Effect of Pressure Fluctuations on Water Main Failure Rates

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Abstract

The Water Corporation installs pressure reducing valves (PRV) on water mains to ensure that the maximum working head is managed to an acceptable level. These valves can fail and cause the pressure to equalise across the valve – effectively increasing the internal fluid pressure in the downstream pipe sections. The objective of the project is to investigate the effect of PRV failures on the lifetime of the legacy pipelines.

The objective of this project is to allow the Water Corporation to effectively manage its pipeline replacement strategy by replacing legacy pipelines before their failure rate becomes uneconomic. A reliability evaluation strategy will be used to evaluate existing PRV and water mains failure data produced by the Water Corporation. The data is to be grouped into PRV affected pipe networks called "Zones" and materials datasets. Both the PRV and water mains data will be plotted and fitted to a probability distribution such as the Weibull distribution, and then correlated to explore the effect of PRV failure on the water mains distribution.

1. Introduction

The Water Corporation installs pressure reducing valves (PRVs) on water mains to ensure that the maximum working head is managed to an acceptable level. These valves can fail and cause the pressure to equalise across the valve – increasing the internal fluid pressure in the downstream pipe. Former Perth Region Asset Manager Peter McRae identified that the increase in pressure may significantly affect the failure rates of the water mains downstream of the PRVs. Any increase in failure rates would increase the amount of corrective maintenance required for the successful operation of the water mains network. This would significantly increase costs / necessitate an investigation of effects of pressure spikes on the water mains.

PRVs are located throughout the Water Corporation water mains network. The water mains network consists of various larger diameter mains (i.e. trunk and distribution mains) feeding smaller diameter reticulation mains. The smaller diameter (i.e. reticulation) mains feeding off the distribution mains create sub-networks which are termed "Zones".

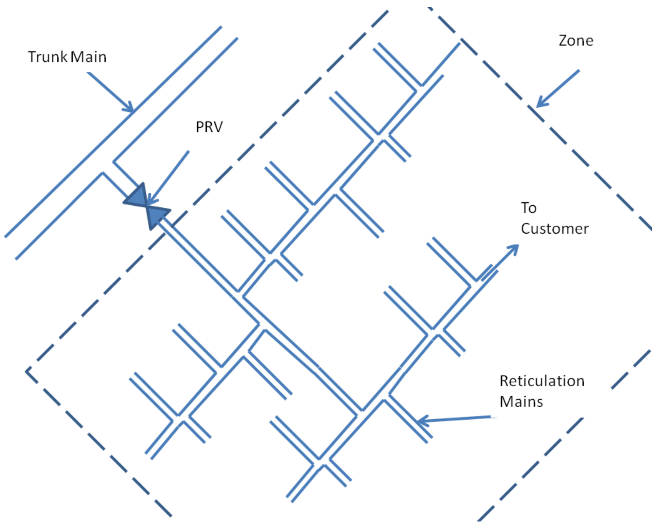

Figure 1: Diagram of a idealised subsection of a water mains network.

Currently, preventative maintenance is not undertaken on the smaller diameter reticulation water mains network, as it is thought not to be cost effective. Larger diameter distribution and trunk mains are condition monitored, and are refurbished depending on their condition. The current reticulation water mains replacement strategy is to add water mains that have failed more than 3 times in a rolling twelve month period to a replacement program, where they are monitored and eventually replaced. This is done to ensure that Water Corporation meets its customer charter, which requires a reliable supply of water to its customers.

Due to the nature of the Water Corporation's pipe system, a large number of constantly varying factors lead to their failure. These characteristics can be summarised into three main factor groups; operational, environmental and physical. These are shown in Table 1 below.

Physical	Environmental	Operational
Pipe Material	Pipe Bedding	Pressure Fluctuations
Pipe Wall Thickness	Trench Backfill	Leakage
Pipe Age	Soil type	Water Quality
Type of Pipe Joints	Ground water content/presence	Flow velocity
Pipe Lining/Coating	Climate – Soil moisture content	Operation & maintenance practices
Pipe Installation Methods	Stray Currents	
Pipe Manufacture	Disturbances(Seismic/Road Traffic)	

Table 1: Factors affecting pipe deterioration (adapted from Al-Barqawi and Zayed (2006).

This kind of problem lends itself to a statistical evaluation. There are two main approaches suggested by literature to predict when a pipe main will fail. The first approach involves acquiring data and applying a probability distribution to failure data (Belmonte , Mulheron & Smith 2009). This requires plotting the cumulative failure function and then fitting an applicable probability distribution such as the Weibull or Log-normal to the resultant plot (Debon et al 2009). As water mains failure data is readily available from the Water Corporation, this project is well suited to the first approach.

The objective of the project is to investigate the effect of pressure spikes associated with a PRV's failure to maintain a constant pressure on the failure rate and effective lifetime of water mains, with the eventual objective of using the knowledge gained via this project to make effective decisions about water mains/PRV replacement. Due to the large costs associated with water mains failure and replacement, it is important to make effective management decisions in order to be cost efficient (Davis & Marlow 2008). Having knowledge of failure rates and effective lifetime of water mains allows management to make pro-active decisions about water mains replacement instead of reactive decisions dictated by mains failure

2. Process

Two main methodologies were used throughout the project. These two methodologies were used to help solve the two major objectives of the project; the first being to establish if there is a possible link between pressure spikes in water mains and an increased number of failures. The second is investigating the current failure data to help predict future failure rates of water mains.

The first methodology investigates the link between pressure spikes and failures. This involved the acquisition of the time series pressure data from the Water Corporation PI database. Once this data was acquired it was needed to define a "pressure spike". Water supply systems, and therefore pressures, are dynamic to cater for constantly varying demand. Therefore it was decided to define a spike as any time period where the pressure was greater than two standard deviations above the mean. This spike data, when combined in the mains failure data can be used to calculate the number of failures occurring in a given time period after the spike. Various plots or tables can then be generated to give an indication of a relationship between the pressure spikes and water mains failure.

The second methodology analyses the failure data using a probability plot. Using the statistical software package Minitab, the life time data can be used to generate an estimate of the cumulative failure distribution which, can in turn be used to predict the likelihood of future failures. Each observation is plotted against its corresponding cumulative probability. The cumulative probabilities are generated using the median rank method using the following equation:

$$F(t_i) = \frac{i - 0.3}{n + 0.4} \qquad (2.1)$$

Where;

- i is the rank of the corresponding lifetime of the corresponding water main; and
- n is the number of observations

Various different distributions can be fitted to the resulting set of data points. Within the reliability field the Weibull distribution is most commonly used to plot experimental data. This being due to its flexibility as it has no distinct shape and thus can fit well experimental data distributions. Once a Weibull distribution is fitted, its parameters (β, η) can be estimated and thus defined in the following equation:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (2.2)$$

Where;

- R(t) is the probability of survival at give time t;
- t is time in years;
- β is a dimensionless shape parameter; and
- η is a dimensionless scale parameter

Various assumptions are made to make this methodology possible due to the constraints of the data available for the project. They are as follow:

- That the water mains are comprised of many small discrete subsections and therefore the estimated lifetime of the pipe is the time between the commissioning date and failure date.
- The same discrete subsection has not previously failed.
- The supplied failure data is accurate.

3. Results and Discussion

Investigating the number of failures a week after a determined spike yielded results that suggest that spikes have a small effect on the failure rate of the mains within the area.

Area	Number of spikes	Average Failure Rate(failures per day)	Number of Spike Resulting In a above normal failure rate	Percent of Spikes Resulting in Above average Failure	Percentage of above average failure Inducing spike with a duration larger than one hour
Austin Ave	249	0.20	141	57%	72%
Treasure Rd	30	0.36	23	77%	65%
Hale Strelitza	108	0.07	32	30%	6%
Medina	472	0.05	20	4%	75%
Sultana Rd	53	0.09	26	49%	8%

Table 2: Table of Spike-Failure Analysis

The results are summarized in Table 2 above. Each area has different characteristics, this being shown by outer suburbs have younger mains compared to the inner suburb mains. This meaning that each area is only expected to react in a similar fashion if the area has similar characteristics.

Only the Treasure Rd and Austin Ave areas, which contain older and increased lengths of pipe mains give the impression that they are significantly affected by pressure spikes. Another important observation to make is that pressure spikes with a longer duration (greater than one hour) have a dramatic affect on failure rates as shown in Table 2. This conclusion can also be validated due to there being two known situations where PRVs have failed and the number of water mains failures significantly increased very shortly after the resultant pressure spikes. Consistent with anecdotal evidence supplied by Jason Sadler of the Water Corporation. This pattern however, does not follow across to other areas such as Sultana Rd, Medina and Hale-Strelitzia areas. This suggests that the mains within these areas are not susceptible to prolonged pressure spikes. At a glance this may be due to the relatively younger age or material type of the water mains within these areas, however further investigation are required to verify this hypothesis.

Weibull distributions have been fitted to the current failure data to help predict future failure rate. This method allows for parameter estimation of the fitted Weibull survival function R(t) and gives insight in the failure behaviour of the water mains.

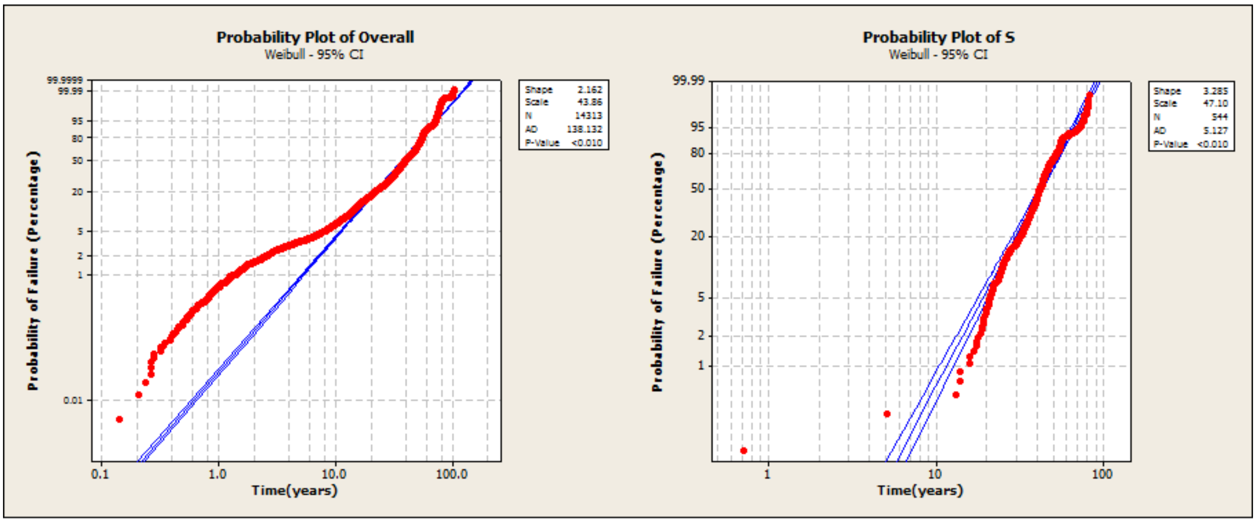

Figure 2: A Weibull probability plot of all failures(left) and Steel(right) within the Perth Metropolitan Region

Figure 2 shows that for both overall and material specific plots there is changing failure behaviour over the lifetime of the mains. Steel has been chosen as an example and is only one of the many materials being investigate. The steel probability plot implies that the failure behaviour of the pipes follows the typical bathtub curve model. The first five data points of the steel plot show that initially failures are random representing a constant/slightly increasing failure rate representing that the mains are within the normal operating period. Later in the lifetime of the water mains the failure rate rapidly increases suggesting the water mains are reaching their end of life.

The fitted line for the overall failure does not provide a good fit. The reason for this being that each material displays different failure behaviour and thus is likely not to be a good predictor of failure rates on a case by case basis. The failure behaviour of steel mains display much more consistent behaviour and thus have a much better goodness of fit test statistic produced by the Anderson- Darling test. To further better the goodness of fit, each plot can be split into multiple segments to reflect the changing failure behaviour of the water mains.

4. Conclusions and Future Work

It has been found that a link between pressure spikes and the failure rates of water mains does exist. However it is important to understand that this link only exists under certain environmental conditions are strongly linked to increased incidence of failure as seen in Table 2. Within areas which contain older mains which are reaching their end of life are effected by pressure spikes with higher durations (greater than one hour). This conclusion however needs to be validated and further investigated. It further appears that the failure rates of mains within zones can be estimated using Weibull probability plotting methods. Generally the aims of the project have thus been achieved.

Ongoing work includes a more thorough investigation into validating the conclusion that younger mains are relatively unaffected by pressure spikes. Also, further work is required for interpreting and validating probability plots to provide better estimations of future failure rates. Additional investigation into the Water Corporation water mains replacement strategy is required to allow for a possible cost benefit analysis. This could be used to improve the business case for a water mains replacement situation.

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6. References

Al-Barqawi, H, Zayed, T, 2006, 'Condition rating model for underground infrastructure sustainable water mains' Journal of Performance of constructed facilities, vol. 20, no. 2, pp. 126-135. Available from: Science Direct. [1 March 2010].

Billinton, R, Allan, Ronald 1992, Reliability Evaluation of Engineering Systems: Concepts and Techniques, Plenum Publishing, New York.

Belmonte, H, Mulheron, M, Smith, P 2009, 'Some observations on the strength and fatigue properties of samples extracted from cast iron water mains' pipelines' Fatigue & Fracture of Engineering Materials & Structures, vol. 32, pp. 916-925. Available from: Web of Knowledge. [20 February 2010].

Wolstenholme, L 1999, Reliability Modelling: A Statistical Approach, Chapman & Hall/CRC, Boca Raton.