Validation of Cast Iron Pipe Modelling

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Abstract

Cast Iron (CI) pipe failure can have environmental, economic and social consequences. The Water Corporation has spent approximately AUD 10 million on fixing cast iron pipe failures in the past 12 years. The objectives of this project are to identify factors influencing cast iron pipe deterioration, explore relationships between these factors and CI pipe burst numbers of small and large CI pipes and develop statistical models to assist Water Corporation CI pipe condition assessment and replacement program. Log-linear model and Cox proportional hazard model indicate that CI pipe burst numbers and deterioration rates primarily depend on physical variables such as pipe age and diameter, and environmental variables such as soil aggressiveness and pipe location. Small CI pipes installed during 1930-1950, located in more aggressive soil environments and distributed along the Swan River and coast tend to have a higher number of bursts. Large pipes located in acid sulphate soil with high risk of corrosion or more aggressive soil environment have more bursts.

1. Introduction

Cast iron (CI) pipe failures can have significant impacts on customers, community and the organization. In the past 12 years, CI pipes located in the Perth metropolitan area had 9,752 bursts, affecting approximately 309,000 customers and costing Water Corporation approximately AUD 10 million in repairs (Water Corporation 2012). The significant disruption and costs are cause for increasing concern for the Water Corporation. The Asset Management Branch (AMB) of Water Corporation (WC) endeavours to improve the WC service assets reliability monitoring and assessment of asset performance, condition and risk, and the analysis and planning of asset maintenance. In order to reduce the maintenance costs of cast iron pipes, AMB is developing a risk based condition assessment and renewals strategy, which depends on a thorough understanding of variables affecting CI pipe deterioration.

A number of statistical predictive models of CI pipe failures have been developed (Wang 2008). Pipe age was (always) considered to be the only deterioration factor in those models. Statistical analysis carried out in a previous Water Corporation project has identified that soil aggressiveness, depth to ground water and operating pressure are also CI pipe deterioration factors in Perth metropolitan area (Wei, 2012). However, in that project only pairwise correlations were considered. The objective of this project is to validate these and other deterioration factors and to achieve a better understanding of relationships between those factors and CI pipe deterioration.

2. Methodology

Figure 1 outlines the methodology followed to achieve the objectives of this project.

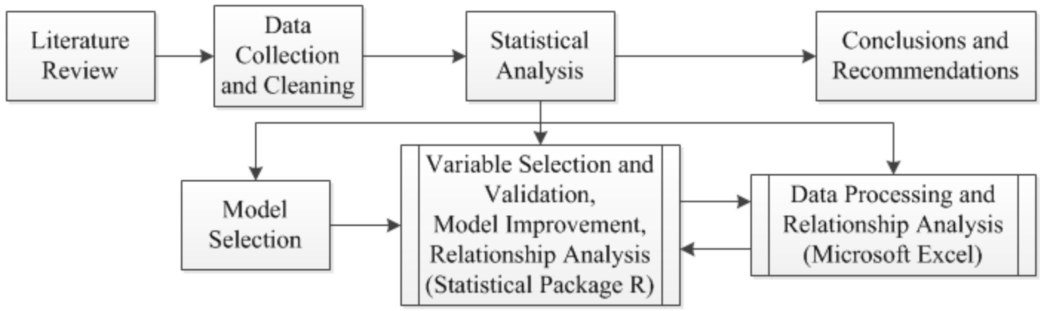

Figure 1 Process diagram outlining project methodology

2.1 Data Collection and Cleaning

Data was available on 41,003 CI pipes with a total length of 2,846 kilometers installed from 1900 onward. Data on total of 4,839 CI pipe bursts observed from 1999 to 2010 in the Perth metropolitan area were extracted for analysis from Water Corporation's database. Variables included pipe physical factors (such as age and diameter), environmental factors (such as soil aggressiveness and ground water level), and operational factor (such as month installed and operating pressure). Microsoft Access and Excel were used to sort and clean data, which was then imported into the statistical package R.

2.2 Statistical Analysis

CI pipes were divided into two groups: large CI pipe group of 1,045 CI pipes with diameter at least 300 mm; and small CI pipe group of 40,000 pipes with diameters less than 300 mm. Two different types of models were fitted to the data; a generalized log-linear Poisson regression model and Cox proportional hazards model. Software packages R, Microsoft Excel and Microsoft Access, were used.

2.2.1 Log-linear Model

A log-linear model is a generalized linear model for Poisson (count) data (Farewell, Hallett, Hannam& Jones 2012). This is essentially a regression model, with the log of the Poisson mean as response. In particular, if $X \sim Poi(\mu)$ and $x_1, x_2,\ldots, x_k$ are covariates, then the model is:

$$\mathrm{Log}\,(\mu) = \alpha + X\beta,$$

where μ is the mean number of CI pipe bursts between 1999 and 2010, $X = (x_1, x_2, \ldots, x_k)$ is a vector of covariates. $\boldsymbol{\alpha}$ is the intercept term and $\boldsymbol{\beta}=(\boldsymbol{\beta}_1, \boldsymbol{\beta}_2,\ldots, \boldsymbol{\beta}_k)^T$ is a column vector of regression coefficients. The log-linear model determines whether there are any significant relationships between the mean number of bursts and the covariates and if the distribution of the number of CI pipe bursts among those deterioration factors can be explained by a simpler, underlying structure.

2.2.2 Cox Proportional Hazards Model

Cox proportional hazards model can be used for analysis of burst-time data (the time between bursts) and is used to examine the relationships between the burst time data and covariates. Most commonly, this examination entails the specification of a linear-like model for the log hazard (Fox, 2002). For example, a parametric model based on the exponential distribution may be written as:

$$\log h(t) = \log h_0(t) + \boldsymbol{\alpha} + \boldsymbol{\beta}_1 x_1 + \boldsymbol{\beta}_2 x_2 + \cdots + \boldsymbol{\beta}_k x_k$$

In this project, pipe burst is regarded as "death" of pipe and t is the time between the first and second bursts from 1 July 1999 to 30 June 2010. $\boldsymbol{\alpha}$ is the intercept term and $\boldsymbol{\beta}_1$, $\boldsymbol{\beta}_2$,…, $\boldsymbol{\beta}_k$ are regression coefficients. $h_0(t)$ is the baseline hazard. The model assumes that $h_0(t)$ captures any time dependence and that the covariates are time-independent.

3. Results and Discussion

3.1 Log-linear Model Results

Category	Variables	Significant Variables (Small Pipe Group)	Significant Variables (Large Pipe Group)
Physical factors	Length; Age; Diameter	Length; Age	Length
Environmental factors	Ferrous Soil Aggressiveness Rating (FSAR); Acid Sulphate Soil Rating (ASSR); Total Dissolved Salt Level (TDS Level); Ground Water Depth; Pipe Location	FSAR; ASSR; TDS Level Pipe Location;	FSAR; ASSR;
Operational factors	Operating Pressure; Month Pipe Installed	Month Pipe Installed	Month Pipe Installed
Others	Whether a main road/Hwy is within 10 meters; Distance from pipe to boundary	Whether a main road/Hwy is within 10 meters	--

Table 1 Significant Variables in Log-linear Model

As can been seen in table 1, twelve variables were included in the log-linear model. Of these variables, eight are significant for the small CI pipe deterioration and only four were significant for large CI pipes. No significant interactions between variables were found. Key findings are summarized below.

3.1.1 Small CI Pipe Group

<u>Model equation:</u>

Log(Mean pipe burst number μ) = -2.782+ 0.005 Pipe Length + 0.867 FSAR 2 + 1.207 FSAR 3 + 1.308 FSAR 4 + 0.188 ASS_Class 2 + 1.051 TDS_Level 3 + 1.683 TDS_Level 4 + 0.972 TDS_Level 5 + 0.536 Inland +0.662 Along the Swan River + 0.594 Along the coast +(-1.323) Pipe Installed in 1920s + (-0.818) Pipe Installed in 1930s + (-0.850) Pipe Installed in 1940s +

(-0.804) Pipe Installed in 1950s + (-1.548) Pipe Installed in 1960s + (-1.770) Pipe Installed in 1970s + (-1.782) Pipe Installed in 1980s + (-0.228) Pipe Installed in March + (-0.331) Pipe Installed in August + (-0.397) Pipe Installed in November

Pipe Length

The model shows that as length of pipe increases, the number of pipe burs increases.

Pipe Installed Decades/Age

According to the model, there is a strong correlation between average number of CI pipe bursts and decade in which the pipe was installed (pipe age). In general, as pipe age increases, average number of pipe bursts gradually increases. However, the average burst numbers for CI pipes installed in 1930, 1940 and 1950s are extremely high. A hardness test experiment conducted in 2012, showed that average hardness of CI pipes installed in 1950s is 30% lower pipes installed in other decades (Wei, 2012), which suggests that higher burst number of pipes installed in 1950s is a result of the lower strength of those pipes. Renewal team of Water Corporation has been assessing CI pipe condition in the Perth CBD area. The team found that most CI pipes recorded as being installed in 1930s and 1940s in CBD area were actually installed in 1890s and recorded dates in the database were the reline date of those CI pipes (Water Corporation, 2013). This reveals that most of the pipes “installed” in 1930 and 1940 in CBD area are actually much older, which might be able to explain the abnormally high pipe burst numbers in 1930 and 1940. However, the length of CI pipes “installed” in 1930s and 1940s in CBD area are only a very small proportion of the total CI pipes installed in those two decades in the Perth metropolitan. Therefore, further investigations are required to identify whether pipes lying in other areas also have the same issue.

Ferrous Soil Aggressiveness Rating (FSAR)

Another significant deterioration factor validated by the model is ferrous soil aggressiveness. Water Corporation developed a system to rate ferrous soil aggressiveness (FSAR) considering soil salinity, PH and waterlogging. Higher FSAR indicates a more aggressive soil condition. Aggressive soil conditions can be strongly corrosive to CI pipes due the electrochemical conditions at the soil-metal interface. The log-linear model indicates that average CI pipe burst number increases as FSAR (1-4) increases. However, when FSAR=5, there is no correlation between pipe burst numbers CI pipes and FSAR. Data exploration revealed only seven kilometers of CI pipe located in FSAR=5, accounting for 0.25% of the total length of small CI pipes in Perth metropolitan area. Thus there is insufficient burst data to explain the relationship.

Acid Sulphate Soil Rating (ASSR)

Acid sulphate soil can potentially be very corrosive in areas that have been formerly drained (Fairwell.etc, 2012). Water Corporation ranked the acid sulphate soil according to the risk of corrosion to buried ferrous iron assets (1-none known risk Soil; 2-moderate to low risk; 3-high to moderate risk). The log-linear model shows that CI pipes in ASSR=2 areas where the risk of corrosion is higher have higher average number of bursts than pipes located in ASSR=1 areas. No significant relationship is found between pipe burst and ASSR =3. One possible reason is that there are too few data corresponding to ASSR =3.

Total Dissolved Salt Level (TDS Level)

TDS represents the concentration of total dissolved content in water. Higher levels of TDS have higher concentration of chloride and sulfate which will accelerate corrosion of metals (SDWF 2013). The model indicates that CI pipes have more bursts on average in the areas where TDS level is high.

Pipe Location

The log-linear model reveals a strong relationship between number of CI pipe bursts and pipe locations. In this model, CI pipes were sorted by suburbs which were divided into four groups: along the Swan River, along the coast, in the hills and in other areas. The model indicates that pipes in suburbs that are located along the coast or along the Swan River have more bursts compared to pipes located in the hills or in other areas. One possible reason is that, according to the GIS map, older pipes as being identified installed during 1930-1940 are mainly laid along the Swan River and coast. In addition, a majority of suburbs with higher total dissolved salt levels are distributed along the Swan River and coast.

Month Pipe Installed

The model indicates that pipes installed in August and November have relatively fewer bursts. Further investigations are required to uncover whether there is any structure in the data that may be relevant to the month pipe installed.

Whether a main road/highway is within 10 meters

The model indicates that the pipe tends to have fewer bursts if there is a main road or a highway within 10 meters. One of the possible reasons is that maintenance work could have been undertaken on the pipes during construction or maintainance of the main roads or highways.

3.1.2 Large CI Pipe Group

Model equation:

Log(Mean pipe burst number μ) = -2.307+ 0.006 Pipe Length + 1.070 FSAR 3 + 1.578 ASS_Class 2 + 1.604 ASS_Class 3 + (-2.195) Pipe Installed in Feburary + (-1.372) Pipe Installed in January + (-2.430) Pipe Installed in November

Pipe Length

Pipe burst increases as the pipe length increases.

FSAR

Pipes in FSAR=3 area have more bursts than in others.

ASSR

The model shows that average number of bursts for large CI pipes increases as ASSR increases.

Month Pipe Installed

The model indicates that large CI pipes installed in January, February and November have fewer bursts.

3.2 Cox Proportional Hazard Model Results

Model equation (Small CI Pipe Group):

Log h(t) = log h_0(t)+ 0.002 Pipe Length + (-0.440) Diameter + 0.489 FSAR 3 + 0.546 FSAR 4 + 0.360 Inland + 0.409 Along the Swan River + 0.447Along the coast

The model indicates that as pipe length and FSAR increases, the pipe failure rate increases. Pipes lying along the coast and the Swan River have higher failure rates than pipes lying in the hills and other areas. Pipes with larger diameters have lower failure rates. The reason is because the thickness of pipe increases as the pipe diameter increases. As a result, a longer time is required for pipe corrosion.

Large CI Pipe Group:
Only 58 CI large pipes burst twice during 1999 to 2010 so the data are insufficient to fit a reasonable hazards model.

4. Conclusions and Future Work

Both log-linear model and Cox proportional model indicate that for small CI pipes, soil aggressiveness, FSAR and pipe locations are significant factors. Pipe age, ASSR and TDS level are only significant factors for log-linear model. For large CI pipes, FSAR and ASSR are two of the most significant factors. All of those significant factors can be considered in the CI pipe condition assessments. Water Corporation has initiated a structured CI pipe condition assessment and the above information will allow Water Corporation to achieve a more targeted CI pipe condition assessment and data collection program.

In the future, spatial aspects of data will be possible to model and linear networks modelling will be promising when more data are available and the accuracy of the data is enhanced.

5. Acknowledgements

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