Critical factors for restoration of water supply pipelines in the Hutt City, New Zealand after a magnitude 7.5 earthquake from the Wellington fault

John X. Zhao, Jim Cousins, Biljana Lukovic and Warwick Smith[1]

[1] *GNS Science, Lower Hutt, New Zealand, Email: j.zhao@gns.cri.nz*

ABSTRACT :

The water distribution network for Hutt City consists of nearly 700 km of pipes, 6500 valves, 4000 hydrants, and 21 reservoirs located on the surrounding hills. The bulk water is pumped to hillside reservoirs from trunk lines and some water for the city is also taken from artesian wells located on the floor of the Lower Hutt Valley. The Wellington fault, capable of generating an M_W=7.5 earthquake with a return period about 600 years, lies at the western side of the Hutt Valley and passes through both residential and commercial areas. The shaking intensity from this earthquake is expected to be MMI 9 (where MMI is Modified Mercalli Intensity) or greater over the entire City. We simulate the damage to the pipelines using fragility curves derived from overseas data, which are functions of MMI, material type and soil condition. We use a Poisson process to generate damage locations along a pipe, given an expected break rate, then repair the network using an algorithm based on a likely restoration sequence. First all valves are closed. Then starting from a reservoir, a valve is opened and pressure is established. We account for pipe repair time (a function of pipe diameter), opening and closing of valves, checking hydrants and traveling from one location to another. Multiple crew repair parties are used. In the present study, we have excluded the repair time required for damages to the bulk supply pipes (trunk lines) that carry water from water treatment plants to the reservoirs of the surrounding hills in the Hutt City, the reservoirs, wells and the customers own pipes that link individual properties to the council-owned distribution system

KEYWORDS: water pipe damage/restoration, life line engineering

1. INTRODUCTION

Hutt City comprises the localities of Petone, Lower Hutt, Stokes Valley, Wainuiomata and Eastbourne (Figure 1). The Wellington fault, capable of generating a M_W 7.5 earthquake with a return period about 600 years, lies at the western side of the Hutt Valley and passes through several residential areas and one business district (that of Petone). The estimated shaking intensity from this earthquake is expected to be MMI 9 (where MMI is Modified Mercalli Intensity) or greater over the entire City. Site conditions range from rock and stiff soils on the hills surrounding the Hutt Valley and from shallow stiff soil to deep soft soils in the valley.

The bulk water is pumped to hillside reservoirs, from where it is mostly gravity-fed to consumers through distribution networks. The subject of the present modelling is the post-earthquake restoration of the distribution network that provides water throughout Hutt City, a network that consists of nearly 700 km of pipes, 6500 valves, 4000 hydrants, and 21 reservoirs. The digital location for pipe-connection positions, valves, hydrants and reservoirs / pumping stations were supplied by the Hutt city council and the data was then used to generate to an interconnected water distribution network using a GIS system.

Table 1 shows the distribution of pipe materials and diameters for those pipe segments with a length longer than 0.5km. Among the material types, asbestos cement pipes have a total length of 266km (39% of total length for all pipes), about 20% are made of galvanized iron, and 19% is concrete lined steel. Table 1 also shows the likely failure types with three categories, namely brittle, average and ductile, and these failure types are accounted in the fragility curves. Table 2 shows the categories of site conditions. Site classes correspond to those of the current NZ design code (NZS 1170.5:2004 – Standards New Zealand 2004). The level of damage is assigned as “low” for site classes A and B, as “average” for site classes C and D and “high” for site class E.

Table 3 shows the pipe distribution among site classes and failure categories. 60% are on shallow/deep soil sites, 23% are on rock sites and only 17% are on soft / liquefiable soil sites. Among about 6500 valves, over 1800 have poor or very poor condition, scattered across the water distribution network.

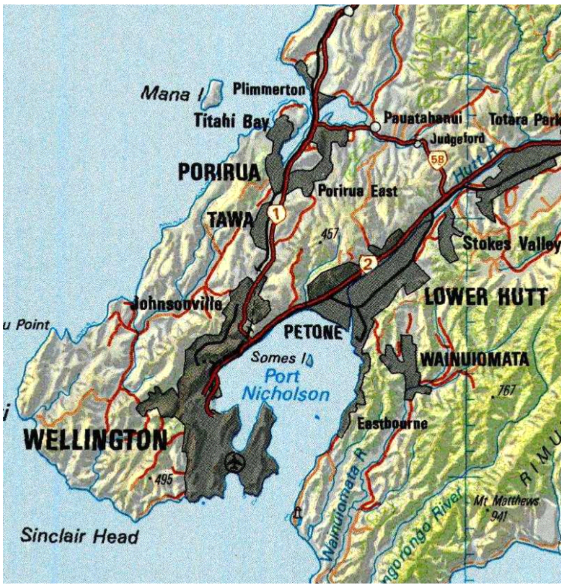

Figure 1 Map of the Hutt City location

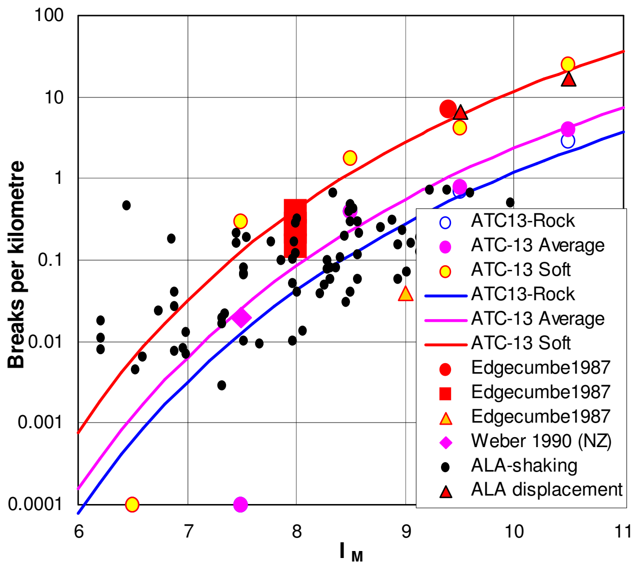

Figure 2 Fragility curves used in the present study

Table 1 Distribution of pipe length (km), diameter, materials and failure types

		Diameter group (mm)					Total length	
Material type	Failure types	20-75	100	150	175-250	>250	(km)	%
Asbestos Cement	Brittle	4	139	94	27	2	266	39
Cast Iron	Ductile	1	3	3	2	5	14	2
Concrete Lined Steel	Average	2	72	21	13	25	133	19
Galvanised Iron	Average	133	1				134	20
HDPE	Ductile	9	1	2			12	2
MDPE	Ductile	27	2	1	1		31	5
Polyethylene	Average	13	1	1	4		19	3
PVC	Average	3	11	13	4	4	35	5
Reinforced Concrete	Brittle		2	1			3	0
Steel	Ductile	1	2	4			7	1
Total length (km)		205	238	144	55	41	685	
%		29.9	34.8	21	8	6		

Note: the entries for pipe length < 0.5km are not shown but included in the total pipe length

The present study is limited to estimating the repair time for water distribution network only, i.e. the repair time for damages to the bulk supply pipes (trunk lines) that carry water from water treatment plants to the reservoirs of the surrounding hills in the Hutt City, damage to the reservoirs wells and the customers own pipes that link individual properties to the council-owned distribution system, are not included.

2. METHODOLOGY OF RESTORATION FOR WATER DISTRIBUTION NETWORK

FORTRAN computer software largely developed previously (Davenport et al 2006) was used to model the physical restoration process. The basic restoration process is:

1) divide the network into a number of sub-networks to facilitate error checking and using multi-ple repair crew parties;
2) simulate damage for a given scenario earthquake assuming that the number of breaks have Poisson distribution with an expected median break rate computed from the fragility curves as a function of modified Mercalli intensity (using an attenuation model), pipe material type and site conditions;
3) close all valves in a sub-network and record the time for closing valves and travelling from the location of the one valve to another;
4) starting from a reservoir or a dummy water supply reservoir of a sub-network, open a valve and to check leakage for all pipes before next downstream valve, and record the time for pipe inspection and time for travel from one location of the pipe to another;
5) repair pipes that have leaks and record repair time for each crew repair party, including any possible idle time for any crew party;
6) record time for crew repair parties to move to the next break location and for hydrant inspec-tion;
7) repeat the above process until the next valve in the sub-network is reached
8) check if all pipes, valves and hydrants have been visited. If not, open the next valve and go back to step 4, until all pipes, valves and hydrants have been visited.

Table 2 Soil conditions (NZS 1170.5: 2004) and relative fragility

Site description	Site class	Relative fragility
Hard Rock	A	Low
Weak Rock	B	Low
Shallow Soil	C	Average
Deep Soil	D	Average
Soft Soil	E	High

Table 3 Pipe distribution in km among material and site categories

Soil type	Material failure type			
	Average	Brittle	Ductile	Sub total
Rock	68	68	20	156
Shallow & deep soil	225	156	31	412
Soft soil	37	47	33	117
Sub total	330	271	84	685

The fragility function for the pipes was derived from overseas data and it has the following functional form (Jim Cousins, 2007, unpublished data, based on overseas data from ALA 2001 and NZ data from Butcher 1998, and other sources)

$$\log_{10}(R_{break}) = \log_{10}(F) + \log_{10}(a) + 4 + \frac{b}{I_M - c} + \log_{10}(R_{imd}) \quad (1)$$

where R_{break} is the number of breaks per kilometre, and I_M is the MM Intensity computed by Dowrick and Rhoades (1999) attenuation models. Parameters a, b, and c are constants determined by regression analyses for the collected data. R_{imd} is the immediate repair rate to account for the possibility that pipes with minor leaks do not have be repaired immediately after a major earthquake. Parameter a depends on site condition and parameter F is a factor to account for pipe material types listed in Table 3, and they takes the following values

$$a = \begin{cases} 6.0 & \text{for weak strong rock sites} \\ 12.0 & \text{for shallow and deep soil sites} \\ 60.0 & \text{for soft / liquefiable soil sites} \end{cases} \qquad F = \begin{cases} 0.75 & \text{for ductile pipes} \\ 1.25 & \text{for brittle pipes} \\ 1.0 & \text{for all other pipes} \end{cases} \quad (2a,b)$$

Note that the number of breaks per kilometre for shallow and deep soil sites is twice that of rock sites and the break rate for soft and/or liquefiable soil sites is 10 times of that of rock sites. The number of breaks per kilometre for brittle pipes is 1.67 times that of ductile pipes. Figure 2 shows the fragility curves used in the present study together with the data from New Zealand and overseas.

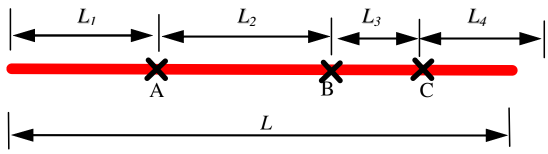

Figure 3 Generation of pipe damage locations

To generate the locations of pipe damage in a probabilistic manner, we assume that pipe damage follows a Poisson process with a mean reoccurrence rate equal to repair rate, R_{break} that is a function MM Intensity. Along the pipe length, the location of the k^{th} pipe break can be computed by,

$$L_k = -\frac{1}{R_{break}} \ln(1 - x_k) \qquad (3)$$

where x_k is a random number uniformly distributed between 0 and 1. Let L_1 be the first location of damage from the start node (not necessarily the upstream node), and L_k be the distance between the $(k-1)^{th}$ and k^{th} locations of damage, the k^{th} locations on the pipe is at a distance of the sum of L_1, L_2,⋯, L_k, measured from the start node (Sheldon, 2000). When the accumulative distances exceeds the length of a pipe, the generation of the breaks for this particular pipe is completed. Figure 3 provides an illustration of the pipe damage generation. In this example, three locations of damage are generated at A, B and C, respectively, in the pipeline, because the cumulative length of the fourth location of damage exceeds the pipe length.

We made the following assumptions for the restoring process:

1) 0.15 hours for closing a valve and 0.1 hours for opening a valve;
2) Inspection time 0.5 hours/km;
3) 0.5 hours for repairing one break on a 20mm pipe and 5 hours on a 500mm pipe. The repair time for pipes with other diameters is interpolated;
4) 0.2 hours for checking a hydrant;
5) 0.2 hours for travel preparation time (loading gear); and
6) A travel speed of 15km/hour.

Travel time associated with all repair work is computed from the straight line between two locations without involving the locations of useable roads. This may be overly optimistic and the effect of this assumption is offset by the low travel speed of 15km/hour.

Before restoration starts, all valves must be closed and the time for closing valves and associated travel is over 1100 hours. The total time is over 340 hours for pipe inspection and over 850 hours for checking hydrants. All the time associated with these activities is independent of earthquake magnitude, once there is sufficient damage to the network that water pressure is lost. As closing valves does not require significant amount of technical skill, the time for this procedure before the start of restoration procedure is not included in the total required time presented in the present study.

We simulated the restoration operations using multiple repair crew parties. For an area (a sub-network) with a large number of failures, multiple repair crew parties can be used. We assume that the crew parties share the inspection time and time for checking hydrants, and this assumption simplifies the book keeping in the computer code. When the total time for all sub-networks is estimated, the working order of the crew parties is arranged in such a way that the idle time for all crew parties is to be kept to a minimum. When a dummy reservoir (a pipe from a nearby sub-network) is not available, i.e., the crew party in the nearby sub-network has not yet reached this particular pipe (dummy tank), some crew parties will have to be idle. The idle time is then computed and added to the repair time of the idle crew parties.

We also model a scenario in which only a portion of the damaged pipe lines need to be repaired immediately after the earthquake. Minor damage and leaks can be repaired at a later date without losing a significant amount of water. The data from the 1994 Northridge earthquake suggests that only 20% of the damage has to be repaired immediately (immediate repair rate = 20%) (Shi 2006) and we use an immediate repair rate of 30% in the present study.

3. RESULTS OF SIMULATION OF RESTORATION OF THE WATER DISTRIBUTION NETWORK FOR HUTT CITY

For modeling, the water distribution network was divided into 30 sub-networks and many sub-networks contain at least one reservoir. For those sub-networks that do not have a reservoir, we use a dummy one which is connected to a nearby sub-network. All pipes directly connecting the reservoir in this sub-network to the node that will be used as dummy reservoir for anther sub-network, will be assigned the highest priority, so that the dummy reservoir can be available at the earliest possible time. When total repair time is computed, the time for the dummy reservoir being available is accounted for 100 simulations of restoration are enough for each sub-network to achieve a stable mean and variance of repair time. We use geometric mean, the exponential of the average values for the natural logarithm of the repair time for each simulation. When the total time is summed up, one of the 100 simulations from each sub-network is randomly selected and again 100 summations are performed for the entire network.

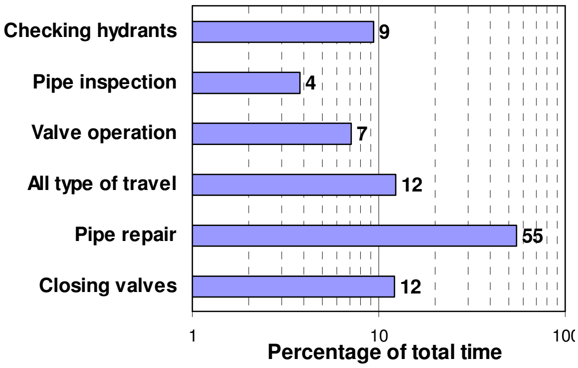

Figure 4 The proportion of time for each type of tasks for the restoration of water supply

Table 4 The average number of breaks in 100 simulations for a Wellington fault earthquake

Material names	Material type	No. of breaks	%
Asbestos Cement	AC	1451	44
Concrete Lined Steel	CLS	503	15
Galvanised Iron	GI	464	14
PVC	PVC	249	8
Cast Iron	CI	175	5
MDPE	MDPE	145	4
Others		310	11
Total		3325	

Table 4 shows the number of breaks simulated for an M_W =7.5 earthquake from the Wellington fault. The average number of breaks is 3325 with 44% from asbestos cement pipes. Though the break locations are generated randomly with a given average break rate for a given average MM intensity, the standard deviation for both the number of breaks and the repair time is very small.

Figure 4 shows the break down of restoration time. 12% of the total time (9120 hours) is for closing valves before the actual restoration starts and a similar portion of the total time is for all types of travel during the restoration process. 55% of the total restoration time is for actual repairs, 9% for checking hydrants, 4% for pipe inspection and 7% for opening valves during the restoration process.

Figure 5 shows the variation of total repair time (excluding the time to close all valves before the restoration process starts) in hours (Figure 5a) and in months (Figure 5b) with the number of crew parties. For one crew party, the repair time is over 7940 hours for an immediate repair rate of 100% and about 3970 hours for an immediate repair rate of 30%. Note that the time for an immediate repair rate of 30% is significantly larger than 30% of the total repair time for an immediate repair rate of 100%. This is a result of essentially constant time (independent from immediate repair rate) for checking hydrants, pipe inspection, and valve operations. The repair time decreases linearly with increasing number of crew repair parties on a log-log scale. The slope of the straight line fitted to the data is -0.9 for an immediate repair rate of 100% and -0.8 for an immediate repair rate of 30%. The smaller slope for an immediate repair rate of 30% may be a result of increased idle time for repair crew parties from that of an immediate repair rate of 100%. When 35 crew parties are used, the total repair time is reduced to about 400 hours for an immediate repair rate of 100% and 250 hours for an immediate repair rate of 30%. If 100 crew repair parties can be used, 161 hours will need for an immediate repair rate of 100% and 95 hours for an immediate repair rate of 30%. It is questionable whether such a large number of repair crews can be assembled for the Hutt City after an M_W =7.5 from the Wellington fault, because Wellington, Porirua and Upper Hutt would suffer similar levels of damage to the Hutt City.

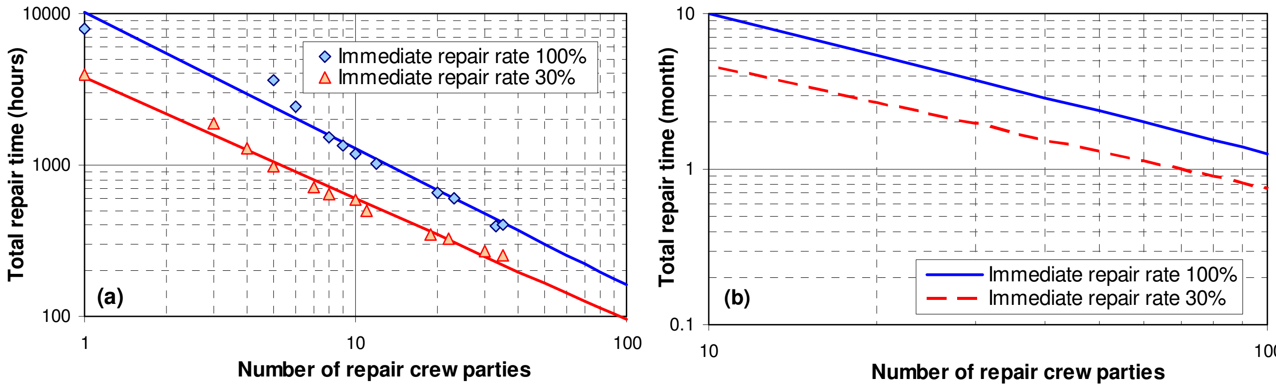

Figure 5 The variation of repair time with the number of repair-crew parties for two scenarios: with 100% and 30% immediate repair rates, (a) variation of the number of hours; and (b) variation of the number of months with the number of repair crew parties

It is not easy to appreciate the length of repair period in terms of the number of hours and so we convert the repair time into the absolute time, i.e., months. Figure 5(b) shows the variation of repair time in months with the number of repair crews. To derive the number of months, we assumed that each crew party will work 10 hours a day, and six days a week and we allow two shifts per day so that the equipment can be used for 20 hours per day. Under these assumptions, the repair time in months is presented in Figure 5(b). If 10 crew parties can be deployed, all repairs in the distribution network in the Hutt City can be completed in just over 10 months and 30% of the damages that lead to moderate and large leaks can be repaired within about 5 months. If 100 crew parties can be assembled, moderate and large leaks, 30% of the breaks, can be repaired in just over 3 weeks, and all repairs can be carried out in about 5.5 weeks. During the repair time, water can be available to the critical facilities, such as hospital and rest homes, well within the required total repair time when high priority for repairs can be assigned to the pipes that carry water from wells/reservoirs to the critical facilities.

Such a long restoration time (a few months) can be an overwhelming factor impeding post earthquake recovery for both residential and commercial communities in the Hutt City. A possible solution is to investigate mitigation methods to reduce the restoration time after a large earthquake. On option is to replace the pipes that have brittle failure mechanisms with ductile pipes, in particular for those brittle pipes installed before 1980s. We simulated two scenarios: to replace 50% and 100% of all pipes with brittle failures, such as asbestos cement pipes, reinforced concrete and pitch fibre pipes with modern pipes such as high density polyethylene pipes. Figure 6(a) shows that if 50% of the brittle pipes are replaced with ductile pipes, the number of breaks in asbestos cement pipes and the replaced pipes is reduced from 1447 breaks with an approximate repair time of 2150 hour, down to 1162 (1730 hours), a 20% decrease. If all brittle pipes are replaced by ductile pipes, the number of breaks in the replaced pipes is further reduced to 867 (1290 hours), a 40% decrease. The decrease in repair time is just over 860 hours, relatively small compared with total repairing time of 7950 hours, merely a 10% decrease. However, if spare parts (joints) and new asbestos cement pipe are few or no longer available at all, it would be vital to gradually replace this type of pipe now rather than after an earthquake, as the time to replace these pipes then could be tens times of estimated repair time for breaks. An unfortunate feature is that asbestos cement pipes with a total length of 266km scatter across nearly all areas in the Hutt City, with Wainuiomata having 20%. It is possible that the breaks in the other pipes may not be found / repaired before a large number of asbestos cement pipes in the upper stream are replaced. The delay in the water restoration could be far too long to be accommodated.

The total length of pipes in soft / liquefiable soils is close to 120km (17% of all pipes), as shown in Table 4, the majority of which is in Seaview, Petone and Wanuiomata. The break rate for soft / liquefiable soil sites is 10 times that of rock sites and 5 times that of shallow and deep soil sites. We simulate an "improved" scenario that "super" ductile pipes can be used to reduce the break rate for soft / liquefiable soil sites to that for average (shallow and deep) soil sites. Figure 6(b) shows the number of breaks if break rate for 50% and 100% of all pipes on the soft / liquefiable soil sites can be reduced to that of the average soil sites for the corresponding failure types, i.e. taking a=12.0 in Equation (2a), instead of 60.0 for soft / liquefiable soil sites. If the break rate for 50% of the pipes in soft/liquefiable soil sites can be improved to have a break rate at shallow and deep soil sites, the total number of breaks (across all sub-networks) can be reduced from 3314 to 2595, a decrease of 22%. If all pipes on the soft/liquefiable sites can be improved, the total number of breaks can be further reduced to 1876, a decrease of 43%. The repair time is reduced from 7930 hours to 6620 hours, a 17% reduction, for 50% improvement, and to 5300 hours, a 33% reduction, for 100% improvement. Note that the total repair time includes the time for pipe inspection, checking hydrants, and opening valves plus associated travel time, all of which are not affected by pipe failure mechanisms and site conditions. The time for these activities leads to a smaller reduction percentage of total repair time than that of number of breaks.

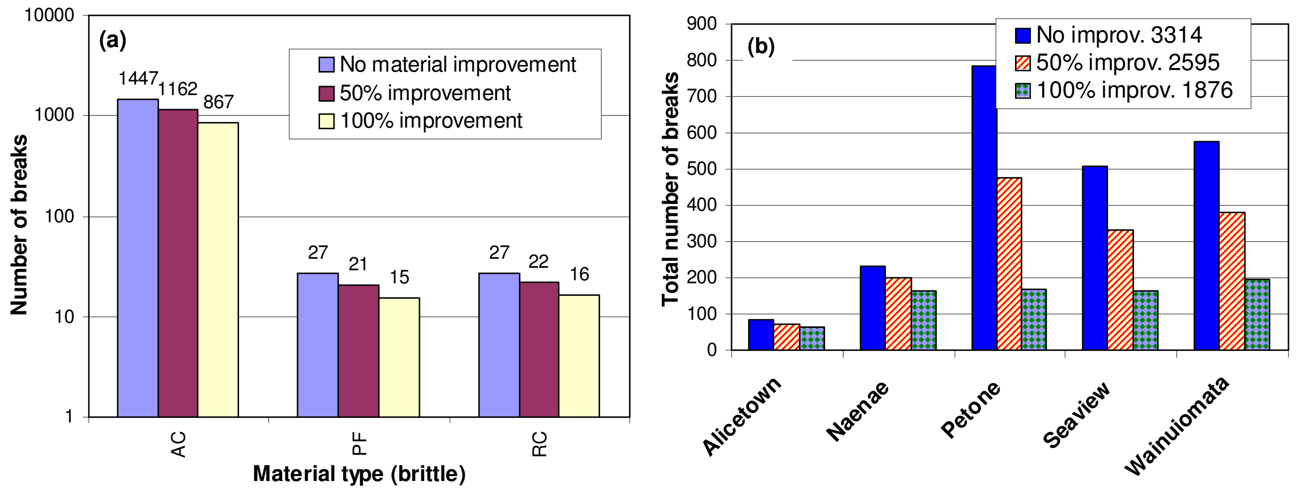

Figure 6 Effect of improvement on the number of pipe breaks for different material-improvement levels in (a) and soft / liquefiable (Class E) soil sites in (b)

The Wellington fault passes through the eastern site of the Hutt Valley, including the business district of Petone. There about 40 pipes that lie across the fault surface trace and 3-4km of pipe running in parallel with the fault surface trace within a distance of a few metres. We expect that all the pipes crossing the fault trace will be severely damaged beyond repair and those pipes running close to the fault will also need to be replaced. The time for replacing these pipes is not included in the present study.

A critical assumption made in the present study is that the existing reservoirs and pumping stations are functional. This is because the repair strategy requires pressurised water for detection of breaks, and work cannot be carried out if water in the reservoirs is lost and bulk supply line (the pipe that supplies water to the reservoirs) is not functional. Hence there is a built-in delay between the earthquake and the start of restoration. This delay is additional to the restoration times estimated here.

4. CONCLUSIONS

We present the preliminary results for the restoration time of water distribution network of the Hutt City after an M_W =7.5 earthquake from the Wellington fault. Among the 685km of distribution pipes, on average 3325 breaks occurs with over 40% from asbestos cement pipes and 29% from concrete lined steel and galvanised iron pipes. 80% of the breaks are from pipes with a diameter of 20-175mm.

We identified a number of critical factors for the restoration process:

1) Many of the 21 reservoirs must have enough water for checking pipe links. If any reservoir on the surrounding hills is not available, it is unlikely to be possible to repair the pipes on the hills around the reservoir and to the areas of the valley floor that have to use the water from the dam-aged/un-functional reservoir;
2) A large number of breaks would occur on asbestos cement pipes. If they cannot be repaired be-cause of unavailable new pipes or joints and therefore the pipes have to be replaced, a very long delay may be likely across the whole distribution network;
3) 117 km of pipes on soft / liquefiable sites produce disproportionately large number of pipe breaks;
4) Over 1800 of valves are in poor or very poor conditions with a diameter range of 40-150mm. We expect that a significant number of them could be damaged. The number of valves in existing stocks and lead time for purchasing new ones may delay the repair, because repair to the pipes down-stream of a damaged valve may not be possible.

ACKNOWLEDGEMENT

The authors would like to thank the Earthquake Commission and the Foundation for Research Science and Technology (FRST Contract C05X0301) for funding this research, Gary O'Meara from Capacity Ltd. for helpful advices and the Hutt City Council for providing pipe network data. We would like to thank Dave Brunsdon of Kestrel Group Ltd, Dick Beetham and S. Uma of GNS Science for their review of the manuscript.

REFERENCES

ALA, 2001. American Lifelines Alliance (Eidinger, J.M., Principal Investigator, et al) “Seismic fragility formulations for water systems”. (2001). (Available online from http://www.Americanlifelines alliance.org/Products.htm).

Butcher, G., Andrews, L. and Cleland, G. (1998) The Edgecumbe earthquake, a review of the 2 March 1987 Eastern Bay of Plenty earthquake. Centre for Advanced Engineering, University of Canterbury, Christ-church.

Davenport, P.N., Lukovic, B. and Cousins, W.J. (2006). “Restoration of earthquake damaged water distribution systems”, in “Remembering Napier 1931”, Proceedings of the 2006 Conference of the New Zealand Society for Earthquake Engineering, 10-12 March, 2006, Napier. Paper No. 44.

Dowrick, D.J. and Rhoades, D.A. (1999) “Attenuation of Modified Mercalli Intensity in New Zealand earthquakes”. Bulletin of the New Zealand National Society for Earthquake Engineering, 32(2): 55-89.

Standards New Zealand, 2004. Structural Design Actions – Part 5 Earthquake Actions –New Zealand. New Zealand Standard NZS1170.5:2004, 76p. (2004).

Sheldon, M.R., (2000), “Introduction to Probability and Statistics for Engineers and Scientists”. 2nd Edition, Harcourt and Technology Company, San Diego, CA.

Shi, P. (2006) “Seismic response modelling of water supply systems”, A Dissertation Presented to the Faculty of the Graduate School of Cornell University in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy.