Seasonal factors influencing the failure of buried water reticulation pipes

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ABSTRACT

While the use of environmental factors in the analysis and prediction of failures of buried reticulation pipes in cold environments has been the focus of extensive work, the same cannot be said for failures occurring on pipes in other (non-freezing) environments. A novel analysis of pipe failures in such an environment is the subject of this paper. An exploratory statistical analysis was undertaken, identifying a peak in failure rates during mid to late summer. This peak was found to correspond to a peak in the rate of circumferential failures, whilst the rate of longitudinal failures remained constant.

Investigation into the effect of climate on failure rates revealed that the peak in failure rates occurs due to differential soil movement as the result of shrinkage in expansive soils.

Key words | asset management, climate, diameter, failure, material, soil

INTRODUCTION

Water reticulation pipe failure is undesirably common. For example one major Australian water utility reported a failure rate of 85.7 failures/100 km/year in 2006–2007 (National Water Commission & WSAA 2008) or around 9.7 failures per day. While there has been extensive work in investigating the causes of failures and the factors affecting the number of failures, little work has been done to address the specific context of climate related failures in Australia.

Previous studies have explored historical data to identify how attributes of the pipe and its surrounding environment affect pipe network failure trends. These are well described in a review by Burn et al. (2009). Location specific studies have reported results for Canada and northern USA (Kettler & Goulter 1985; Rajani et al. 1996; Kleiner & Rajani 2000, 2002; Pelletier et al. 2003; Hu & Hubble 2007), southern USA (Hudak et al. 1998), the Netherlands (Vloerbergh & Blokker 2007), the United Kingdom (UK) (Newport 1981; Boxall et al. 2007) and Australia (Constantine & Darroch 1995; Constantine et al. 1996; Kleiner & Rajani 2000; Jarrett et al. 2000a, 2002, 2003).

These studies found that most static factors (factors that remain constant after pipe installation, e.g. pipe material, pipe diameter) impacting the failure rate are common to all networks. Failure rates have been found to increase as pipe diameter decreases, to increase as the shrink/swell potential of the soil increases and to vary strongly for different material types. Numerous authors have identified that pipe age also has a strong influence on pipe failure. These relationships have been used as the basis for many statistical models for the prediction of pipe failure. These models have been well described in review papers by Jarrett et al. (2000b) and Kleiner & Rajani (2001). However dynamic factors (factors that change over time or cannot be known prior to pipe failure, e.g. age at failure), other than pipe age, particularly those affected by environmental conditions are specific to each region of the world and have not been studied thoroughly.

The effect of dynamic factors, such as soil temperature, water temperature and soil moisture on pipe network failure have been investigated by several authors. These factors can potentially be correlated with annual peaks in failure rates (Kleiner & Rajani 2000, 2002). Generally speaking, annual peaks have been reported to occur in either winter (Habibi 1994; Rajani & Zhan 1996; Rajani et al. 1996) or summer (Hudak et al. 1998; Chan et al. 2007). However some authors have reported peaks of varying amplitudes in both summer and winter (Newport 1981; Hu & Hubble 2007). Hu & Hubble (2007) reported that the major peak occurred during summer, with a minor peak in winter. By contrast, Newport (1981) reported the opposite, with the major peak occurring during winter and the minor in summer.
Investigations into the source of the winter peaks observed in Canada and the USA identified low soil temperatures and/or low soil moisture content as likely causes. Based on these observations, models were developed by Rajani et al. (1996) for calculating thermal loading and Rajani & Zhan (1996) for calculating frost loading of buried pipes in freezing environments. Newport (1981) reported that the winter peak seen in the UK was directly related to the occurrence of frost.

The summer peaks observed in pipe failures have received less attention, with only limited research conducted on the cause of these failures. Hudak et al. (1998) observed that the peaks during summer followed extreme dry periods in southern USA. Newport (1981) reported a similar observation for the UK, although these peaks were minor compared to those in winter and they were less common. Hu & Hubble (2007) reported that in Canada the summer peak observed was related to differential soil movement.

Hudak et al. (1998) and Clark (1971) noted that failures occurred in the presence of soil with high shrink/swell potential. Contrary to this, Boxall et al. (2007) reported no appreciable relationship between soil shrink/swell potential and pipe failure.

This paper presents an analysis which identifies variations in buried water pipe failure rates observed during the year and determines the most likely cause(s) of this variation, with specific reference to temperate, non-freezing environments such as Australia. Static and dynamic factors highlighted by previous studies as influencing the failure of buried pipes are used as the basis for the analysis. This study analyses pipe network data recorded by two adjacent Australian water utilities over a 10-year period.

Types and causes of water pipe failures

The modes by which water reticulation pipes can fail are well described by Rajani et al. (1996). For the purposes of this paper a brief summary is presented below.

The failure of a buried pipe occurs when the applied stresses exceed the structural capacity of the pipe to resist them. Pipe structural capacity reduces over time due to material deterioration, the mechanism of which is dependent on the pipe material.

The type of failure experienced by a pipe is dictated by the loading conditions to which it is subject. The two most prevalent failure types seen in the data used in this analysis are longitudinal failures (also known as splits or long splits) and circumferential failures (also known as circular breaks, broken backs or broken bellies). Longitudinal and circumferential failures result from tensile stress acting in the circumferential and longitudinal directions, respectively.

Circumferential tensile stresses are primarily the result of normal internal operating pressure, surge pressure or the freezing of the water inside the pipe. Longitudinal tensile stresses can result from flexural loading or restrained thermal contraction. Combined longitudinal and circumferential stresses can result in spiral failures.

THE DATA

The pipe network data were obtained from two Australian water utilities for a 10 year observation period between September 1996 and August 2006 inclusive. Pipe and failure data were obtained for all in-service reticulation pipes during the observation period, including pipes installed during the observation period. Incomplete records were removed from the data prior to analysis. The final dataset included over 12,000 km of reticulation pipe and around 40,000 failures recorded over a 10 year period.

Daily climate data were obtained from the Australian Bureau of Meteorology for 10 weather stations distributed within the pipe networks. Data were obtained from five years prior to the start of the observation period until its end.

METHODOLOGY

This analysis investigates both the static and dynamic factors of the pipe networks. However, the focus of the analysis and the results which are discussed in this paper are those factors which relate to variations in the monthly failure rate. Monthly failure rates within a calendar year are referred to as intra-year failure rates for the remainder of this paper.

Climatic parameter calculation

The importance of climatic parameters in understanding intra-year variation in failure rate was identified by several authors including Habibian (1994), Hu & Hubble (2007), Hudak et al. (1998) and Rajani & Zhan (1996). For this reason climate parameters are investigated to identify which parameter(s) correlated best with failure rate. The
literature identifies temperature and soil moisture content as being significant climate related factors affecting pipe failure. Following this, thirteen monthly summary parameters are included in this investigation to describe climatic conditions: minimum antecedent precipitation index (API), average API, maximum API, minimum temperature, maximum temperature, average rainfall, monthly rainfall, monthly evaporation, monthly evapotranspiration, average evaporation, net evaporation, average evapotranspiration and net evapotranspiration.

API is calculated as a daily time series using Equation (1). As the initial value chosen for the calculation of API affects subsequent results, API is calculated starting five years prior to the start of the observation period to negate this effect. The initial value \( API_{n-0} \) of 0.0 is used in these calculations.

\[
API_n = k \times API_{n-1} + P_n, \quad n = 0, 1, 2 \ldots m
\]

where \( API_n \) is the API at day \( n \), \( P_n \) is the precipitation recorded for day \( n \) and \( k \) is a coefficient set as 0.85 in line with Zhou et al. (200b).

The monthly summary parameters for temperature and API are determined as the minimum, maximum and average values during each month. Monthly rainfall, monthly evaporation and monthly evapotranspiration are the sum of the daily rainfall, potential evaporation and potential evapotranspiration in each month, respectively. Average rainfall is calculated as the monthly rainfall divided by the number of days with recorded rainfall. Average evaporation and average evapotranspiration are calculated from the monthly evaporation and monthly evapotranspiration, respectively, divided by the number of days in the month. Net evaporation and net evapotranspiration are calculated from the monthly evaporation and monthly evapotranspiration, respectively, less the monthly rainfall.

Each of the thirteen monthly summary parameters is calculated for each of the 10 weather stations for every month over the 10 year observation period. This created a total of 1,200 month-weather station data points for each monthly summary parameter. Pipes are assigned the climate data of the closest weather station to ensure any spatial variation is accounted for.

### Climatic parameter correlation investigation

To determine the level of correlation between each monthly summary parameter and failure rate the range of values calculated for each monthly summary parameter is broken into discrete intervals. The exposed length and number of failures of all month-weather station data points within each interval are summed and the failure rate of each interval calculated. This allows temporally and/or geographically disparate data to be combined.

Different trendlines are then fitted to the data and the most appropriate is determined based on the strength of the correlations. The coefficient of determination \( (R^2) \) is used as the metric to compare the strength of correlations. ANOVA (analysis of variance) is then conducted on the parameters with the best results to statistically determine the reliability of the correlation observed.

#### Parameter effect

As the failure of buried pipes is strongly influenced by both static and dynamic factors, the relationships between pipe material, pipe diameter, soil shrin/swell potential and climate are investigated. The relationship between observed failure type and climate is also investigated. Climate is represented by the monthly summary parameter which best correlated with the intra-year variation in failure rates. The effect of climate on the failure rates for each factor was investigated by plotting histograms for each category within each factor. A category refers to the different values within each factor, e.g. cast iron and PVC-U are categories of pipe material. A trendline is then fitted to the histogram for each category.

The presence of an effect is determined using two tests based on the trendlines for each category within each factor. An effect is said to be present if either one or both of the following tests returned a positive result.

Test 1: The relative values of maximum failure rate for each category determined from the trendlines are compared to the relative failure rates of that category without reference to the effect of climate. Where the maximum failure rate determined from the trendline is higher or lower than expected, an effect was said to be present. A positive result for Test 1 indicates that when subject to the most deleterious climatic conditions, pipes within that category exhibit more/less failures due to the presence of these conditions than expected.

Test 2: The trendline gradient of each category is compared to that of the trendline fitted to the entire dataset. Where the gradient is higher or lower than that of the entire dataset an effect is said to be present. A positive result for Test 2 indicates that pipes within that category exhibit higher/lower than expected sensitivity to changes in climate.
For the purpose of this analysis it is assumed that no pipes are subject to special conditions. All pipes are assumed to be subject to the same loading and environmental conditions. The combined effects of multiple covariates are not considered in this analysis. Pipe age has not been included explicitly in this analysis. However, it is accounted for within the analysis by consideration of pipe structural capacity reduction.

RESULTS AND DISCUSSION

The intra-year variation of failure rates in each year of the observation period is shown in Figure 1. A peak in failure rates is clearly observed at the start of the year, its seasonal occurrence (corresponding to mid to late summer) is similar to the peak observed by Hudak et al. (1998) for southern USA. It should be noted that data are not available prior to September 1996 and after August 2006.

The summer peak in failure rates seen in Figure 1 can be seen most clearly in 1997, 2001 and 2003, with failure rates peaking above 8.5 failures/100 km/month (equivalent to over 102 failures/100 km/year) in all three years. The highest failure rate was recorded in February 1997, exceeding 9.5 failures/100 km/month. However, the summer peak is not observed every year. Significant differences in the variation of intra-year failure rates are observable over the observation period. For example, in 1999 and 2002 there were relatively consistent intra-yearly failure rates, varying by around 2 failures/100 km/month. This contrasts strongly with 1997, 2001 and 2003, where intra-yearly failure rates varied by up to 7.5 failures/100 km/month.

Climatic parameter correlation investigation

Pipe failure rates were calculated with reference to discretised monthly summary parameters to detect potential correlations. A range of trendlines were then fitted to the data. An exponential trendline was found to provide the best fit.

Using an exponential trendline, minimum API and net evaporation were both found to correlate strongly with failure rate, with $R^2$ values of 0.78 and 0.74, respectively. Figure 2 and Equation (2) show the histogram and fitted trendline for minimum API, respectively. Equation (3) shows the fitted trendline for net evaporation. An ANOVA of the data for minimum API and net evaporation indicated that there is indeed a dependence of failure rate on both parameters. The results indicated that there is negligible probability ($<0.0001$) that the variation observed could be explained without the use of the trendlines determined during the regression analysis. As minimum API was the monthly summary parameter which best correlated with failure rate, it will be used to represent climate for the remainder of this paper.

The correlation between minimum API and failure rate indicates that as minimum API decreases failure rate increases. API can be used as a measure of soil moisture content (Blanchard et al. 1981), where the soil moisture content increases as API increases. From this relationship, it can be inferred that as the soil moisture content decreases failure rate increases. This result is in agreement with the observations made by Hudak et al. (1998), Kleiner & Rajani (2000) and Newport (1988), for southern USA, southern Australia and the UK, respectively. The relationship between soil and minimum API is investigated and discussed below.
Following this, the cause of the variation in the amplitude of the observed peak in failure rate during mid to late summer, Figure 1, was investigated. It was found that in the months January through March for years where peaks in failure rates were observed, low values of minimum API were recorded (around 50% lower than the observation period average). Conversely, higher values of minimum API (around 50% higher than the observation period average) were calculated in those years in which no peak was observed.

\[
\text{Failure Rate} = 3.34 \times e^{-0.089 \times \text{Minimum API}} \quad R^2 = 0.78 \quad (2)
\]

\[
\text{Failure Rate} = 2.72 \times e^{0.005 \times \text{Net Evaporation}} \quad R^2 = 0.74 \quad (3)
\]

where Failure rate in failures/100 km/month, Minimum API in mm and Net Evaporation in mm.

**Effect of climate on failure rates for static factors**

The effects of climate on failure rates were investigated in regard to pipe material, pipe diameter and the shrink/swell potential of the soil, referred to as soil type for the remainder of this section, surrounding the pipe. Due to the number of pipe materials and diameters present in the data, only the four materials (cast iron, asbestos cement, PVC-U and ductile iron) and the three diameter groups (50 to <100, 100 to <150 and 150 to <200 mm) with the greatest in-service length were included in the analysis (Table 1). These materials and diameter groups accounted for over 80% of the pipe length for each factor.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Material Category</th>
<th>Length (km)</th>
<th>% of total length (km)</th>
<th>Number of failures</th>
<th>% of total failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Cast iron</td>
<td>3,881</td>
<td>32</td>
<td>25,898</td>
<td>65</td>
</tr>
<tr>
<td>Asbestos cement</td>
<td>1,987</td>
<td>17</td>
<td>8,477</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>PVC-U</td>
<td>2,893</td>
<td>24</td>
<td>1,673</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Ductile Iron</td>
<td>1,566</td>
<td>13</td>
<td>1,913</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>50 to &lt;100</td>
<td>754</td>
<td>6</td>
<td>2,358</td>
<td>6</td>
</tr>
<tr>
<td>100 to &lt;150</td>
<td>6,372</td>
<td>53</td>
<td>27,213</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>150 to &lt;200</td>
<td>2,913</td>
<td>24</td>
<td>7,644</td>
<td>19</td>
<td></td>
</tr>
</tbody>
</table>

**Material**

The parameter effect investigation for pipe material and minimum API produced a negative result for Test 1 for all materials. Test 2 produced a positive result for cast iron and PVC, and a negative result for asbestos cement and ductile iron. The failure rate of cast iron was found to increase faster than expected as minimum API decreased, whilst for PVC-U it increased slower than expected as minimum API decreased. For all materials, the failure rate was found to increase as minimum API decreases.

As discussed in the introduction, the failure of buried pipes occurs when the applied stress exceeds the pipe structural capacity. Therefore two possible situations exist. The increase in pipe failure rate occurs due to an increase in applied stress or an increase in the rate of deterioration of pipe structural capacity.

As all pipes are assumed to be subject to similar conditions, the higher and lower sensitivity of cast iron and
PVC-U, respectively, is a result of the materials response to these conditions. To determine the most likely situation, the effect of changing minimum API was investigated in relation to pipe capacity. As asbestos cement and ductile iron did not show an interactive effect with minimum API, the behaviour of these materials has not been investigated.

Corrosion is a long-term process which reduces the capacity of cast iron pipes, the rate of which is dependent on soil corrosivity. The corrosivity of a soil increases as its resistivity decreases (Sadiq et al. 2004), and soil resistivity decreases as soil moisture content increases (Zhou et al. 2001a). Consequently, the corrosion rate and the rate of capacity deterioration would be expected to decrease as minimum API decreases (indicating a decrease in soil moisture content). This does not explain the increase in failure rate. It is therefore likely that the increase in failure rate, results from an increase in the applied stress.

The capacity of PVC-U pipes reduces as a result of slow crack growth from defects in the pipe wall. The rate of slow crack growth is dependent on the initial defect size and pipe stress conditions (Burn et al. 2005). The initial defect size is determined at the time of or prior to pipe installation and is not related to minimum API. Consequently, the increased failure rate is most likely due to an increase in the applied stress.

**Diameter**

Results from both Test 1 and Test 2 did not indicate an effect of minimum API on diameter. It should be noted that this does not mean that there is no variation in failure rates between diameter groups. Only that the variation seen in response to minimum API is consistent with the expectations tested in Test 1 and Test 2.

**Soil**

The effect of minimum API on the failure rate of pipes in different soil types was investigated for all four soil types present in the dataset: very expansive, expansive, slightly expansive and stable. Test 1 and 2 both produced positive results for very expansive soils. Pipes in these soils were found to experience a higher than expected maximum failure rate and their failure rate increased faster than expected as minimum API decreased. Test 1 and 2 both produced negative results for the remaining soil types. These results indicate an effect of minimum API on the failure rate of pipes in different soil types.

As discussed in the introduction, the failure of buried pipes occurs when applied stress exceeds pipe structural capacity. The higher sensitivity of pipes in very expansive soils to minimum API, in comparison to other soil types indicates that these pipes are subject to higher increases in the applied stress as minimum API decreases.

Following this, the applied stress in increases as soil moisture content decreases. A reduction in soil moisture content of expansive soils results in shrinkage. Therefore, soil shrinkage is the cause of the increased stress. Further as very expansive soils are by definition strongly affected by soil moisture change, these soils would impose harsher conditions on pipes than less expansive soils.

**Effect of climate on observed failure type**

The effect of minimum API on failure type was investigated for circumferential and longitudinal failures. Other failure types were not included. Results from Test 1 did not indicate an effect. Test 2 produced a positive and negative result for circumferential failures and longitudinal failures, respectively.

Analysis of intra-year failure rates for each failure type revealed that failure rates for longitudinal failures were relatively consistent over the course of the calendar year, whilst circumferential failures showed a clear peak. The intra-year failure rates for longitudinal failures varied by around ±30% from the average. In contrast, circumferential failure rates showed a clear peak toward the end of summer, varying by around +100% from the average in summer and by around −60% in winter. Capacity reduction should result in an increase in failures irrespective of the type. However, the summer increase in circumferential failures indicates an increase of the associated loading types at this time.

Circumferential failures result from longitudinal stresses caused by flexural loads and/or restrained thermal contraction (Rajani et al. 1996). As the increase in failures occurs in summer the latter cause can be excluded. Therefore, the increase in circumferential failures is most likely due to an increase in flexural stress.

**Summary**

The results detailed above indicate that the summer peak observed in failure rates is attributable to a peak in circumferential failures. The peak in the circumferential failure rate results from differential soil movement. The differential soil movement results from soil shrinkage occurring as soil moisture content decreases. This induces flexural stress in buried pipes due to a loss of support beneath the pipe. This
occurs most noticeably in very expansive soils. It is for this reason that rigid cast iron pipes are particularly sensitive to climate whilst flexible PVC-U pipes show only a slight response.

This conclusion is supported by several authors who have attributed peaks in failure rate to the action of expansive soils (Clark 1971; Hudak et al. 1998; Hu & Hubble 2007).

CONCLUSION

This paper has presented an analysis which identified variations in buried water pipe failure rates observed during the year and determined the most likely cause of this variation, with specific reference to temperate, non-freezing environments such as Australia. Pipe failure rates were found to peak in mid to late summer, attributable to a reduction in soil moisture content causing soil shrinkage, resulting in a peak in circumferential failures.

The strong correlation found between climate and pipe failure rate means that modelling which does not account for climate related effects will not adequately account for temporal variations in failure rate.

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