic Christchurch Cathedral. The Central Business District (CBD) of Christchurch, which was the 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 estimated to be in the range between 25 and 30 billion NZ dollars (or 15% to 18% of New Zealand's GDP).

This paper focuses on the performance of potable water system of Christchurch during the 2010-2011 earthquakes and particularly examines the impacts of liquefaction on this pipe network during the 22 February 2011 earthquake (Cubrinovski et al., 2011). Characteristics of soil liquefaction and lateral spreading are first described, followed by detailed GIS analysis of the performance of the potable water system. The performance of different pipe materials is comparatively examined, and correlation between the damage of the network and severity of liquefaction is established. Performance objectives for the system are critically reviewed based on scrutiny of the observed performance of the system during the 2010-2011 earthquakes using domestic service, quality and business continuity criteria. Finally, a simple method for liquefaction zoning is presented providing basis for immediate use by designers, planners and decision-makers in the post-quake recovery of buried pipe networks.

SOIL LIQUEFACTION

Following the 22 February earthquake, an intensive drive-through reconnaissance was conducted through Christchurch to document the severity and extent of liquefaction throughout the city. The drive-through survey aimed at capturing surface evidence of liquefaction as quickly as possible and quantifying the severity of liquefaction in a systematic manner. The resulting liquefaction map (Cubrinovski and Taylor, 2011) is shown in Figure 1 where four areas of different liquefaction severity are indicated: (a) moderate to severe liquefaction (red areas; very large areas covered by large volumes of sand ejecta, mud and water, large distortion of ground and pavement surfaces, and significant liquefaction-induced impacts on buildings and infrastructure), (b) low to moderate liquefaction (yellow areas; with generally similar features as for the severe liquefaction, but of lesser intensity and extent), (c) liquefaction predominantly on roads with some on properties (magenta areas; heavy effects of liquefaction were seen predominantly on roads, with large sinkholes and 'vents' for pore pressure dissipation, and limited damage to properties/houses), and (d) traces of liquefaction (red symbols; with clear signs of liquefaction, but limited in extent and severity). The solid blue lines indicate roads where no signs of liquefaction were observed. The suburbs to the east of CBD along the Avon River were most severely affected by liquefaction and lateral spreading, which coincides with the area where approximately 7000 residential properties were considered not economical to repair and were abandoned. It is important to emphasize that the severity of liquefaction was not uniform and varied substantially even within one zone. In this sense, the liquefaction map is generalized area-based map (both spatially and in terms of severity) and is not applicable on a property basis. It does provide however an excellent record of observed ground performance associated with liquefaction caused by strong ground shaking.

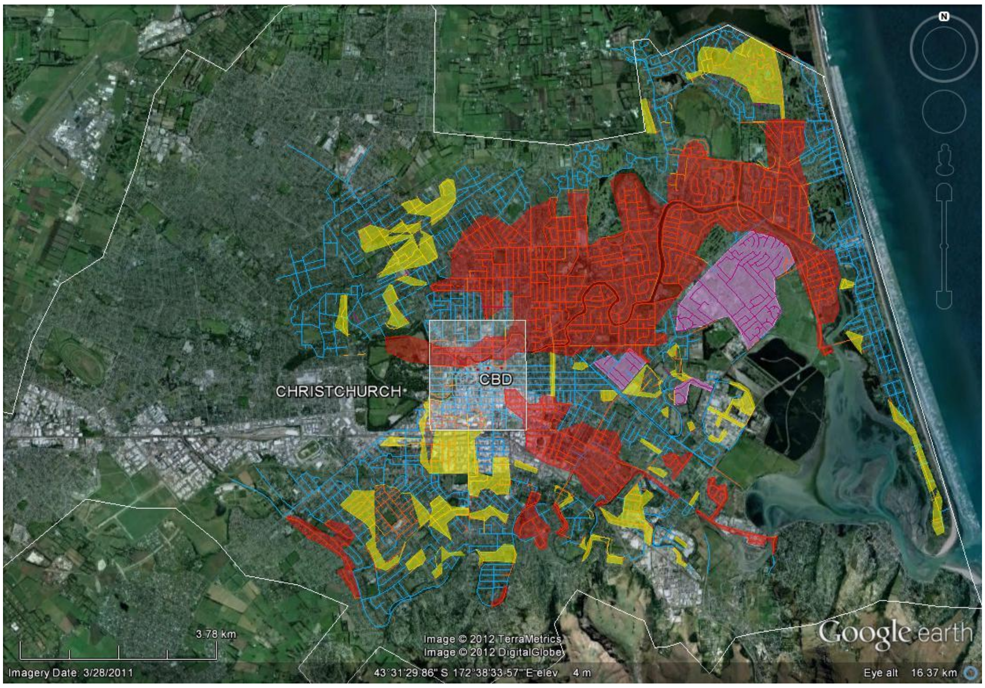

Figure 1. Liquefaction map of Christchurch after the 22 February 2011 earthquake (Cubrinovski and Taylor, 2011); the map coverers only parts of Christchurch and is area-based (i.e. it cannot be used on property basis)

Note that many sites in areas of moderate to severe liquefaction repeatedly liquefied in subsequent earthquakes producing strong or moderate ground shaking. Such extensive and severe liquefaction in native soils is exceptional by international standards. Several factors contributed to the very low liquefaction resistance of these soils: by their composition (non-plastic sands and silty sands), in situ state (loose to medium dense fully saturated soils with high water table), depositional environment (fluvial deposits) and age (relatively young soils) these soils have very high liquefaction potential (Cubrinovski and McCahon, 2011). In addition, the groundwater regime involving intense groundwater flow through artesian aquifers, wells and natural springs, was another factor contributing to the high liquefaction potential.

The liquefaction resulted in excessive and non-uniform ground deformation including large vertical displacements (settlement), lateral displacements, cracks and fissures in the ground, ground distortion and large volumes of sand/silt/water ejecta on the ground surface. The land damage was particularly pronounced in areas affected by lateral spreading along the Avon River (Cubrinovski et al., 2012). The permanent lateral displacements due to spreading reached up to 2.0 m at the river banks, and the zone affected by spreading extended up to a distance of 100-250 m from the waterway. The spreading induced substantial differential ground movements including large extensional deformation of the ground. For example, the extensional strains in the zone of largest ground cracks were on the order of 5-10% while the 'average' extensional strains in the area affected by spreading were approximately 0.5% - 1.0%. The spreading was often accompanied by slumping of the river banks (large settlement/subsidence), which was particularly noticeable at the approaches of bridges (Cubrinovski et al., 2013). Both lateral and vertical ground displacements induced by spreading where spatially non-uniform resulting in large localized deformation, stretching, tensile cracking and shearing of the ground. Such non-uniformity of the ground deformation was further exacerbated by the spatial variability in the severity of liquefaction, soil-structure interaction, and seepage action during water flow and dissipation of excess pore water pressures. Clearly, the buried pipes were subjected to very large, and highly non-uniform ground deformation and seismic loads which were often above the available capacity of the pipe network to sustain such movements/loads, hence resulting in widespread damage and numerous failures/breaks.

POTABLE WATER SYSTEM

Characteristics of the system

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 1700 km of watermains and 2000 km of submains (CCC 2010a). The water is supplied from approximately 150 wells at over 50 sites, 8 main storage reservoirs, 37 service reservoirs and 26 secondary pumping stations. The system is divided into distinct pressure zones and uses bulk storage reservoirs to assist in meeting peak demands and providing for emergencies. The wells and pumping stations are evenly distributed throughout the city, providing efficient delivery of water at a relatively uniform pressure within each zone.

Watermains and submains are located almost exclusively within legal roads, at shallow depths. The preferred location for principal watermains is in the carriageway, about 2.0-2.5 m from the kerb. Submains are typically installed beneath footpaths approximately 150mm from boundaries. Submains are served from crossovers which are usually located at fire hydrants. All crossovers are 50mm in diameter regardless of the submain size, with the preferred connection into either a tapped hydrant riser or into the main at a hydrant tee. The system is designed so that turning off a maximum of five valves can isolate any area in the network that serves no more than 50 properties. A typical layout of watermains and submains is shown in Figure 2.

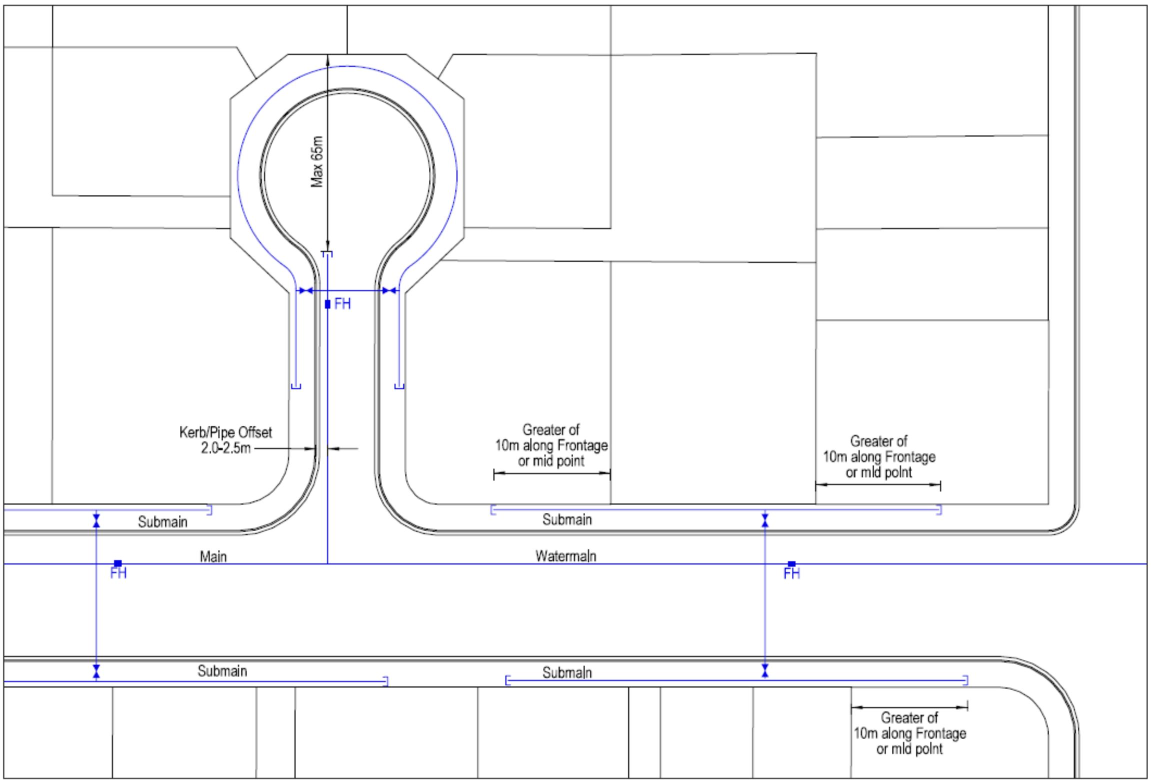

Figure 2. Typical layout of potable water mains and submains in Christchurch (CCC, 2010a)

Standard diameters of watermains are 100 mm to 600 mm, while submains have diameters of 50 mm and 63 mm. Watermains are laid in trenches 200-300 mm wider than the pipe diameter, at relatively shallow depths. The cover thickness depends on the pipe size, location and material, but is usually about 800mm (at least 750mm, but no more than 1.5m) for the standard mains diameters. Typical thickness of cover for submains is 300-500 mm. The trenches are backfilled with native soils and are compacted to 95%, 90% and 70% of the material's maximum dry density for trafficked, pedestrian and landscape areas, respectively. A sandy gravel (AP20 material) with at least 55% gravel size particles and 8-15% fines is used for haunching and bedding (CCC, 2010b).

A GIS layout of the watermains network is shown in Figure 3 in which three different colours are used for the pipes (solid lines) to distinguish between different pipe materials: polyvinyl chloride (PVC) pipes (green), polyethylene (PE) pipes (magenta) and other material pipes (grey). Out of the 1511km pipe length (covered in the preliminary analysis presented herein), 797km, or 52.7%, of the watermains are asbestos cement (AC) pipes; 398km, or 26.4%, are PVC pipes; 27km, or 1.8%, are steel pipes (S); only 15km, or nearly 1.0%, are PE pipes, and 273km, or 18.1%, are pipes made of other materials. The stated percentages and distribution of materials comprising the watermains system reflects various phases in the historical development of the system and selection of pipe materials. In recent years, three pipe materials have been used for watermains: ductile iron, PVC and PE, with combination of criteria being used in the selection of the pipe material (CCC, 2010a).

The submains network predominantly consists of PE pipes with a pipe length of 1318km, or 84.6%, out of the total length of 1557km, with PVC pipes and Galvanized Iron (GI) pipes having 52.3km and 161.9km, or 3.3% and 10.4%, of the total length, respectively. The water supply network is designed for an asset life of 100 years, which is also the minimum required design life of the pipes and fittings.

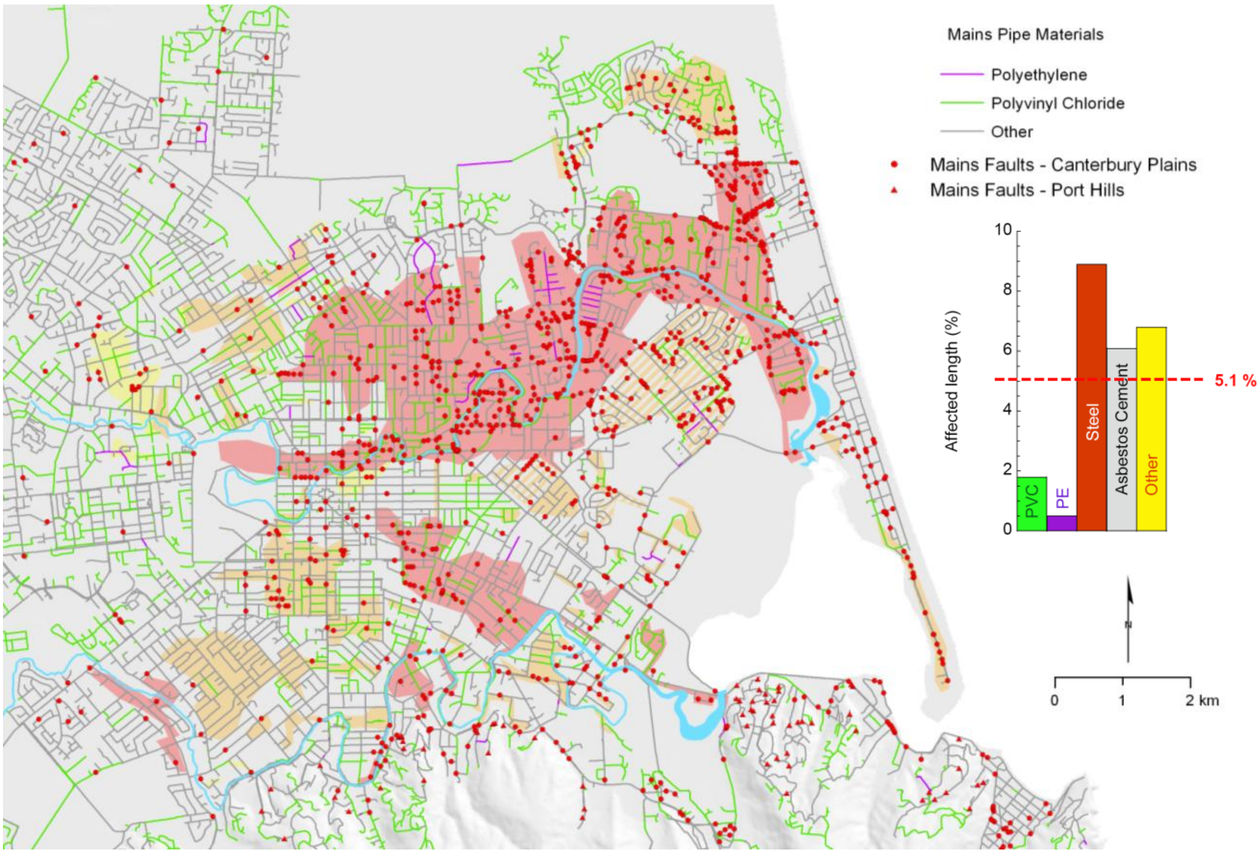

Figure 3. Locations of breaks/repairs (red symbols) of the watermains network of Christchurch caused by the 22 February 2011 earthquake (the background colours show the liquefaction map given in Figure 1)

Damage to the pipe network in the 22 February 2011 earthquake

Preliminary analyses of the performance of the potable water system were conducted in order to comparatively evaluate the performance of different pipe materials and correlate the pipe network damage to the liquefaction severity (Cubrinovski et al., 2011). The liquefaction-correlation analysis was conducted only for the area covered in the drive-through ground surveying shown in Figure 1, in order to compare rigorously the performance of the network across areas of different liquefaction severity including areas of no liquefaction.

Watermains. Figure 3 shows the location of repairs/faults on the watermains network following the 22 February 2011 earthquake (red symbols). In the inset of the figure, the performance of different pipe materials is summarized in a bar chart (for areas in the plains, excluding the hills). It shows that 5.1% of the total length of watermains was damaged, or 77.5 km out of 1511 km considered in the analysis. Steel pipes suffered the largest damage (8.9%), followed by AC pipes and other material pipes (6.1% and 6.8%, respectively), whereas much better performing were the PVC (1.8%) and PE (0.5%) pipes. It is noted that the sample lengths of PE and S pipes are considered insufficient for a robust statistical analysis and hence the respective results should be treated with caution.

Figure 3 also indicates in the background (with red, orange and yellow colours) the liquefaction map shown in Figure 1. Using this setup in the GIS framework, it was possible to correlate the reported pipe damage with the observed severity of liquefaction. The analyses indicated that 34 km of the damaged pipes or 58% of the damaged length in the area covered by the ground surveying 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. Thus, there is a clear link between liquefaction severity and damage to the pipe network. To further scrutinize the correlation between the damage to pipes and liquefaction severity, the results were summarized in Table 1 and in a series of bar charts shown in Figure 4. These results indicate that: (a) For all pipe materials, there is a clear increase in the affected length (percentage of damage) with increasing liquefaction severity; (b)for S, AC and other materials pipes, the percentage of damaged pipes in areas of severe liquefaction was very high, between 15% and 22%, and (c) PVC pipes suffered two to four times less damage than S, AC and other material pipes.

Table 1. Damage to watermains caused by the 22 February 2011 earthquake in relation to the pipe material and observed liquefaction severity

Pipe material	Total length (km)	Damaged length						
		Severe Liquefaction, in km & (%)	Low-Mod. Liquefaction, in km & (%)	Traces of liquefaction, in km & (%)	No Liquefaction in km & (%)	Not inspected, in km & (%)	Total length, km	Damaged length (%)
PVC	398.4	3.8 (7.9)	1.1 (3.7)	0	0.5 (0.73)	1.8 (0.72)	7.2	1.8
PE	14.6	0	0	0	0.07 (2.7)	0	0.1	0.5
S	27.3	1.0 (20.7)	0.5 (17.6)	0.04 (5.3)	0.3 (6.5)	0.6 (4.1)	2.4	8.9
AC	797.2	20.2 (22.1)	7.9 (10.6)	1.0 (9.9)	8.0 (5.8)	12.0 (2.5)	49.1	6.1
Other	273.5	9.0 (15.4)	2.3 (7.8)	0.4 (11.4)	2.5 (3.3)	4.5 (4.2)	18.7	6.8

*) Figures in brackets indicate percentage of damaged pipes within the particular class

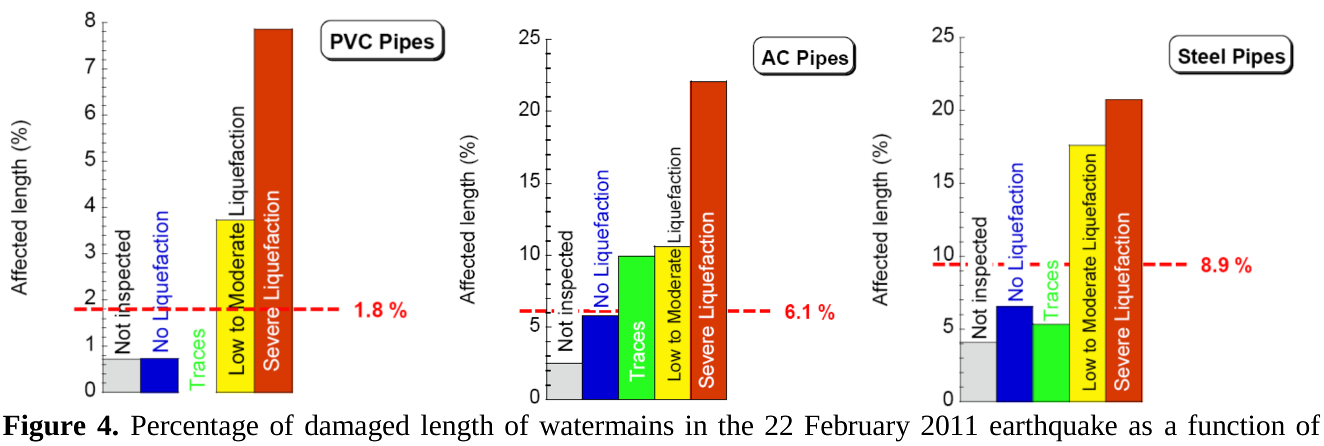

Figure 4. Percentage of damaged length of watermains in the 22 February 2011 earthquake as a function of pipe material and liquefaction severity

Submains. The submains network is shown in Figure 5 together with the locations of pipe breaks/repairs caused by the 22 February 2011 earthquake. Equivalent GIS based analyses to that presented above were also conducted for the submains network, the results of which are summarized in Figure 6. Key findings from these analyses include: (a) For PE pipes, the percentage of damaged length ranged between 1.4% (not inspected areas) and 5.2% (areas of severe liquefaction). Again, there was a clear increase in damage with liquefaction severity; (b) PE pipes suffered, on average, five to six times less damage than GI pipe; (c) GI pipes performed poorly with 17% damaged length in low to moderate liquefaction areas and 26% in areas of severe liquefaction,

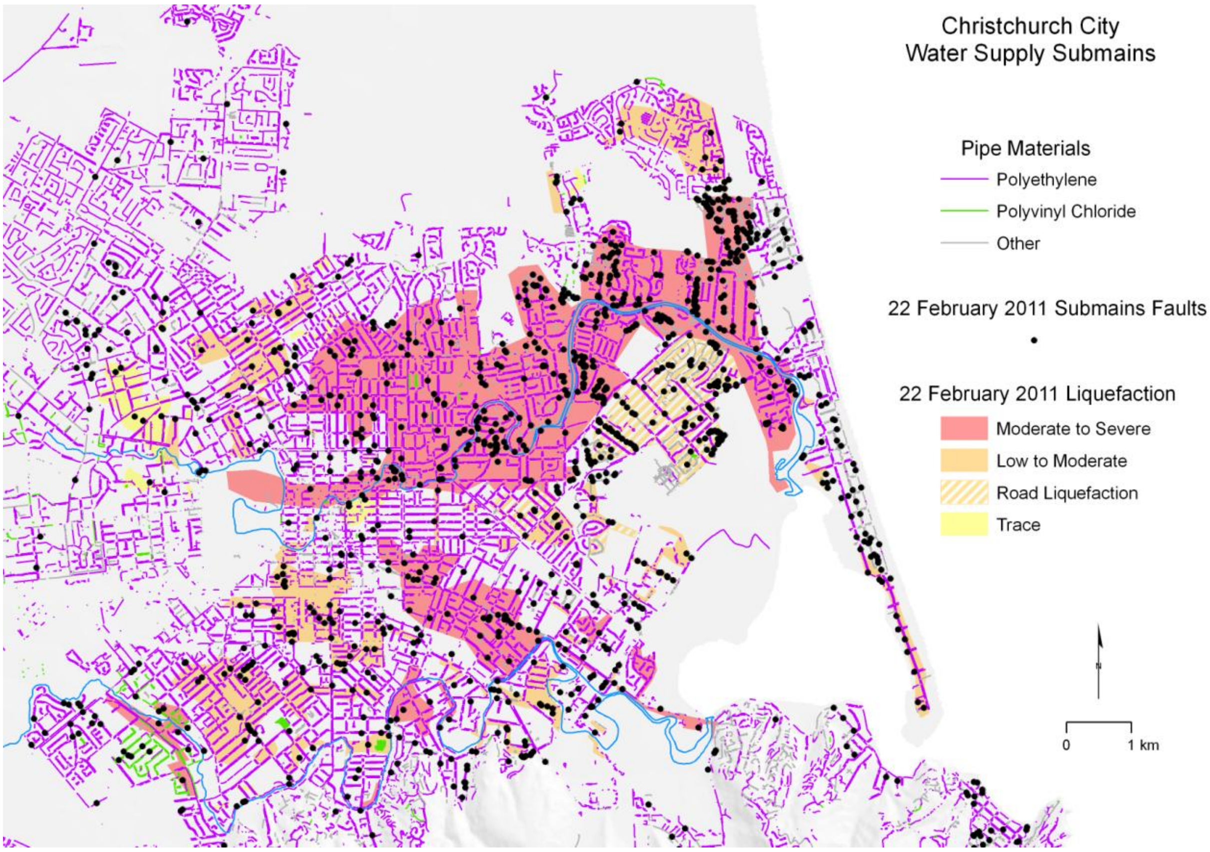

Figure 5. Locations of breaks/repairs (red symbols) of the submains network of Christchurch caused by the 22 February 2011 earthquake (the background colours show the liquefaction map given in Figure 1)

and (d) Comparing the repairs to watermains and submains, it appears that for each pipe material the percentage of affected submains was larger than the respective percentage of the affected mains. The total damaged length of submains was smaller, however, because over 80% of the submains were comprised of the well performing PE pipes.

It is important to emphasize that even though in these preliminary analyses the damage is always associated with a certain pipe material, the nominally defined 'failures' include (and probably are dominated at least for the PE pipes) by failures of particular components (joints, connections, fire hydrant details, crossovers, laterals) rather than actual failures of the pipe itself.

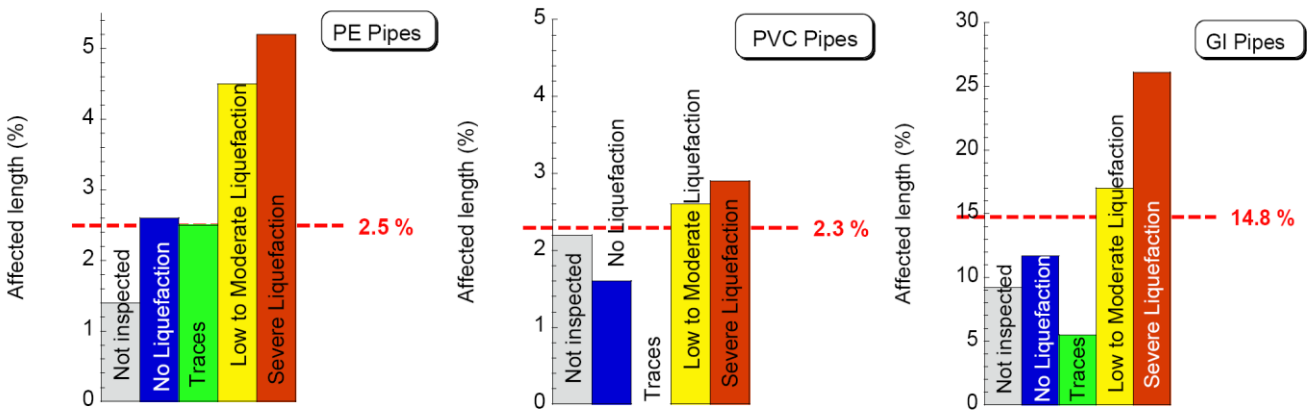

Figure 6. Percentage of damaged length of submains in the 22 February 2011 earthquake as a function of pipe material and liquefaction severity

Repair rates

The repair database for the potable water system provided by CCC (Christchurch City Council) and SCIRT (Stronger Christchurch Infrastructure Rebuild Team) included continuous daily repair records. O'Rourke et al. (2012) summarized these records as shown in Figure 7. The daily repair rates as a function of time are shown in Figure 7a in which several major earthquake events are indicated. Figure 7b shows the cumulative frequency of mains repairs derived from Figure 7a, from the 22 February 2011 earthquake to just before the 13 June 2011 earthquake. It can be seen that the initial frequency of repairs was very high (on average 40 repairs per day in the first three weeks after the earthquake), which through a transitional period (with 12 repairs per day) reduced after 50 days to a post-quake steady state repair rate of about 2-3 repairs per day. Note that the pre-quake repair rates for the potable water network of Christchurch were about 0.5 repairs per day on average.

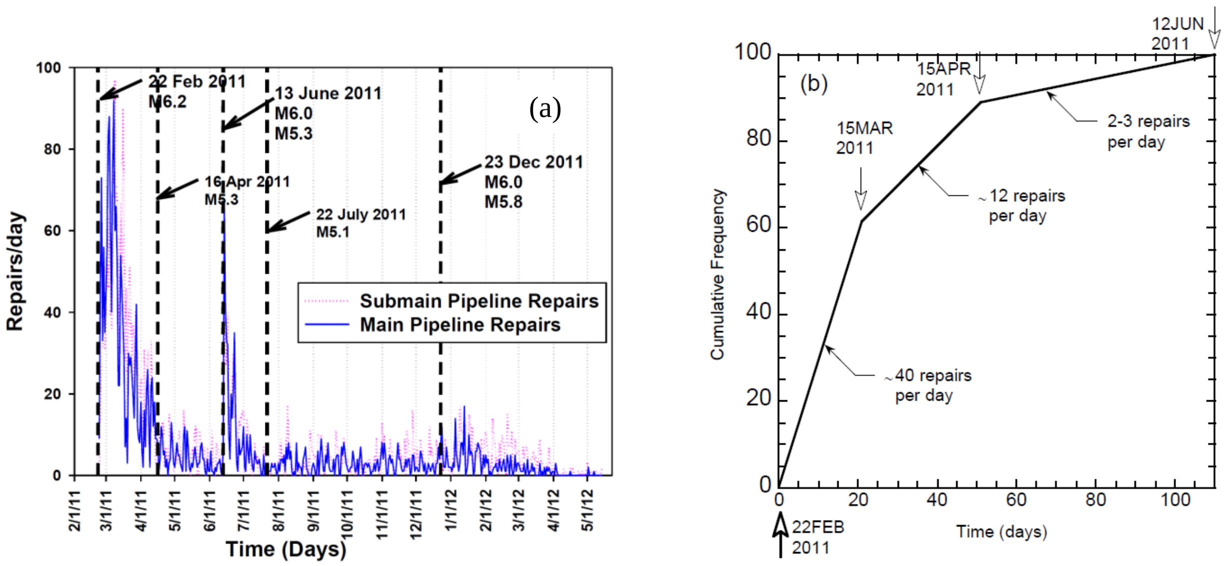

Figure 7. Mains and submains repairs with respect to time after the 22 February 2011 earthquake (after O'Rourke et al., 2012)

PERFORMANCE OBJECTIVES

Unlike ordinary buildings and high-importance structures for which a probabilistic hazard analysis is commonly adopted in the seismic assessment, a scenario-based assessment is considered more relevant for spatially distributed systems (such as pipe networks) since it provides more realistic scenario for the impacts of an earthquake on the whole network including direct damage to certain facilities and parts of the network, and also consequent loss of service due to interdependencies. In this context, the 2010-2011 earthquakes provided abundant information on the performance of the potable water and wastewater systems including feedback from residents and managers on the provided level and quality of service after the earthquakes.

The performance-based design of pipe networks (and any other structure for that matter) requires as a starting point to set the *performance objectives* for the system. These objectives are related to the severity of the ground shaking (i.e. smaller and more frequent earthquakes, versus large but rare events) as well as expected levels of service under different earthquake events or thresholds of tolerance of the community for different lifelines. Since such objectives were only loosely defined under the "provision of service", a discussion was initiated within the city council to address questions such as: "what are according to the Council, acceptable levels of service for the water and wastewater systems, for major events such as these earthquakes?"; "what is the acceptable percentage of the population to be without service, and for what period of time?". The ultimate goal was for CCC to establish specific performance objectives for the Water Supply and Wastewater Systems which will provide appropriate design objectives and performance that is balanced between effort and cost (capital and operational), and aims at realistic (achievable) but also acceptable performance levels from the public and the community as a whole. Table 2 (Henderson, 2011) below summarizes the provisional performance objectives derived independently by the CCC asset management team based on their technical and operational scrutiny of the performance of the systems in the 2010-2011 earthquakes and community reaction (Henderson, 2011). It is interesting to note that these criteria are in good agreement with those recommended by ALA (2005).

LIQUEFACTION RESISTANCE INDEX (LRI) MAP

CCC (service provider and owner/manager of the system) and SCIRT (organization in charge of rebuilding the infrastructure of Christchurch after the earthquakes) worked in parallel on quickly restoring water and wastewater services and also developing plans and strategies for rebuilding these systems. Hence, there was an immediate need for liquefaction zoning across the city that will provide assessment criteria for the design and decision-making in rebuilding the pipe networks. To this goal, a Liquefaction Resistance Index (LRI) map, shown in Figure 8, was developed (Cubrinovski et al., 2011) in which five zones of different liquefaction resistance are indicated. The map is based solely on observations from the 2010-2011 earthquakes, and in particular, use of dense array of recorded ground motions, and systematically documented manifestation (severity) of liquefaction (liquefaction map shown in Figure 1).

Note that the liquefaction resistance is defined in relative terms (e.g. Zone 3 has, on average, three times greater resistance than Zone 1), and that it specifically refers to shallow depths of the deposits (from the water table to 2 m below the water table) in which the pipelines are buried. For each LRI

Table 2. Provisional Performance Objectives for the Potable Water and Wastewater Systems of Christchurch Developed Based on Observations/Experience from the 2010-2011 Earthquakes (Henderson, 2011)

	Domestic Service - Disaster Recovery- Design Level of Service	
Time after quake	*Water Supply*	*Waste Water*
48 (72) hours	90% of Premises	85% of Premises
48 (72) hours	95% Critical facilities	95% Critical Facilities
4 (7) days	95% of premises	n/a
7 (14) days	99.5% of premises	90% of Premises
1 (2) month	n/a	99.5% of Premises
	Quality -Disaster Recovery -Design Levels of Service	
Time after quake	*Water Supply*	*Waste Water*
2 weeks	n/a	80% of effluent reaches treatment
1 month	90% of city receives water conforming to NZDWS	90%
3 (6) months	n/a	99%
3 months	n/a	Treatment (or lack of) not causing significant adverse environmental
6 months	n/a	Full Consent Compliance
	Business Continuity -Disaster Recovery -Design Level of Service	
Time after quake	*Water Supply*	*Waste Water*
1 month	95% of Industry/ commercial activity able to resume normal	90% of Industry/ commercial activity able to resume normal business
3 months		95%
6 (12) months		99%

zone, characteristic ranges of ground deformation (i.e. strains, settlements and lateral displacements) were also specified thus providing means for quick assessment and preliminary design considerations when rebuilding the pipe networks. Details of the methodology used in the development of the LRI map are given in Cubrinovski et al. (2011).

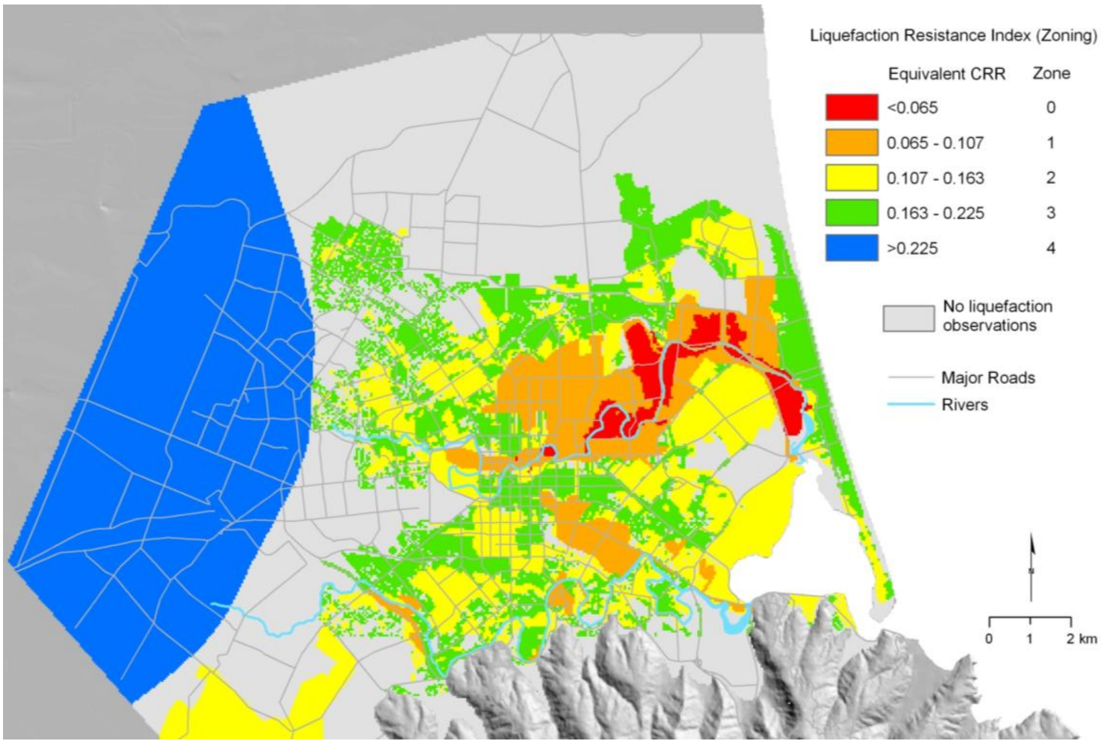

Figure 8. Liquefaction Resistance Index Map of Christchurch at water table depth based on observed liquefaction manifestation and recorded ground motions in the 2010-2011 earthquakes (Cubrinovski et al., 2011)

CONCLUDING REMARKS

Widespread liquefaction and associated lateral spreading in the 22 February 2011 earthquake caused extensive damage to the potable water system of Christchurch. There was a clear link between the severity of liquefaction and damage to the pipe network, with nearly 80% of the damaged watermains being in liquefied areas. Ductile materials and flexible pipe systems, such as PVC and PE pipes, performed very well and suffered several times less damage than other material pipes (i.e. asbestos cement and galvanized iron pipes in particular).

Even though a large number of breaks/repairs have been reported, the potable water service was quickly restored, and proved to be much more resilient than the wastewater system. It took 50 days to reach a post-quake steady state of 2-3 repairs per day for the watermains, which is about four times the average pre-quake rate of repairs. The city of Christchurch is now embarking on a long term and difficult recovery/rebuild after the 2010-2011 earthquakes. CCC and SCIRT are implementing a rebuild activity for the Christchurch infrastructure including the water and wastewater systems on the order of 500 million NZ dollars per year.

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References

American Lifelines Association (ALA) (2005). Seismic guidelines for water pipelines: March 2005.

Christchurch City Council (2010a). Construction Standard Specification, Part 4: Water Supply, p. 59.

Christchurch City Council, (2010b). Infrastructure Design Standard, Part 7: Water Supply, p. 46.

Cubrinovski M, Hughes M, Bradley B, McCahon I, McDonald Y, Simpson H, Cameron R, Christison M, Henderson B, Orense R and O'Rourke T. (2011). Liquefaction impacts on pipe networks. Short Term Recovery Project No. 6, Natural Hazards Research Platform, *University of Canterbury Report*, p.149.

Cubrinovski M, Taylor M 2011. Liquefaction map of Christchurch based on drive-through reconnaissance after the 22 February 2011 earthquake, University of Canterbury.

Cubrinovski, M., and McCahon, I. (2011). Foundations in deep alluvial soils. *Report for the Canterbury Earthquakes Royal Commission*, August 2011, p.38.

Cubrinovski M, Robinson K, Taylor M, Hughes, M and Orense R (2012). Lateral spreading and its impacts in urban areas in the 2010-2011 Christchurch earthquakes. *Special Issue on Canterbury Earthquakes, New Zealand Journal of Geology and Geophysics*, 255-269.

Cubrinovski M, Haskell, J., Winkley, A., Robinson and Wotherspoon L. (2013). Performance of bridges in liquefied deposits during the 2010-2011 Christchurch (New Zealand) earthquakes. *ASCE Journal of Performance of Constructed Facilities, Special issue on 'Performance of Bridges under Critical Natural Hazards'*, (in print).

Henderson, B. (2011). Pipe networks resilience level of service, Internal CCC discussion document.

O'Rourke, T., Jeon, S.-S., Toprak, S., Cubrinovski, M., Jung, J. (2012). Underground lifeline system performance during the Canterbury earthquake sequence. Keynote Paper, *Proc. 15WCEE*, Lisboa, September 2012, p.24.