SEISMIC DAMAGES IN PIPELINES IN THE LIGHT OF PREVENTIVE MAINTENANCE

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Abstract: Learning from earthquakes has provided substantial progress in most of the engineering fields. The experience from the performance of pipelines during last earthquakes provided invaluable information and lead to new developments in the analysis and technologies. One of the important observations is that the pipe material and joint type are important for the response to earthquake loading. However, pipe compositions of pipeline systems may differ in cities and countries. The comparisons of water distribution networks in various countries show that pipe compositions (including joint types) in the water distribution networks differ significantly from country to country. The history and development of water supply systems in urban areas of countries affect the existing pipe compositions. Especially, asbestos cement and old cast iron pipes are well known for their high damage rates during earthquakes. It is better to put in the most proper pipeline from the start as replacing or retrofitting the pipelines later requires substantial investment. However, for the existing distribution systems, “preventive maintenance” and “proactive management” concept is getting more attraction. The primary goal of PM is thus to prevent the failure of components of the network before they actually occur by using advanced methods of statistical and risk analysis. This paper evaluates the water pipelines and seismic damage to the pipelines from the recent earthquakes in the light of preventive maintenance concept. Especially, the water pipelines performance during Christchurch earthquake in New Zealand is taken as a case study here.

Key words: Water Distribution Systems, Earthquake, Christchurch, Breaks, Leaks

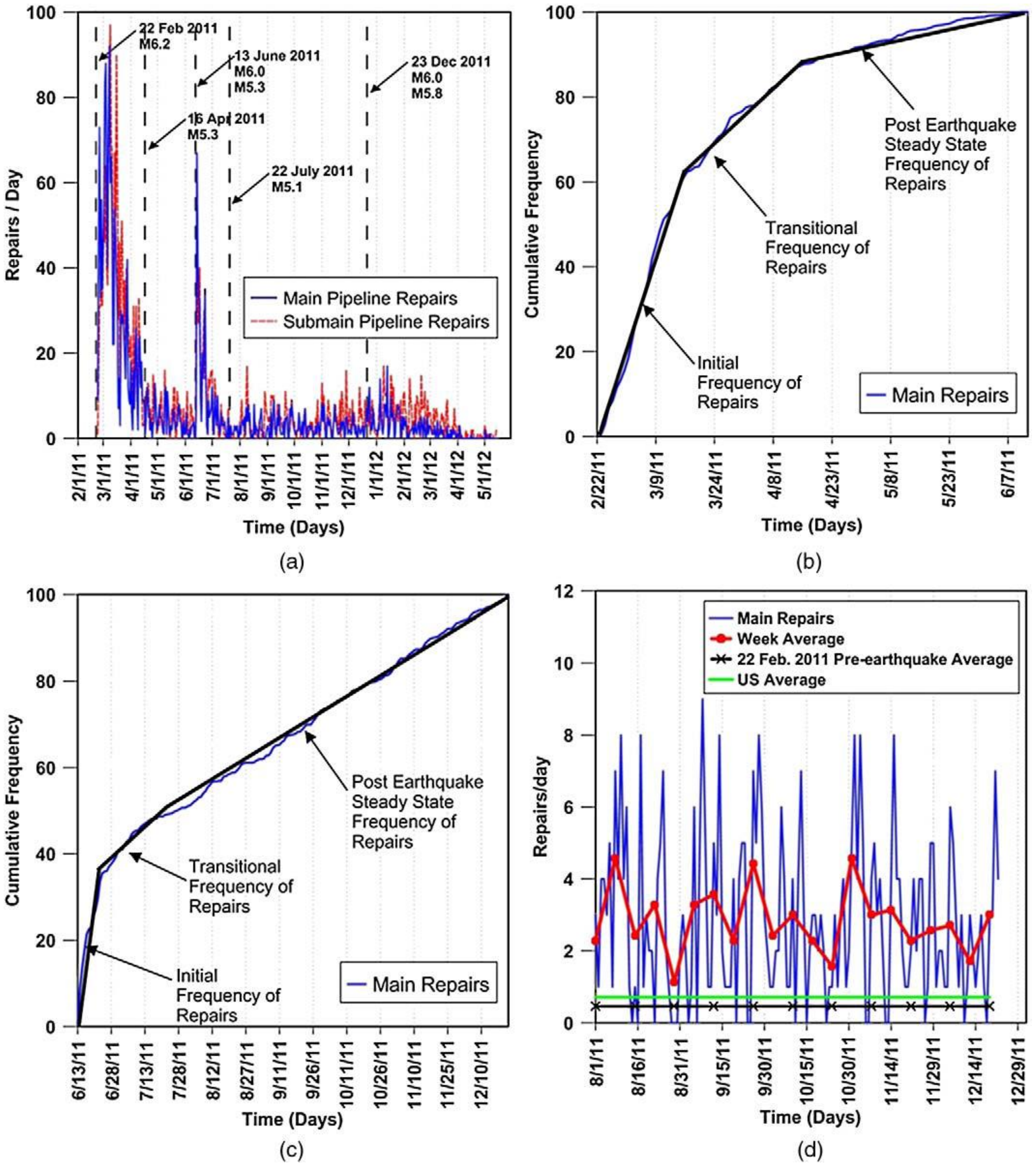
1. INTRODUCTION

During the service life of pipelines, as soon as the demand by the loading exceeds the capacity of the pipeline, damage occurs and the material (petroleum, gas, water, etc.) carried by the pipelines leaks. In essence, considering the pipeline is designed appropriately, any damage can occur as a result of increase in the loading or the decrease in the capacity. Increase in the loading can be for example due to traffic or temperature loads whereas decrease in the capacity can be for example due to worn-out pipes (Toprak et al., 2012). Buried pipes of a distribution system are worn in the length of time because of the temperature, soil moisture, corrosion and other aging effects. Aging of a pipe is unavoidable but this process may be delayed by some precautions. Cathodic protection for steel pipes, lining and coating for steel and ductile iron pipes are some anti-aging techniques. In the design phase of a water distribution system, analyzing the temperature changes in the area, pressure values of the system, chemical components of the soil and ground water helps for the selection of long life pipe material and suitable burial depth of pipes.

Because of the above stated factors, water distribution systems require maintenance repairs even without a seismic loading. Natural disasters such as earthquakes apply extreme loadings in a very short time and result in more damages. Depending on the number and type of damages pipeline systems may not convey the material they are carrying as designed and the performance level decreases. Because of the extensive damage occurred after some major earthquakes, it was observed that the performance levels of the pipeline systems dropped to zero and months, even years were required to bring the performance levels to the original state. Canterbury earthquake sequence in New Zealand can be given as a recent example. Following the 7.1 Mw Sept. 4, 2010 Darfield earthquake, thousands of aftershocks with Mw as high as 6.2 have been recorded in the area of Christchurch, NZ. These earthquakes, termed the Canterbury earthquake sequence are unprecedented in terms of repeated earthquake shocks with substantial levels of ground motion affecting a major city with modern infrastructure. Furthermore, the earthquakes were accompanied by multiple episodes of widespread and severe liquefaction with large permanent ground deformation (PGD) levels imposed on underground lifelines during each event (e.g., Toprak et al., 2015b, O'Rourke et al., 2012; 2014).

The water supply repair database for Christchurch is composed of continuous daily repair records for return of services covering a long period of Canterbury earthquake sequence (O'Rourke et al., 2012; 2014). The repair records include information on type of repair, location, and time. Figure 1a presents the daily repairs for mains and submains as a function of time. Submains are pipelines with diameters less than 75 mm, which branch off mains to provide water to a limited number of houses. Also shown in the figure are the two large earthquakes and select aftershocks. Figure 1b shows the cumulative frequency of main repairs, defined as cumulative percentage of total repairs, derived from Figure1a, from the time of the 22 February 2011 earthquake to just before the 13 June 2011 earthquake. It can be seen that the initial frequency of repairs is very high and reduces through a transitional phase to a steady state rate of repair, leading to the 13 June 2011 earthquake. A similar pattern of RRs is shown by the cumulative frequency distribution after the 13 June 2011 earthquake, with initial, transitional and post-earthquake steady state repair conditions identified in Figure 1c.

O'Rourke et al. (2012 and 2014) used the time at the start of the steady state repair conditions as the end of repair activities directly related to the large earthquakes. Several aftershocks during the immediate and steady state repair periods triggered local liquefaction and pipeline repairs, thus contributing to elevated repair rates. Moreover, ongoing repairs to roads and adjacent utilities also disturbed water mains already vulnerable because of main shock events. Hence, the daily repair rates approximately two months after main earthquakes depicted in Figure 1a are above the pre-earthquake average shown in Figure 1d. At some time after one of the large earthquakes, daily repairs will reduce to a rate consistent with aftershock effects as well as post-earthquake construction and associated maintenance requirements, which in this study are linked to steady state conditions. Figure 1d shows the repair rates per day and daily rate (total repairs for each week divided by seven days) for the steady state conditions after the 13 June 2011 earthquake. For comparison, the Christchurch average pre-earthquake (Christchurch City Council, 2006) and average U.S. water distribution system (Bardet et al. 2010) repair rates are shown in the figure. It can be seen that the steady state repair rate after large earthquakes in Christchurch is approximately three to four times greater than RRs not affected by prior earthquakes. This shows the adverse effect of seismic actions on weakening of pipelines or delineating minor damages even in the long term. Black (2013) made similar observations and stated that aside from the major pipe bursts that occurred immediately during the main earthquakes, more subtle damage also occurs and this damage may take weeks, months or years before it shows at the surface. This subtle damage includes leaks at deflected run-lead joints on cast iron (CI) and steel mains, joints on all pipe materials partially pulled out, breakage of CI gibault joints due to poor installation or over deflection due to permanent ground deformation (PGD) Black (2013).



(a) (b) (c) (d)

Figure 1. Water distribution repair characteristics with respect to time: (a) Daily main and submain repairs; (b) cumulative frequency of repairs between 22 February and 13 June 2011;(c) cumulative frequency of repairs between 13 June and 23 December 2011; and (d) observation of repairs in post-earthquake steady state stage. (O'Rourke et al. 2012; 2014)

According to Goodman and Burnie (2011), there are seven elements of a distribution integrity management program (DIMP) plan: Knowledge and understanding of the distribution system; identification of threats; evaluation and ranking risks; measures to address risks; Measuring the performance; periodic evaluation and improvement; reporting the results annually. DIMP contributes to "preventive maintenance" and "proactive management" concept. The primary goal of PM is to prevent the failure of components of the network before they actually occur by using advanced methods of statistical and risk analysis. This study presents and discusses the damages in the Christchurch water supply system in the liquefaction areas during the 22 February 2011 earthquake to help preventive maintenance assessments and loss estimation studies.

2. DAMAGE CHARACTERISTICS AND ASSESSMENTS

Lifelines are usually configured as networks. Carrying water from source to customer requires a network that consists of reservoirs, tanks, pipes, pumps, valves etc. It is also a requirement that water supply systems should provide water to customers at the desired flow rate and pressure. Damage to lifelines not only results in physical impairment and cost of repair at specific locations, but also the losses of connectivity and potential for more widespread and serious losses of functionality throughout the network (Wang and O'Rourke, 2008). Basic level seismic assessment studies of water supply systems generally predict the extent of the damages by using the loss estimation methods. More comprehensive seismic assessment studies model the system as a whole and use hydraulic network concepts. A hydraulic network is a mathematical model of a water distribution system in which the physical components are represented as nodes and links. Pipes are represented by links in the hydraulic network, junctions of the pipelines are represented by nodes and they accepted as water discharge points to the customers. In the event of an earthquake a water distribution system may sustain various kinds of damage. Previous research shows that buried pipelines in a water distribution system are the most vulnerable components (ATC, 1991). GIRAFFE (Graphical Iterative Response analysis for Flow Following Earthquakes) software and its methodology developed at Cornell University is a good example to use for the hydraulic analysis of the damaged water supply systems (Cornell University, 2007). GIRAFFE works iteratively with the EPANET which is a computer program that performs extended period simulation of hydraulic and water quality behavior within pressurized pipe networks (EPA, 2000).

In loss estimation studies and hydraulic models, pipe damage can be categorized as a break or leak in accordance with the characteristics of the damage. Being a break or leak affects the performance of the system. A break is defined as the complete separation of a pipeline, such that no flow will pass between the two adjacent sections of the broken pipe. In case of the break, water flows from the two broken ends into the surrounding soil. A leak is defined as a gap in pipe, such that water will continue to flow through the pipeline, while some loss of pressure and flow through the leak. Leaks may be classified into five types as annular disengagement, round crack, longitudinal crack, local loss of pipe wall and local tear of pipe wall which are frequent leak types for metallic pipes (Shi and O'Rourke, 2008). As an example, HAZUS which is common loss estimation software considers two damage states for pipelines as leaks and breaks (HAZUS, 2007). Generally when a pipe is damaged due to ground failure, the type of damage is likely to be a break while when a pipe is damaged due to seismic wave propagation, the type of damage is likely to be leak. In the HAZUS loss methodology, it is assumed that damage due to seismic waves will consist of 80% leaks and 20% breaks, while damage due to ground failure will consist of 20% leaks and 80% breaks.

The repair records from Christchurch water supply system for the 22 February 2011 earthquake include information on type of repair, location, and time, but do not always provide enough information to determine if the repair is a leak or a break (loss of continuity due to joint pullout or pipe separation after rupture). The authors of this paper did their best with the existing database to assess the pipe damages according to pipe material type. The focus of the study is the pipeline damages in the liquefaction areas of Christchurch. Figure 2 shows coverage of liquefaction associated with pipeline distribution and repairs for 22 Feb. 2011 earthquake. The damages in liquefaction zones can result from lateral strains or angular distortions in the soil. A comprehensive discussion of the correlations between pipeline damages and lateral strains or angular distortions is available in Toprak, et al. (2014; 2015a) and O'Rourke et al. (2014). The total length of pipelines in liquefaction areas are; 405.7 km asbestos cement (AC), 130.9 km cast iron (CI), 111.9 km polyvinyl chloride (PVC), 48.9 km modified polyvinyl chloride (MPVC) and 141.9 km other types. Figure 3 shows different pipe damages from during Canterbury earthquake sequence.

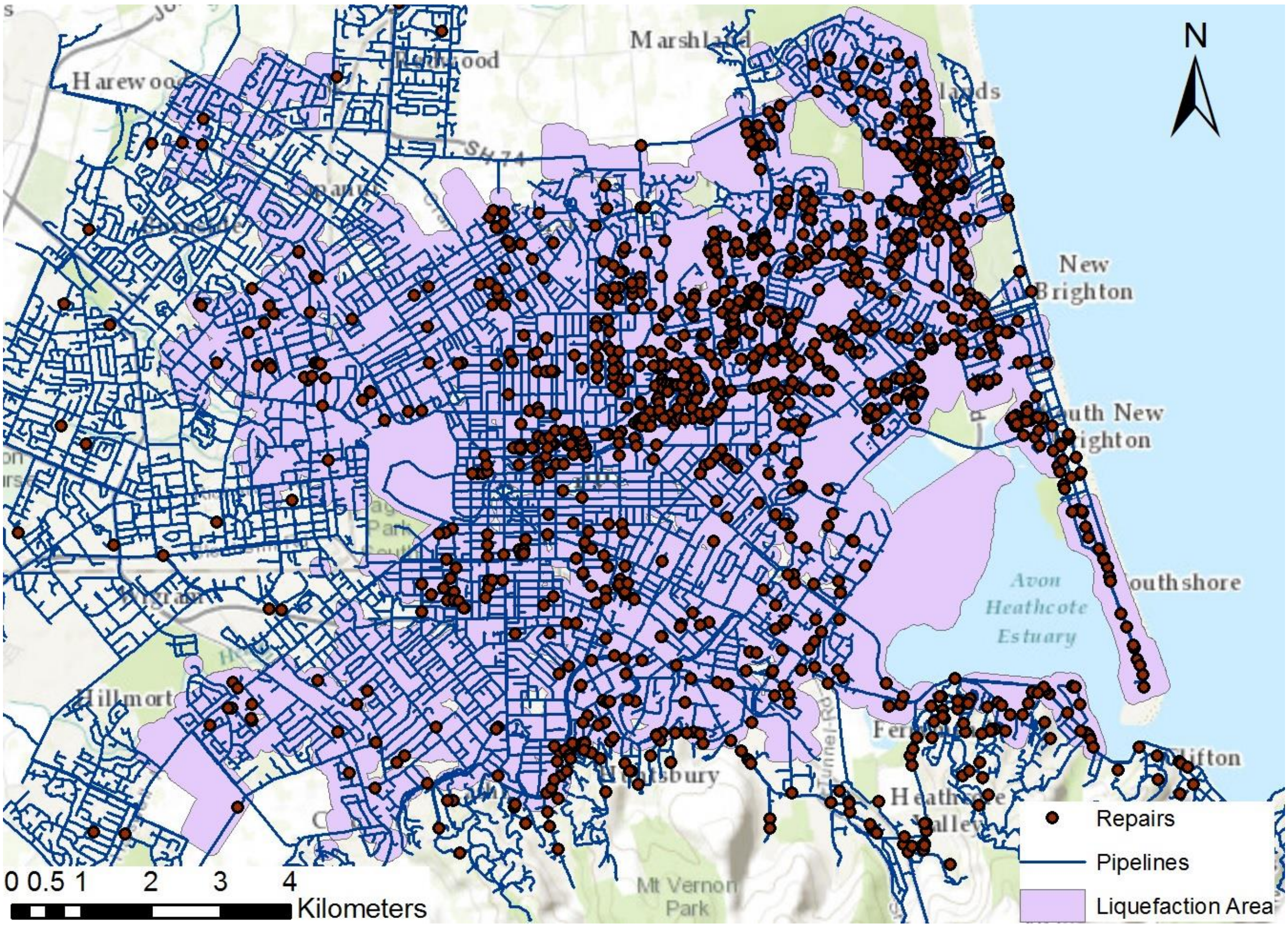


Figure 2. Pipeline distribution and repairs with liquefaction area for 22 Feb. 2011 earthquake

Figure 4a shows the break and leak distribution of the pipeline damages in the liquefaction area. According to the results, almost two thirds and a third of the damages are break and leak, respectively. Figure 4b and 4c show the break and leak distributions, respectively with respect to pipe material. According to analysis of the damage database, CI and AC pipelines have similar rates of breaks and leaks. Their rates are consistent with the rates for all pipelines, which is almost two thirds and a third of the damages are break and leak, respectively.

Preventive maintenance assessments should consider both the aging effects and natural disasters such as earthquakes. There are many studies on this topic. Toprak et al. (2012) and Tsakiris et al. (2011) presented an interesting European project with the title “Preventive Maintenance For Water Utility Networks” and acronym “PM4WAT”. The primary objective of the project was to develop an e-learning platform and courseware on Preventive Maintenance (PM) of water distribution networks for vocational training (VET) of water utility operatives and to instruct them how to increase the reliability of the network, decrease disruption of service and save valuable water resources (Toprak and Koc, 2013). The project web site is http://www.teg.cti.gr/pm4wat. The consortium was composed of seven organizations from four European countries, all Mediterranean that face similar problems with water resources and distribution. Some of these countries have old and non-homogeneous networks that are subject to ageing, massive water losses, seismic activity and other natural hazards. The consortium includes universities and research institutions, an ICT organization, VET providers and urban utility networks, selected with a view to their knowledge and experience. The Training Simulator developed as part of the PM4WAT project is based on a Fifth Framework project SEISLINES (Age-Variant Seismic Structural Reliability of Existing Underground Water Pipelines) which was performed between 2000 and 2002 (Stathaki, 2010).

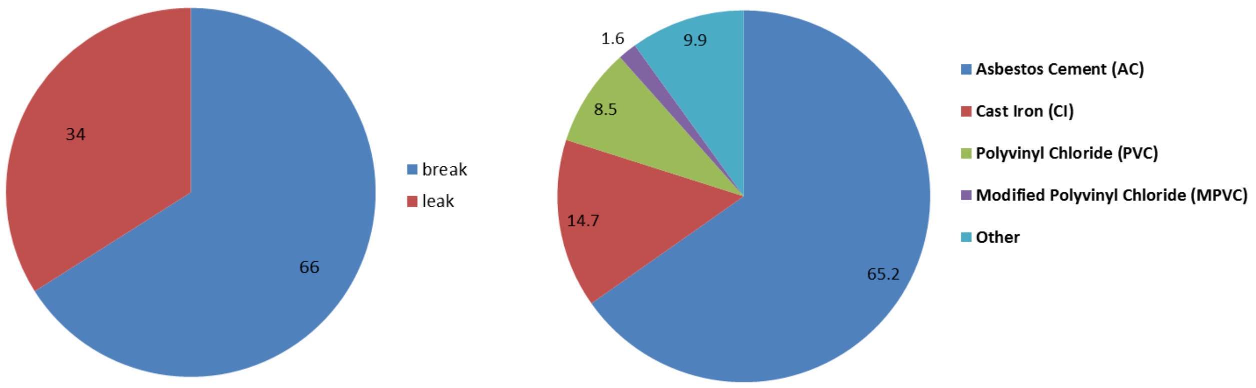
a) DN 100 (4") spiral riveted pipe

b) DN 300 (12") CLS (Concrete Lined Steel) Pipe Split (Photo by P. Free)

c) Fractured DN 150 (6") CI pipe

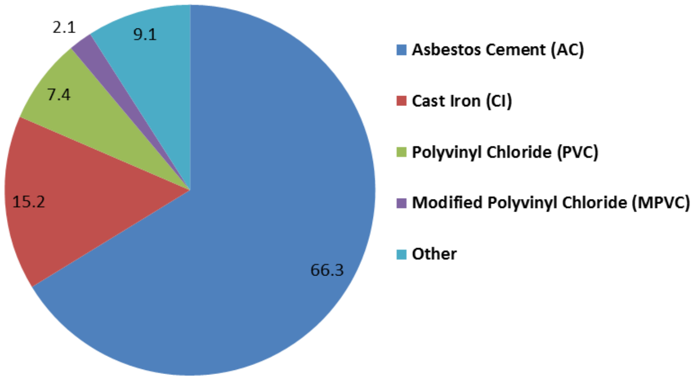
Figure 3. Pipe damages in Christchurch (Black, 2013)

The product of SEISLINE was re-designed and adapted for the purposes of PM4WAT project. The training simulator uses real geographical information on the topology of the water utility networks as well as real data on the properties of the elements in the branches of the network. Such simulators are required to analyze complex water distribution systems for proactive management.



a)Repair distribution in liquefaction area of Christchurch

b)Break distribution in liquefaction area of Christchurch



c)Leak distribution in liquefaction area of Christchurch

Figure 4. Repair (Break and Leak) distribution in liquefaction area of Christchurch

3. RESULTS

Preventive maintenance programs should consider both the aging effects and natural disasters such as earthquakes. Earthquakes apply extreme loadings in a very short time and result in more damages. However, they may have long lasting effects on the pipeline systems. In essence, the adverse effect of seismic actions on pipelines is not only the breaks and leaks occurred just after the earthquake but also the subtle damage which shows weeks, months or years after the earthquake. This observation has also been proven in the 22 February 2011 Christchurch earthquake. For example, the steady state repair rate after large earthquakes in Christchurch is approximately three to four times greater than RRs not affected by prior earthquakes. In the HAZUS loss methodology, it is assumed that damage due to ground failure will consist of 20% leaks and 80% breaks. According to the results from the 22 February 2011 Christchurch earthquake, almost two thirds and one thirds of the damages in the pipelines are break and leak, respectively. A comprehensive study about the pipeline damages during Canterbury earthquake sequence and ground failures is still in progress.

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