Predictive Modelling of Sewer Blockages in Vitrified Clay pipes

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Abstract

Sewer pipe blockages can have severe economic, environmental and social consequences. The Water Corporation has spent more than $18 million on sewer pipe blockage repair since the financial year of 2006 to 2013. This project explores two relationships, the first is what factors influence the mean number of sewer blockages per pipe, and the second is what factors influence the pipe's hazard rate. The results will assist the Water Corporation to prioritise their sewer pipe replacement program. A Poisson log-linear model was used to fit counts of blockages and a Cox proportional hazard model was used to fit the time to the next blockage, against available explanatory variables .The statistical environment R was used for all model fitting. The results show that pipe length and joint type are the most important factors in both the number of failures and hazard rate models. Additional influential factors for the number of failures are age, diameter, depth, gradient, installation month, submergence depth, soil type, whether a road is found within 15 m, and whether a railway is found within 50 m. Additional influential factors on the hazard rate are diameter, gradient, depth, submergence depth, whether a road is found within 15 m.

1. Introduction

Around 26% of installed sewerage pipes in Western Australia, owned by the Water Corporation (WC), are vitrified clay (VC) pipes, but they are associated with more than 60% of blockages in the past 13 years and more than 65% of these are caused by tree root intrusion. Previous studies by WC have indicated that blockage rates are influenced by pipe age, groundwater level, joint type, soil group and seasonal factors (Alguire, 2009). However, due to the limitation of data and software used, the relationships are still not clear. The Asset Management Branch Renewals section in WC is developing a model to predict expected age of first (and ideally second and third) blockage for each of its individual VC pipes, depending on the pipe's physical and operational factors (e.g. whether it's in a road, depth, soil, water level etc.). A thorough exploration and analysis of the data through this project are necessary to achieve the goal. Particular attention has been given to the tree-root blockages in this project. To process the investigation and understanding, statistical tools—Excel and R - are used to analyse VC pipe blockage data from WC database. A log-linear model is developed to model the relationship between the mean blockage numbers and influential factors. A Cox Proportional Hazard model is developed to model the hazard rate.

2. Methodology

2.1 Data Process and Exploratory Analysis

The available data are saved separately in SAP, InfoNet and GIS at the Water Corporation. Records were matched by knowing the pipe ID in Microsoft Access and Excel. Data cleaning and summary are conducted following. Then the data set were saved into CSV file, which is readable in R. The issues with the dataset found in data cleaning are summarized in Table 1.

Issues	Number in the data base
False Gradient	7
Repeated Records	37
Original installation date lost due to replacement	At least 31*
Not identify the road type when a road is found with 15 meters to a pipe	2907

* The pipe could only be identified as installation date lost when blockage report date is before the recorded installation date in this project.

Table 1 Issues with data base found during data cleaning

The dataset used for modelling covers the time from 01/01/2006 to 30/06/2013 in Perth metropolitan region. After data cleaning it contains 44994 pipes and 4515 pipes are recorded with blockage. There are 6884 pieces of blockage records as 1401 pipes have repetitive records over the duration. The highest frequency in data base is 15 blockages for one pipe in the eight years. Most of blockages (66.2 %) were caused by tree root intrusion. Fat causes the second largest percentage of blockages (16.4 %). Therefore particular attention has been given to the tree-root blockage in the project.

2.2 Statistical Analysis

Two types of models are used in the project. The first type of model, generalized log-linear model analyses the relationship between the mean blockage numbers and potential influential factors. The model is as shown below,

$$\text{Log}\ (\boldsymbol{\mu}) = \boldsymbol{\alpha} + \mathbf{X}\boldsymbol{\beta},$$

where $\boldsymbol{\mu}$ is the mean number of blockages between 2006 and 2013, $\mathbf{X} = (x_1, x_2, \ldots, x_k)$ is a vector of covariates. $\boldsymbol{\alpha}$ is the intercept term and $\boldsymbol{\beta}=(\beta_1, \beta_2,\ldots, \beta_k)^T$ is a column vector of regression coefficients.

The second type of model, Cox proportional hazards model, is developed to analyse the relationships between the hazard function (the probability of instantaneous blockage) and potential influential factors, which is of preliminary interest to survival analysis. The model is shown below.

$$\log \frac{h(t)}{h_0(t)} = \mathbf{X}\boldsymbol{\beta}$$

In this project, pipe blockage is regarded as "death" of pipe. Two such models were fitted: first where t is the time between the data collection date and the first blockage, and second where t is the time between the first and second blockage in the record. $h_0(t)$ 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

Category	Potential Influential Variables		Log-linear model	First Cox Proportional hazard model	Second Cox Proportional hazard model
Pipe Attributes	Intercept		1.837		
	Age;		-0.268		
	Length;		0.01079	0.0178	0.004631
	Diameter;	100-200 mm			
		200-300 mm	-1.242	-1.862	
		300-400 mm	-2.419	-3.657	
		>400 mm	-5.189	-4.411	
	Depth;		0.05584		
	Gradient;		-3.376		
	Joint Type-	Mortar			
		Rubber Ring	-0.6208	-0.6426	-0.4037
	Installation decade;				
	Installation month	January			
		February	0.006561		
		March	-0.2089		
		April	-0.2655		
		May	-0.2961		
		June	-0.1297		
		July	-0.1887		
		August	-0.213		
		September	-0.541		
		October	-0.2791		
		November	-0.5161		
		December	-0.1379		
Environmental factors	Groundwater level;				
	Submergence depth;		-0.00443	0.008	
	Soil Type;	Qpb			
		Qpck	0.447		
		Qpcs	0.3929		
		Qpg	0.5025		
		Qra	0.468		
		Qrg	-0.7424		
		Qrs	0.4771		
		Qrw	0.242		
		Water	0.6457		
	Pipe location;				
	Whether a road is found within 15 m;	Not Found			
		Laneway	-0.3007	-0.66	
		Main	-0.2301	-0.6131	
		Minor	-0.1139	-0.3016	
		State High way	-0.134	-0.7098	
	Whether a railway is found within 50 m;	No			
		Yes	1.199		
	Whether waters found within 50 m;				

Table 2 Estimated Coefficients of Influential Variables in Log-linear Model Analysis

3.1 Log-linear Model results

As shown above in Table 2, **length, depth** and **found railway** have positive association with blockages; **diameter, gradient, submergence depth** and **found road** are negatively associated with blockages. Different **soil type** and different **installation month** have different effect on blockages and details could be found in the following section. Experience and literature review suggest that **age** is always regarded as the significant positive factor: the older pipes should experience more blockages (failures) in our expectation. However this model suggests that the interaction between **age** and other factors caused the **age** factor to be negatively associated with blockages. The interpretations of significant factors are shown below.

- Pipe length: The more joints along longer pipes could be potential entries of external objects, such as tree roots or sediments, to cause blockages. Pipe length is one of the most important factors for mean number of blockages according to the model results.

- Pipe diameter: A previous study observed an increase in blockage rates (up to three times more) in 100- and 150-mm-diameter sewer pipes (Beattie and Brownbill, 2007). The exploratory analysis confirmed this view: pipes of diameter 200mm or less accounted for 95% of all blockage record in the database. It is rare to find a blockage in the 400 mm or more pipes and only one such record is available in the database. The estimators of coefficients decrease for larger pipe size in the generalized log-linear model results.

- Pipe gradient: Flat gradient has been identified as one of the basic design causes of blockages in building drainage system, which are also applicable to sewer systems (WSAA, 2009). According to the model results, increasing gradient reduces the number of blockages in individual pipe in a high probability level. It is believed sufficient gradient guarantees self-cleanse.

- Joint type: Most joint types installed in Western Australia are either mortar joint or rubber ring. Older (more rigid) joints are believed to be associated with a higher frequency of blockages than newer weld or joint-free systems (Littlewood, 2000). According to the exploratory analysis, more than 80% sewer pipes were installed in mortar joints in 1900s-1970s and rubber ring took the dominant status afterwards. Model results identify the rubber ring joint is negatively associated with mean number of blockages.

- Installation month: The model results indicate that pipes installed during all month except February tend to have fewer blockages compared with January. Although the reasons haven't been clarified clearly yet, we suggests seasonal factors could have impact on construction condition and workmanship during installation. Defective pipe joints (bad construction condition) due to poor workmanship were found to be the most common cause of blockage formation, which results in the deposition of sediment (sand, gravel, stones) at the bottom of sewers leading to blockages (Lillywhite & Webster, 1978 and Davies et al., 2001). However it needs discussing with experienced workers on site to clarify the reasons.

- Submergence depth: This factor describes the difference between pipe depth and groundwater level, which is believed to influence tree root growth around pipes ("+" when submerged in water) .The model indicates that the pipes submerged below groundwater level experience fewer blockages. We suggest this is because roots require oxygen to survive and therefore will not grow in pipes where the water table is above the pipes (Roberts et al., 2006).

- Soil type: Different soil types might affect the lateral spread of tree roots. Specifically, the roots system could 3, 2, and 1.5 times differ from the crown diameter in sand, loam and clay soils (Kozlowski, 1987). As extensive root systems are more likely to intersect with sewer, the soils that favour root growth are more likely to have blockages.

Qpb	Bassendean Sand	Qrg	Estuarine and lagoonal deposits
Qpck	Tamala Limestone: predominantly calcarenite	Qrs	Safety Bay Sand
Qpcs	Tamala Limestone: Leolian calcarenite, variably lithified	Qrw	Swamp and lacustrine deposits - peat, peaty sand and clay
Qpg	Guildford Clay: alluvium (clay, loam, sand and gravel)	Water	Water of estuaries, lakes and reservoirs
Qra	Alluvium - clay, sand and loam	Qrg	Estuarine and lagoonal deposits

Table 3 Description of Geological Code

- Whether a road/railway is found near pipe: The model indicates that the pipes tend to have fewer blockages if there is a road found within 15 m but tend to have more blockages if there is a railway found within 50 m. The former might be caused by the undertaken maintenance work during construction or maintenance work of the road and fewer trees near the road. The latter could be caused by the cracks or accelerated deterioration due to the unbalanced transport loading.

- Pipe age: Age is always regarded as one of the most significant influential variables for pipe deterioration process. In this project, there is a strong negative correlation between the mean numbers of individual VC pipe blockages and pipe age. We suggest this is due to interaction. The data suggests that pipes were tended to be installed at greater depth (Figure 1). According to the model deep pipes have a higher probability of blockage than shallow pipe. Details will be investigated further in the future work.

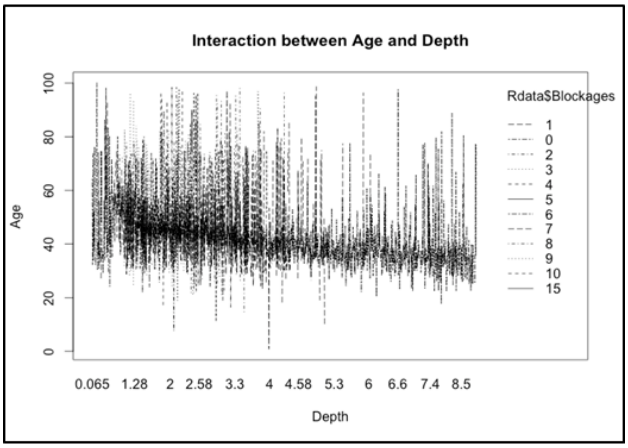

Figure 1 interaction between age and depth

3.2 Cox Proportional Hazard Model Results

For the 1st blockage since data collection, the modelling results identify **pipe length, pipe size, submergence depth, joint type** and **if a road is found near a pipe** are significant factors based on probability. **Pipe length, joint type** and **if a road is found near a pipe** are important factors considering the coefficient value. These results support the results from the generalized log-linear model.

For the time between 1st blockage and 2nd blockage in the record, there are only two significant factors found in this model. Only **joint type** could be identified as the important factor. The first model didn't include the exact time interval as the starting point for pipe life is based on a date data collection is started rather than the installation of the pipe; the data is left-censored.

4. Conclusions and Future Work

Both types of models show that pipe **length** and **joint type** are the most important influential factors. **Age, length, diameter, depth, gradient, joint type, installation month, submergence depth, soil type, whether a road is found within 15 m, if a railway is found within 50 m** are important factors for mean number of blockages. **Length, diameter, submergence depth, joint type** and **if a road found near the pipe** are strongly related to hazard rate. All of those factors can be considered in the VC pipe condition assessments. This information will support the Water Corporation to achieve a more targeted VC pipe condition assessment, data collection and replacement programs.

Other factors, which may enhance the model, including tree/grass density and the identification of location of specific trees with extensive and aggressive root systems, should be included in the further investigation. This is possible with current GIS technology. Another outcome of this model is the potential to consider the results in the design of new sewage piping developments.

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