Impact and Recovery of the Kaiapoi Water Supply Network following the September 4th 2010 Darfield Earthquake, New Zealand

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SUMMARY:
On September 4th 2010, a magnitude M=7.1 earthquake struck the Canterbury region, in New Zealand. During the event, referred to as Darfield earthquake, extensive liquefaction, differential subsidence, and ground cracking associated with lateral spreading occurred in areas close to major streams and rivers throughout Christchurch, Kaiapoi, and Taitapu. The town of Kaiapoi suffered considerable damage to the lifelines systems. This paper presents the analysis of the physical and functional impact of the Darfield earthquake on Kaiapoi water supply network, and the strategies adopted by the local council for assessing the extent of the damage and for promptly restoring the service to the fullest possible extent. The response to different levels of ground deformations for the wide range of pipe materials used within the Kaiapoi water network are analysed by processing and comparing the repair data with the land damage deformation data. The resulting repair rates are compared to previously derived fragility models to assess how closely they have estimated the physical impact of the earthquake on the network. The functionality restoration process and strategies adopted by the Local Council are analysed by assessing the number of people reconnected to the service for each repair and the amount of resources required to operate the repair.

Keywords: 4th September 2010 *Darfield Earthquake, Potable Water Supply Network, Pipeline Repair-Rate, Functionality Restoration.*

1. INTRODUCTION

At 4:35am (NZ Standard Time) on September 4th, 2010, the rupture of an unrecognized Greendale strike-slip fault beneath the Canterbury Plains of New Zealand's South Island produced an Mw 7.1 earthquake that caused widespread damage throughout the region. The hypocentre was about 40 km west of Christchurch City (main and largest city in New Zealand's South Island), at a depth of 10 km. The epicentre was close to the town of Darfield. The event produced a ≥ 28 km long, dextral strikeslip surface rupture trace, aligned approximately west-east, with a component of reverse faulting at depth (Quigley et al. 2010). Strong ground shaking resulted in felt intensities as much as MM9 (New Zealand Modified Mercalli Intensity) and peak ground accelerations over PGA=1.2g for areas close to the fault. During the event, referred to as Darfield earthquake, extensive liquefaction, differential subsidence, and ground cracking associated with lateral spreading occurred in areas close to major streams and rivers throughout Christchurch, Kaiapoi, and Taitapu, severely affecting lifelines systems and building stocks.

This paper presents the analysis of the physical and functional impact of the Darfield earthquake on Kaiapoi, Pines Beach and Kairaki water supply networks, and discusses the approach adopted by the local council for assessing the extent of the damage and for promptly restoring the service to the fullest possible extent. Kaiapoi, situated about 15km north of Christchurch City (Figure 1a) hosts a population of 11800 (according to Statistics NZ, 2011). Kaiapoi is known as the 'River Town' after the Kaiapoi River, a tributary of the Waimakariri River that flows through the centre of the town. Pines Beach and Kairaki Beach are located few kilometres north of Kaiapoi.

Following September 4th, 2010 earthquake, the following peak horizontal ground motions were recorded in Kaiapoi North School, (located at an epicentral distance of 44km, fault distance of 32km, on ground subsoil categories E, as defined in NZS1170.5, 2004): peak ground accelerations, PGA=0.42g, peak ground velocities PGV=0.539m/s, peak ground deformations PGD=0.425m (Cousins et al., 2010). Liquefaction-induced land damage was remarkable in areas close to the Kaiapoi River and other major streams throughout Kaiapoi. 31 km of sewer pipes, 32 km of water pipes, 12 km of drainage pipes, and 37 km of roads were damaged (Figure 1b), most of them (95%+) due to ground settlements or lateral spreads (Eidinger *et al.* 2011). Emergency repairs, including potable water pipe repairs, resulted in a cost of NZ$1,800,000 (at mid-October 2010). A boil water alert was maintained in Kaiapoi area until 19th September. There were no reports of disease due to water quality impacts.

Figure 1. September 4th, 2010 Darfield earthquake: a) Location of Kaiapoi in relation to the Greendale fault trace, Darfield town and Christchurch city (GNS Science, 2011); b) evidences of liquefaction in Kaiapoi.

Waimakariri District Council (WDC), the local council, was challenged with assessing and restoring the damaged networks. The paper is structured as outlined in the following. Section 2 of this paper presents and discusses the damage sustained by the potable water distribution network in Kaiapoi by processing and analysing the repair data collected by the local council. Section 3 presents a comparison between the observed repair rates, RR_O, (defined as the ratio of the number of observed damages over the total length of pipes), following the 4th September Darfield earthquake, and predicted repair rate, RR_P, resulting from analytical equations obtained by regression analysis of worldwide earthquake data (ALA 2001). The strategies and processed adopted to restore the full functionality of the networks in a few days following the earthquake are discussed and presented in Section 4.

2. IMPACT OF THE 4th SEPTEMBER DARFIELD EARTHQUAKE ON THE POTABLE WATER SUPPLY DISTRIBUTION NETWORK

2.1. Kaiapoi and Kairaki/Pines Beach Potable Water Supply System

The water supply systems of Kaiapoi and Kairaki/Pines Beach are urban water supplies with firefighting capacity. In particular, in Kaiapoi water system the water is sourced from six deep artesian wells, three for each one of the two headworks sites: Peraki Street and Darnley Square (Figure 2). All the six wells are secure groundwater sources complying with the microbiological and protozoan requirements of the Drinking Water Standards for NZ (WDC, 2009a, 2009b). Each well features a single submersible pump that pumps directly to storage tanks at the two headworks sites. The total well pump capacity of the system is estimated as 300 L/s or 25,920 cubic meters per day (WDC, 2009a, 2009b). A back-up generator is installed at the Darnley Square headworks to provide reliability of supply during periods of power outages. Darnley Square is the primary headworks and operates virtually 100% of the time. Peraki Street is used during summer months or when demand is high. The Darnley Square headworks features a small duty pump and two large pumps that operate as duty and assist when the small duty pump is not operating. The Peraki Street headworks features two pumps that both operate in tandem with the Darnley Square pumps. VSD (variable speed drives) are installed in both stations. Kairaki/Pines Beach water supply systems have similar structure and characteristics with Kaiapoi one: the water is sourced from two wells both certified as secure groundwater sources. The system includes three well pumps and a back-up generator.

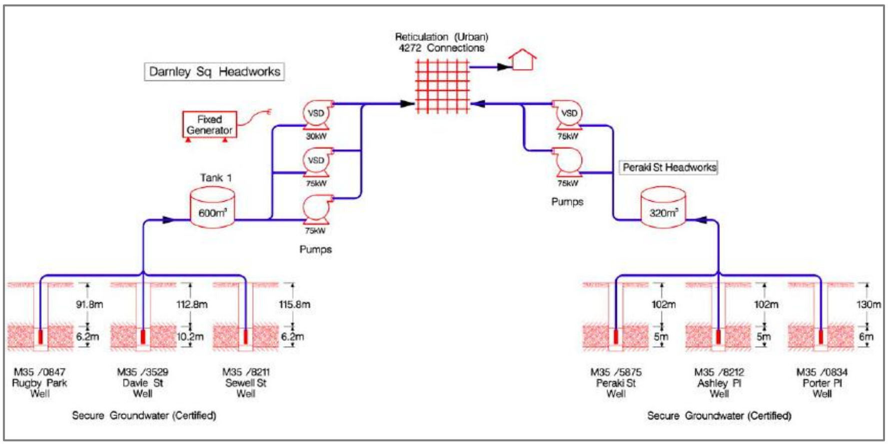


Figure 2. A schematic view of Kaiapoi potable water supply system: principal sources, treatment, and distribution system.

Kaiapoi and nearby Kairaki/Pines Beach water distribution network (referred to as reticulation in Figure 2) includes 106.31 km of mains and rider mains and 4600 service connections (WDC, 2009a, 2009b). Pipe material for mains and rider mains in the reticulation includes: Asbestos Cement, AC; PVC and U-PVC (unplasticised polyvinyl chloride polymer); High, Medium and Low Density Polyethylene, PE. Table 1 shows length (km) of mains and rider mains broken down into the aforementioned materials. The common styles of pipeline mains is Asbestos Cement (AC), or PVC, both with push-on type rubber-gasketed joints and pipeline diameters in the range from 150 mm to 200 mm. Polyethylene pipes, PE, (pipeline diameters in the range from 25 to 50 mm) branch off the mains and run parallel to the roads, serving as headers to the final laterals that serve individual customers (Eidinger *et al.* 2011).

Table 1. Kaiapoi and Kairaki/Pines Beach potable water supply distribution network: mains and rider mains pipe length, diameter, and joint type broken down by material.

Material	Length (km)	Diameter (mm)	Joint Type
Asbestos Cement (AC)	34.52	150-200	rubber-gasketed joints
PVC and U-PVC	35.94	50-100	rubber-gasketed joints
Polyethylene (PE)	35.48	25-50	–
Other	0.37	25-125	–

2.2. Analysis of the Physical Damage occurred to the Potable Water Distribution Network

Following the 4th September earthquake, the power was out for the all town of Kaiapoi. Some parts of the town were not reconnected to the power service for several days. Thanks to the presence of back-up diesel generator, Darnley Square headworks, Kaiapoi water system main Headworks, was operational by 10am on 4th September, 6 hours after the earthquake (Figure 2).

The reticulation of the water system was severely affected (damaged to buried pipes as discussed below). No significant damage was observed to any other system component (e.g. well, headwork, pumps).

Data on the repair activities to the potable water distribution network was collected by Waimakariri District Council and has been analysed in this paper to gain a better understanding of extent and type of damage which occurred to the reticulation of Kaiapoi and nearby Kairaki/Pines Beach water systems. Table 2 shows the number of repairs for the main components of the distribution network namely: main and rider main, house lateral, tody and valve. 140 repairs targeted the damage which occurred to mains or rider mains, 174 repairs addressed problems occurred to house laterals. Figure 3 presents the location of damage survey assessment points and following repairs made to the potable water distribution of Kaiapoi (left) and Kairaki/Pines Beach (right) network following the 4th September 2011 Darfield earthquake. The damage to pipes was spread across Kaiapoi with higher density of repairs near the Kaiapoi River, most significantly on the northern side of the town (Figure 3). To gain a first understanding of the performance of different pipe materials, the map of damage survey points and repairs was overlaid to the map of the water distribution network differentiated per pipe material. Table 2 presents the break-down of pipe repairs made to mains and rider mains for different material types, showing that more than 70% of the repairs targeted Asbestos Cement, AC pipes. 15% of the repair addressed damage to PVC pipes (Figure 4a). AC pipe in the Kaiapoi potable water distribution systems sustained massive damage (Figure 4b) being exposed up to 2 to 4 inches of settlements or 12 to 40 inches of lateral spreads (Eidinger *et al.* 2011).

Table 2. Number of significant repairs made on different components of Kaiapoi water distribution network following 4th September earthquake, broken down by material for mains and rider mains.

Component	N. of Repairs
Main/ Rider	172 (114 AC pipes , 21 PVC pipes, 1 PE pipes, 36 others)
House lateral	174
Toby	76
Valve	43

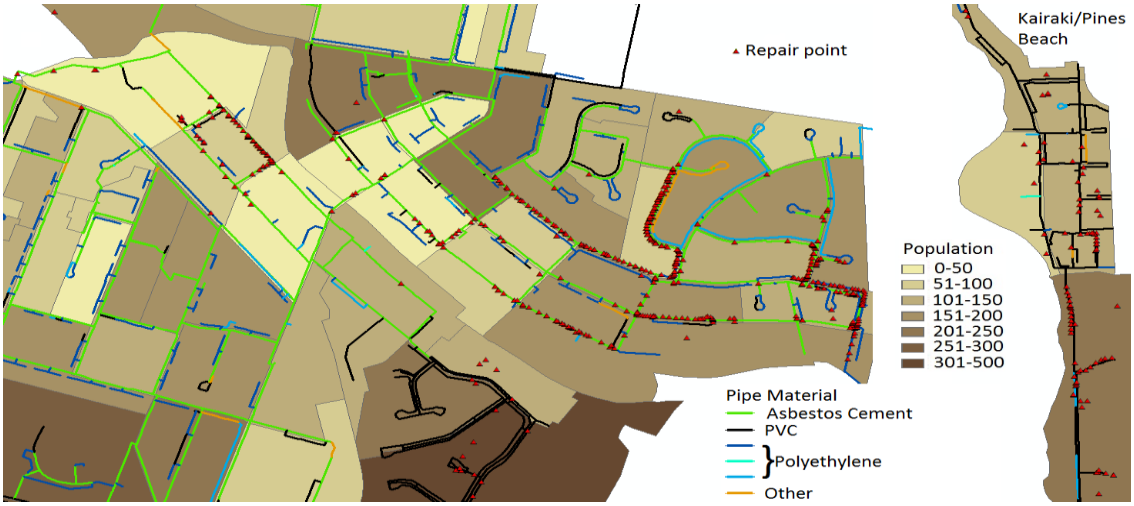


Figure 3. Map of repairs (red triangles) made to the potable water distribution of Kaiapoi (left) and Kairaki/Pines Beach (right) network following the 4th September 2011 Darfield earthquake overlaid to: i) potable water distribution network differentiated per pipe material; ii) population at mesh-block level.

2.3. Analysis of the observed vulnerability of different pipe materials to land deformations

To further investigate the vulnerability of different pipe materials to liquefaction-induced land deformation, maps of the potable water networks and of the repairs undertook after the 4th September Darfield earthquake were overlaid to a map representing the observed land damage deformations (Tonkin and Taylor, 2011). On behalf of the Earthquake Commission (EQC), Tonkin and Taylor (2011) assessed the liquefaction-induced land deformations which occurred in residential areas, following the 4th September 2010 earthquake and designated qualitative levels to describe it, namely: 1) minor to severe liquefaction; 2) moderate to major liquefaction; 3) severe lateral spreading (Figure 5).

The exposure of each pipe material to different levels of ground deformation was assessed and expressed in term of the percent of the total pipe length (Figure 6a). Repairs to mains and rider mains of each pipe material were then counted for each level of land deformation (Figure 6b). The exposure of each pipe material and number of repairs for each level of land deformation were compared to determine the relative vulnerability of each material to land deformations (Table 3).

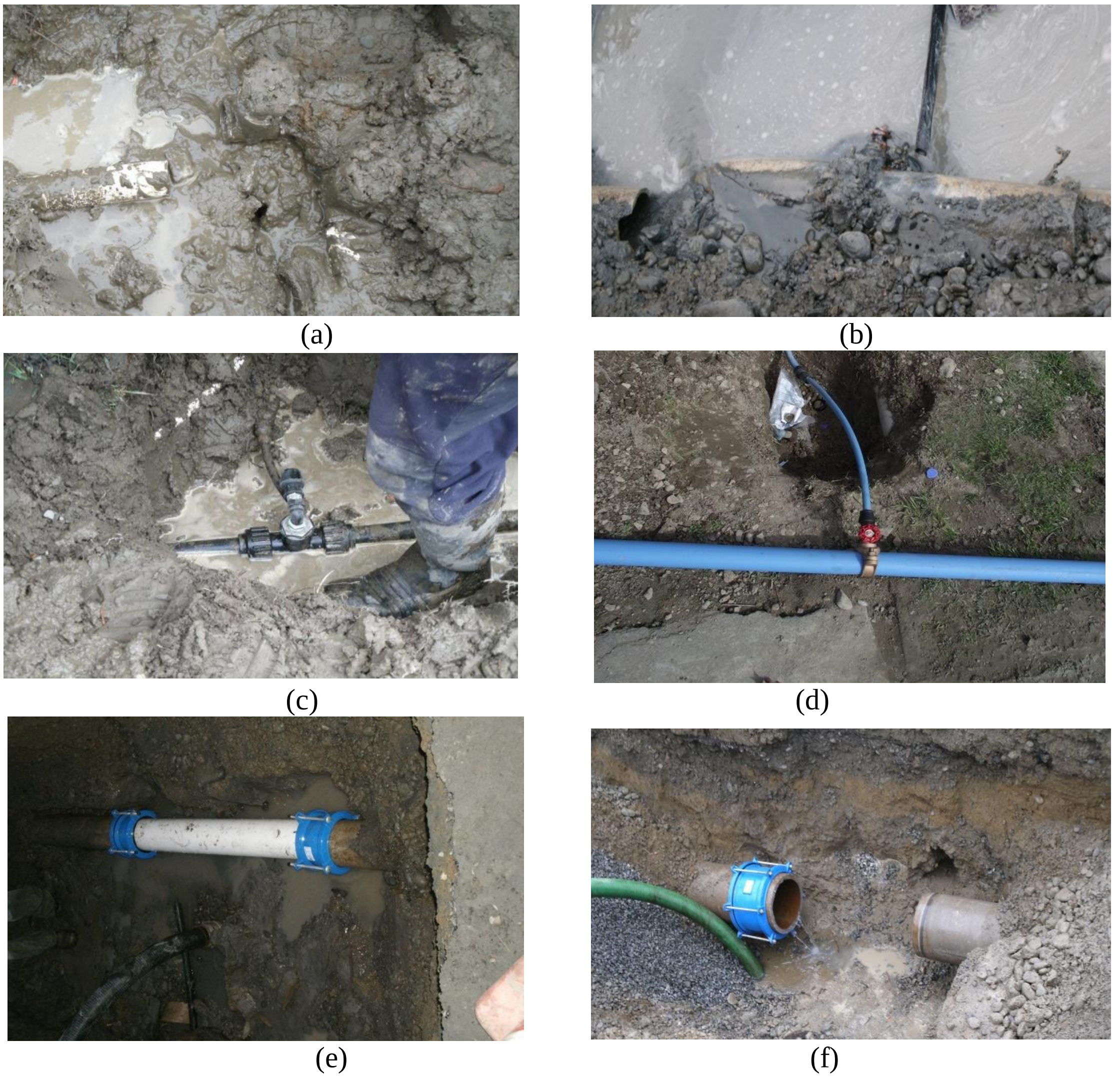


Figure 4. Pictures of damage sustained in Kaiapoi; (a) PVC main pulled away from joint due to severe lateral spreading; (b) AC main broken with broken house lateral connection; (c) disconnected house lateral; (d) temporary PE rider main installed above ground; (e) AC pipe repaired with a section of PVC; (f) water flowing out of cut open section of AC main being repaired (pictures courtesy of Ric Barber, WDC).

The largest proportion of pipes was located in areas that suffered minor to severe liquefaction, with Asbestos Cement AC pipes showing the higher level of exposure (Figure 6a). PVC pipes had the highest exposure to moderate to major liquefaction areas and were the only material present in areas affected by severe lateral spreading. Figure 6b presents the number of repairs made to each material for the same land deformation level. As seen in Table 2, AC pipes clearly had a higher number of repairs compared to the other pipe materials. The same trend was observed even in areas of moderate to major liquefaction where PVC pipes were more exposed (Figure 6a). AC pipes required a comparatively large number of repairs in areas where no land deformation was recorded. Focusing on PVC pipes, although they were more exposed to minor liquefaction, the greatest numbers of repairs resulted in areas of moderate to major liquefaction, (Figure 6). This could suggest a general good performance of PVC pipes when subjected to minor to moderate land deformation, starting to be affected at higher level of land deformations. PE pipes showed, relatively, the best performance with only one repair required in areas affected by minor to severe liquefaction, where PE pipes had an exposure similar to PVC pipes (Figure 6). Two repairs for PE pipes resulted in areas of moderate to major liquefaction. Data reported as “Unknown Results” in Figure 6b is data missing location information and coordinates, which could not therefore be used within the preliminary Geographical Information System, GIS analysis presented in this paper.

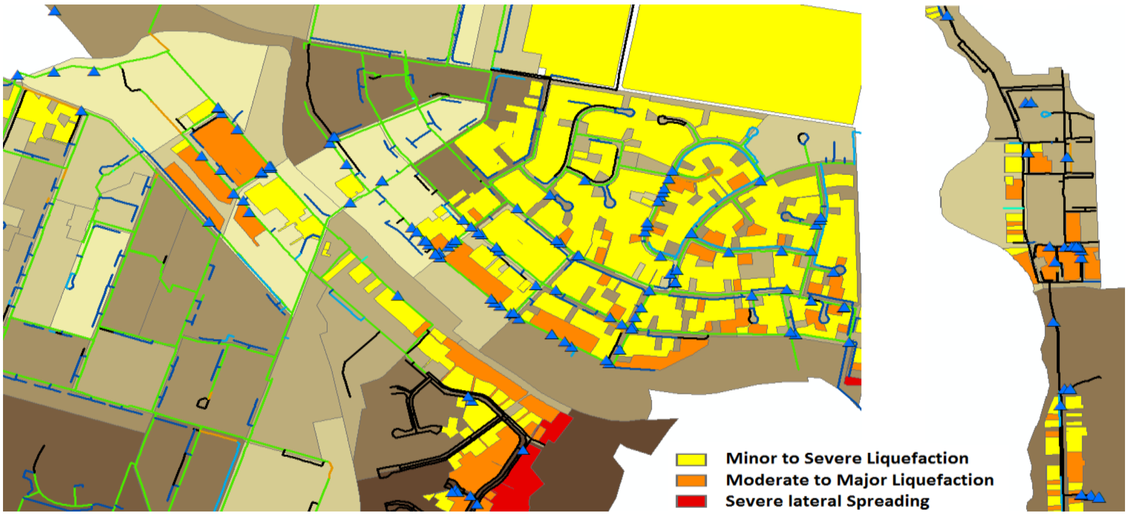


Figure 5. Repairs (blue triangles) made to the potable water distribution of Kaiapoi (left) and Kairaki/Pines Beach (right) network following the 4th September 2011 Darfield earthquake overlaid to the map representing different levels of observed land damage according to Tonkin and Taylor (2011).

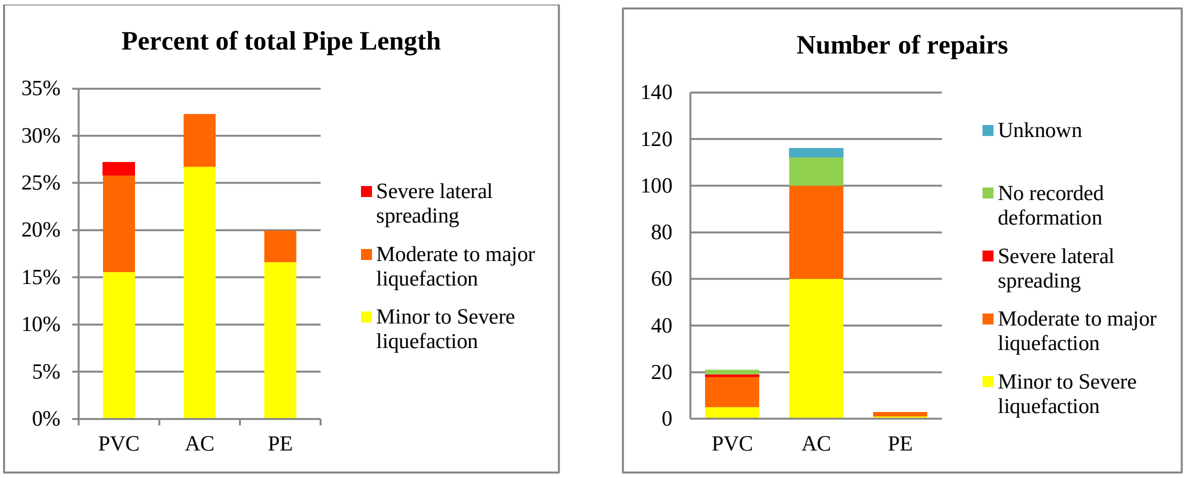


Figure 6. Vulnerability of different pipe materials to different levels of land damage: (as for Tonkin and Taylor, 2011 land damage map): a) percent of total length of pipe exposed to different level of land damage; b) number of repairs made to mains and rider mains of three most common pipe materials (namely, PVC, AC and PE) in Kaiapoi in areas of different land damage.

Table 3. Each pipe material and number of repairs for each level of land deformation

M	MSL			MML			SLS			NRD			Unknown			Total
	R	L	RR	R	L	RR	R	L	RR	R	L	RR	R	L	RR	L
AC	60	9.3	6.44	40	2.07	19.3	–	–	–	12	17.2	0.7	4	5.91	0.68	34.5
PVC	5	5.8	0.87	13	3.59	3.62	1	0.36	2.78	2	26.2	0.08	–	–		35.9
PE	1	6	0.17	2	1.06	1.89	–	–	–	–	–	–	–	28.4	–	35.5

M=Materials; R=repairs; L=Length (km); RR=Repair Rate;
MSL= Minor to Severe Liquefaction; MML= Minor to Severe Liquefaction; SLS= Severe Lateral Spreading; NRD= No Recorded Deformation

3. COMPARISON OF OBSERVED REPAIR RATE WITH REPAIR RATE PREDICTED BY AMERICAN LIFELINES ALLAIANCE, ALA FRAGILITY MODELS

Repair data for Kaiapoi and Kairaki/Pines Beach water networks following the 4th September Darfiled earthquake was assessed by processing the data on repair activities provided by WDC (2010) and compared with ALA repair rate vulnerability models (ALA 2001). Only repairs to mains and rider mains (pipes) were included in the analysis. The repair rate for each material was calculated as the number of repairs made to that material over the total length of that material pipe. From the pipe lengths in Table 1 and the number of repairs in Table 3, the repair rates for PVC and AC resulted respectively 0.59 repairs/km and 3.36 repairs/km.

For the sake of the comparison with ALA repair rate curves study, the assumption was made that the totality of the damage to the potable water distribution networks in Kaiapoi and consequent repair activities were induced by PGD mechanisms. The total observed repair rate, was therefore plotted on ALA backbone vulnerability curves, for PGD mechanisms (Equation 1):

$$RR = K_2(1.06)PGD^{0.319} \qquad (1)$$

where RR, repairs per unit length of pipe, namely 1,000 feet (0.3048 Km) of main pipe; PGD, permanent ground deformation, inches; K_2 modification factor to account for a possible modified seismic behaviour due to: pipe material, joint type. Ground failure mechanisms used in ALA repair rate model for PGD mechanisms include liquefaction (88%) and local tectonic uplift (12%).
Figure 7a shows the ALA backbone RR curves for PGD mechanisms and the data set used for deriving the curves through regression analysis when assuming K_2=1 that generically represents all kinds of pipe materials, joints and diameters (Figure 7a) and recorded PGD=0.45m in Kaiapoi during 4th September Darfield earthquake (Cousin et al. 2010).

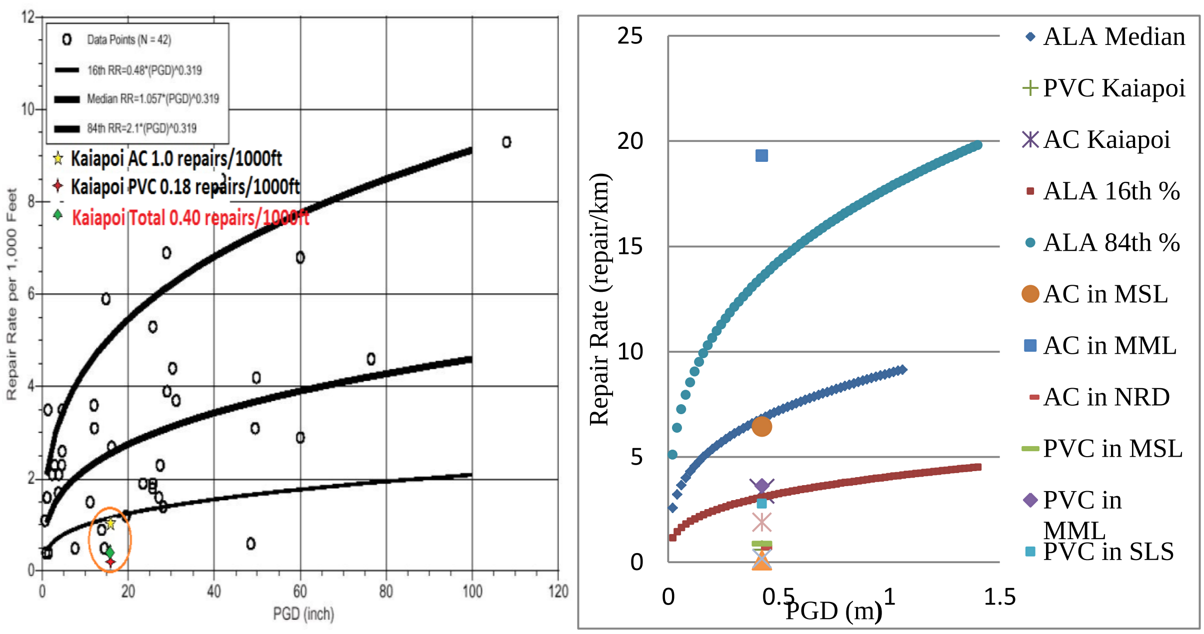


Figure 7. Comparison between observed Repair Rate for Kaiapoi and Kairaki/Pines Beach potable water networks following the 4th September Darfiled and ALA repair rate predictive models: a) ALA backbone RR curve for PGD mechanisms and K_2=1; b) ALA curves for AC and PVC pipes with rubber gasket joints and repair rates of different materials for each level of land deformation (Table 3) (K_2=0.8).

Knowing pipe materials and joint types for all the distribution network in Kaiapoi it has been moreover possible to specify a value for the modification factor in Equation 2 resulting, in K_2 =0.8 for both Asbestos Cement, AC and for PVC pipes with rubber gasket joints (ALA 2001). As a matter of fact, due to the lack of empirical data on PVC pipes, ALA (2001) proposes to consider the performance of PVC pipes, and therefore the expected repair rates similar to AC ones. . Figure 7b shows ALA RR curves for PGD mechanisms, represented in metric system, and when assuming a modification factor K_2=0.8. The repair rates observed in Kaiapoi (converted to repairs/1000ft for Figure 7a) were plotted in the same graphs. The repair rate observed in Kaiapoi for AC pipes is just within the 16th percentile curve. Observed repair rate for PVC pipes is lower than 16^{th} percentile and lower of any data set point. The assumption of PVC pipes, behaving similarly as AC one might be too conservative. It is worth highlighting that the PGD descriptor ignores any variation in the amount of ground displacement and the direction of ground displacement relative to the pipeline. If this level of details is desired, then site-specific analytical methods should be used instead of area-wide vulnerability functions (ALA 2001). Also it is important to remember that ALA models are conceived and designed as area wide functions, providing a repair rate for the whole area as a function of a maximum level of hazard expected in a certain area. Existing repair rate functions may lead to over-estimate the expected repair rate for Kaiapoi and Kairaki/Pines Beach water networks that include 60% PVC and PE pipes.

4. FUNCTIONALITY RESTORATION OF KAIAPOI WATER NETWORK

A prompt restoration of the potable water service functionality was the first priority set by the local Council (Section 4) following 4^{th} September 2010 Darfiled earthquake. To this aim temporary repairs were put in place where possible, including: i) installation of temporary PE rider main above ground (Figure 4d); ii) installation of external clamps and insertion of a new sections of PVC pipe cut into damaged pipes, where the damage was limited (Figures 4e and 4f). AC pipes had to be entirely replaced where the damage was more extensive. Nine crews, comprising of over 30 people, were employed in the immediate recovery phase following the 4th September earthquake. Six affected areas were identified in the territory of Kaiapoi and Kairaki/Pines Beach. Each of the six areas had one or more crews assigned to perform repairs. The crews were asked to report back three times daily on their progress to the Utility Manager at the emergency management centre, EQC, set up by the Council (Figure 8a). The repairs made along with any new required repair were updated daily (Gary Boot and Rick Barber, WDC, personal communication) on both the "Criticality" plan, which showed the most critical mains in WDC network and on the reticulation map (Figure 8b). This enabled WDC Utilities Managers to: get an updated picture of where they were up to; set intervention priorities; and make decision on resources redirection, when and where necessary. While managing the emergency, the local Council did not have an established procedure and/or available tool for assessing and quantifying: 1) the number of costumers that lost access to the potable water service following the earthquake; 2) the number of costumers reconnected to the service after each set of repair; 3) how different repair strategies could have possibly increased or speeded up the restoration of the functionality. However, based on expert judgment the Council was able to estimate that 85% of the water was restored on day one, following the earthquake and 90% of the service was restored on day two (Gary Boot and Rick Barber, WDC personal communication).

A simplified approach has been adopted by the authors and presented in this paper for drawing, based on repair data, a functionality restoration curve, providing the percentage of costumers reconnected to the potable water service as a function of time. Information on date (day and month) was available for each one of the repairs made following 4^{th} September 2010 earthquake. Repairs were frequent and high in number until 30th September 2010; few repairs were made at infrequent intervals after that date (Figure 8). As a first step, a layer, available from Statistics New Zealand and representing population at a mesh block level was overlaid with the pipe network and repair data layers (Figure 3). Reference was made to the repairs to main and rider-mains for estimating areas that could possibly have not access to potable water service. The following three steps were performed:

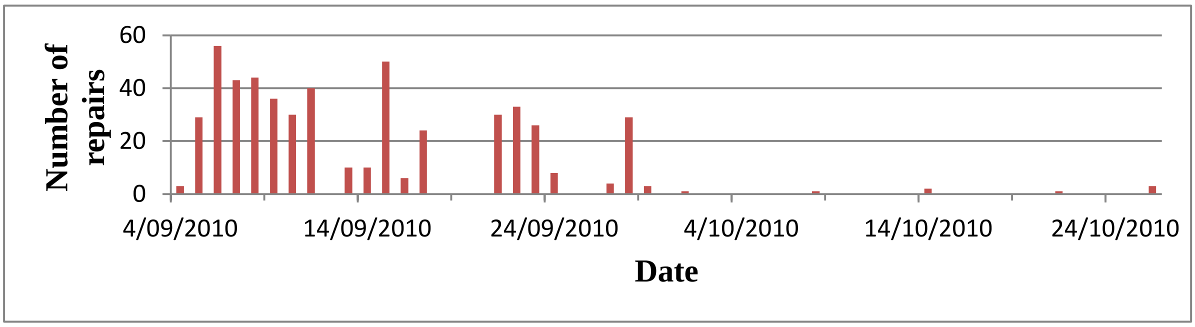
1. For each mesh-block, the number of lateral connections was counted and the average population per connection was assessed;

2. The assumption was made that pipes were non-functional in case of any point of repair enclosed in their length;
3. The number of costumers non-connected to the service was estimated summing on the average population per connection (from step 1) for the number of connections cutting off (step 2), due to on-going repair activities and used.

By performing the aforementioned steps, it was estimated, that around 1700 costumers did not have access to the potable water service in Kaiapoi and Kairaki/Pines Beach immediately following the earthquake. For each day following September 4th, the number of people reconnected to the potable water service was assessed, iterating the same process after identifying the repaired pipes.

(a)

(b)



(c)

Figure 8. Post-event restoration of functionality of WDC water-system: a) meeting at EQC to record and discuss repair progresses; b) works in progress to repair fractured AC sewer rising main pipe in Kaiapoi; c) Number of repairs made in Kaiapoi and Kairaki/Pines Beach from September 4th 2010 to November 2010.

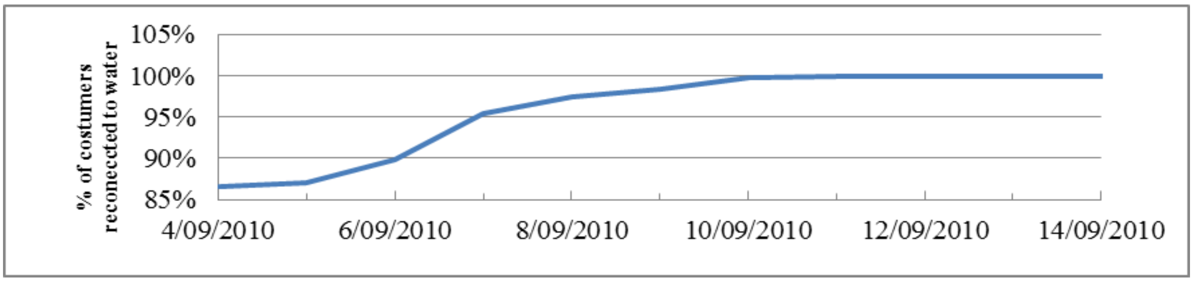


Figure9. Percentage of Kaiapoi population without water over time from September 4th 2010 estimated by combining observed repairs and population data from 2006 Census (according to Statistic NZ).

The cumulative population restored each day was recorded and compared to the total population of Kaiapoi. Figure 9 shows the percent of total population with water as it was restored, with only repairs within Kaiapoi considered (i.e. not Kairaki/Pines Beach). Assuming 5th of September as day one, the numbers resulting from the aforementioned simplified analysis resulted in: 86% of functionality restored on day one; 89% restored on day two. According to this analysis, water was restored to 99.9% of the population by the 11th of September (7 days after the earthquake). These results are very similar to the aforementioned ones provided by WCD Utility Managers. The inclusion of the analysis of the repairs to tobies and house laterals would have refined the analysis presented in Figure 9. Unfortunately a large number of these repair activities did not include information on the date.

6. CONCLUSIONS

Following the 4 September 2010 and 22 February 2011 earthquakes in Canterbury, New Zealand, the Natural Hazard Research Platform (NHRP) of New Zealand funded various projects to support and inform the decision making process during the recovery phase. The "Recovery of Lifelines" project aimed to inform and help meet the short-term operational needs of lifeline utilities by: 1) facilitating the accessibility to lifelines of best practice engineering details, along with hazards and vulnerability information already available from the local and international scientific community; 2) informing the international research community about the lifeline utility needs and information requirements (Giovinazzi and Wilson 2012). The analysis of the damage and restoration of functionality of the Kaiapoi and Kairaki/Pine Beach of the potable water system presented in this paper, and other similar simplified vulnerability and risk analyses performed for different lifelines systems (Giovinazzi et al. 2011, Giovinazzi and Wilson 2012), aimed to inform aspects of the immediate recovery decision making process of lifelines systems following the 4th September 2010 and 22nd February Canterbury earthquakes.

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