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FACTORS CONTRIBUTING TO LARGE DIAMETER WATER PIPE FAILURE AS EVIDENT FROM FAILURE INSPECTION

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Abstract
This paper presents the statistical analyses of pipe failure data on large diameter water mains collected from five Australian water utilities. The analyses were performed to identify the factors that lead to failures of cast iron, steel and ductile iron pipes. Data required for the analyses such as mode of failure, causes of failure, corrosion data, and pit characteristics were obtained from the failure inspection reports provided by Australian water utilities. After studying the failure inspection reports, three main types of corrosion category were identified in the failed pipe sections. Reported corrosion at the time of failure was also used to glean the levels of corrosion that have led to pipe failures. It should be noted that the data reported may not be always totally consistent, but the availability and collection of accurate information on pipe failures is very valuable in advancing pipe failure prediction for pipe asset management.

Keywords
Pipe failure data; failure mode; corrosion; failure prediction

INTRODUCTION

The water utilities in Australia operate supply and distribution networks consisting of mostly ageing, cast iron and steel mains. The failure of large diameter pipes (i.e., pipe diameter ≥ 300 mm) can be highly disruptive to both water utilities and to the public they serve. It can have major consequences in terms of economic loss to water utilities, public safety, damage to property and also have an adverse affect on the overall performance of their assets. Structural failures of large diameter metallic water mains are usually due to a combination of factors, but predominantly occur when pipes deteriorated by corrosion are subjected to excessive internal and (or) external loadings. Thus, the identification of relative contributions of each factor in a specific failure (i.e., physical and corrosion) is often a difficult task and has not yet been resolved satisfactorily. The factors that contribute to a specific pipe failure can be categorized in three principal groups: (a) pipe geometry, material type, pipe-soil interaction and quality of installation, (b) internal loads due to operational and transient pressure and external loads due to soil overburden, traffic loads, frost loads (in cold climate) and third party interference (catastrophic loads), and (c) material deterioration due largely to the external and internal chemical factors; this includes bio-chemical microbiological and electro-chemical activities that lead to corrosion (Rajani and Kleiner, 2001).
To understand in-service pipe failures, it is necessary to have a knowledge of the stresses to which pipes are subjected and any degradation of mechanical performance of the pipe with time that might contributes to failure. Although there may be a range of (sometimes unknown) variables involved, the pipe failure is the result of deterministic process governed by physical conditions. Regardless of the source of loading, a pipe may fail when the generated stress exceeds the nominal material strength or when the stress intensity generated at a critical defect (for instance, as a result of pitting corrosion) exceeds the material toughness of the material, or possibly as a combination of both. Thus, pipelines reach failure states when the pipe at a particular location loses its structural capacity sufficiently with time due to corrosion or damage. Therefore, in order to understand the pipe failure mechanisms, it is necessary to establish the long term corrosion characteristics of pipes in their

buried environment. There are instances however, some pipes have failed without significant corrosion and, in these instances, accumulation of damage due to repetitive loading may be to blame (Rajani and Kleiner, 2010).

Existing physical and statistical models for the prediction of failures in individual water mains address only one or a few factors. Neglecting to account for the important factors can lead to inaccurate conclusions, which result in sub-optimal failure prediction and pipe renewal strategies. The statistical analysis of past pipe failure data that uses available historical data on past failures to identify the possible factors leading to pipe failure is one of the effective ways to study the pipe failure mechanism, causes of failure and deterioration etc. Unfortunately, however, in contrast to small diameter pipe failures, the failure data in large diameter pipes are significantly limited. Despite this, and paying attention to any inconsistencies that may be present in the field data collection, it is valuable to extract any information that can help pipe failure prediction and asset management.

In this study, information (i.e., installation and failure data) on buried large diameter pipes collected from five Australian water utilities are analysed to understand the physical and environmental factors that lead to failure. The failure data were analysed to classify commonly observed pipe failure modes and causes of failure. Corrosion patterns observed in the failed pipe sections were classified into three major groups and the idealisation of the corrosion patterns was made to facilitate pipe failure prediction analysis. Further, on the basis of failure inspection reports, the level of corrosion at the time of pipe failure (using average corrosion rate) was used to examine the likely corrosion levels that had led to pipe failures.

FAILURE STATISTICS

As stated above, the past pipe failure data on buried large diameter pipe were collected from five Australian water utilities and were analysed to understand the physical and environmental factors that could have contributed to their failure. In general, the collected data provided information on pipe diameter, pipe material, location of failure, cause of failure, failure mode, pipe laid year, and year of failure, though all the information was not always available. It is also important to note that not all data had the same level of details because of the differences in data collection procedures followed by different water utilities and hence direct comparison of results was not always possible. Table 1 gives a summary of failure data collected from five water utilities (referred to here by their generic names; utility-A to utility-F). It also shows the average failure per year (i.e., total number of observed failures/period).

Table 1. Summary of collected past pipe failure data

Water utilities	Period	Pipe material	Total length of asset (#km)	Total number of failures
A	2000-2012	CICL, SCL, DI, PVC & AC	3061	2,871
B	1973-2010	CICL, DI, S, & PVC	779	1,052
D	1998-2012	CI, DI, S, & PVC	862	1,023
E	1996-2009	S, AC, CI, & PVC	854	426
F	1997-2012	CI, DI, S, & PVC	426	809

CI: Cast iron; CICL: Cast iron cement lined; S: Steel; SCL: Steel cement lined; DI: Ductile iron; AC: Asbestos cement; PVC: Polyvinyl chloride

In this study, analyses were performed on the data for CI, S, DI and AC pipes that are considered to be affected by corrosion or similar deterioration mechanisms. Table 2 provides the asset length data based on the pipe material.

Table 2. Asset length data on the basis of pipe material

	Water utility				
	A	B	D	E	F
Pipe material	% of pipe asset length				
CI/ CICL	- / 56.65	3.46/ -	- / 48.89	2.76 / 8.47	8.09 / 11.78
S/ SCL	- / 19.64	- / 60.08	- / 24.19	1.19 / 45.08	0.58 / 54.41
DICL	23.69	9.31	26.91	18.56	25.14
AC	0.03	27.15	-	23.93	-

The collected failure data for each water utility were analysed separately and conclusions were drawn on the basis of common trends identified. The following sections discuss the results of the statistical analyses of failure data on the basis of pipe materials, failure modes and causes of failure. Further, the pipe failure inspection reports were analysed to understand the contribution of corrosion on the pipe failures on the basis of observed corrosion pit depth in a failed pipe section and identified failure mode.

Pipe materials

The failure data were analysed on the basis of pipe material. The failure rate per year per km for a specific pipe material was determined using the total number of failures divided by number of years in the observation period and the total asset length of that pipe material. Unlined and cement lined (CL) pipes were treated separately. The pipe failure rate related to pipe material is provided in Table 3. Based on the analysis, the higher failure rates were observed for both unlined and cement lined or cast iron pipes in comparison to other pipe materials for water utilities A, B, D and E. However, a higher failure rate was observed in steel pipes for water utility F. The lowest failure rate for all water utilities on a relative basis is for ductile iron pipes.

Table 3. Summary of pipe failure rates (# no. of failure/ km/ year)

Water utility	Period (# years)	CI	CICL	S	SCL	DICL	AC
A	2000-2012 (13)	-	7.2	-	4.2		2.8
B	1973-2010 (38)	34.5	-	-	3.1	0.1	2.2
D	1998-2012 (15)	-	14.0	-	5.1	0.80	-
E	1996-2009 (14)	7.8	8.9	6	2.4	1.85	4.2
F	1997-2012 (16)	29.5	21.5	42	8.0	8.00	-

Note: These failures rates do not differentiate for the fact that some of the pipes were not cement lined for a period of time since installation.

Failure modes

The actual manner in which the pipes fail is called the failure mode rather than the mechanism that causes the failure. These modes vary depending on the diameter of the pipe and the pipe material. For example, the longitudinal bending induced circumferential ("broken back") failures are more common in smaller diameter pipes that have relatively low water pressure and smaller moments of inertia. On the other hand, the larger diameter pipes experience mainly longitudinal cracking and shearing at the bell due to relatively higher water pressure and moments of inertia. More details of different failure modes observed in pipelines can be found in Makar et al., (2001). The commonly observed failure modes in large diameter pipes and the identified driving factors are summarised in Table 4.

In this study, the observed failure modes were analysed in accordance with pipe material (mainly cast iron and steel) and diameter. The results of the analyses in this paper are limited to water utilities-A and -B only. A detailed presentation of the results of other water utilities can be found in Kodikara *et al*., (2012).

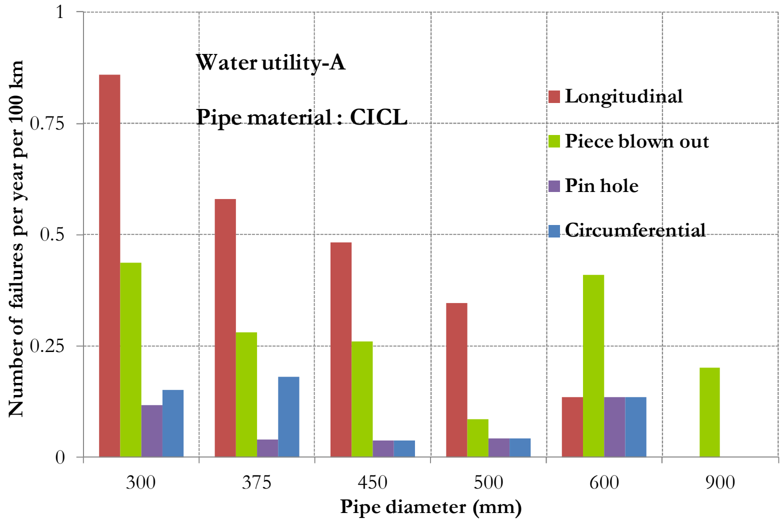
Table 4. Commonly observed failure modes in large diameter pipe and corresponding driving factors

Failure mode	Driving factors
Longitudinal split	Internal pressure and corrosion
Piece blown out	Internal pressure and corrosion
Pin hole	Corrosion
Circumferential break	External loadings and ground movement*
Joint leakage	External/internal loads, thermal loadings and construction defects

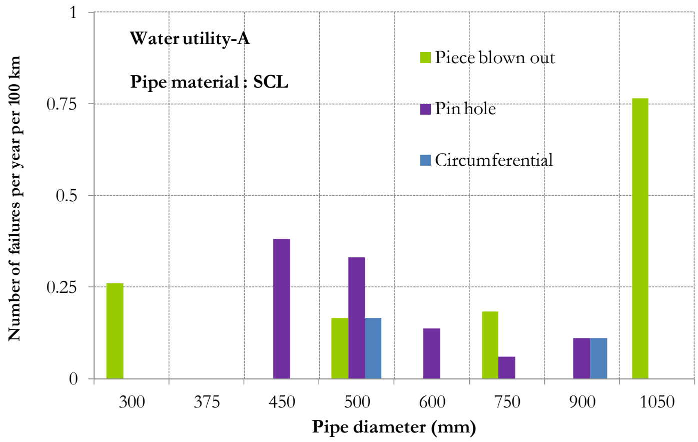
* Note: Not common in large diameter pipes

Figure 1 shows histograms of failure rate vs. pipe diameter based on the failure mode data obtained from water utility-A for cast iron and steel pipes. Failures due to piece blown out and pin hole are observed in the entire diameter range in cast iron and steel pipes. There is, however, some doubt as to how common piece blown failure in steel pipes is since the material is more ductile. Longitudinal spilt, which is one of the dominant failure modes, is observed in CICL pipes up to 600 mm pipe diameters. The circumferential failures are also observed in steel pipes even in 600 mm and in cast iron of 900 mm diameter. Usually, circumferential failures are not common in large diameter pipes due to high moment of inertia that restrains bending, and, therefore, more attention may need to be paid to such information in future.

Figure 2 shows a histogram of failure rates based on failure type using the data obtained from water utility-B for CI and SCL pipes. As observed for water utility - A, a large number of piece blown out and longitudinal spilt failures were observed in cast iron pipes. For steel pipes, a large number of failures were in the mode of piece blown out across the whole diameter range. Such data may need further attention in future for the reasons noted above. Also, failures were observed due to longitudinal spilt and circumferential failure across the whole diameter range.

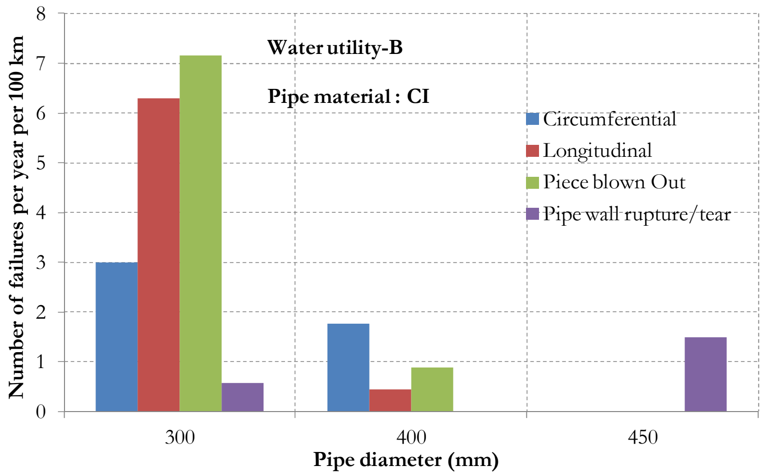


(a) Cast iron cement lined pipes (CICL)

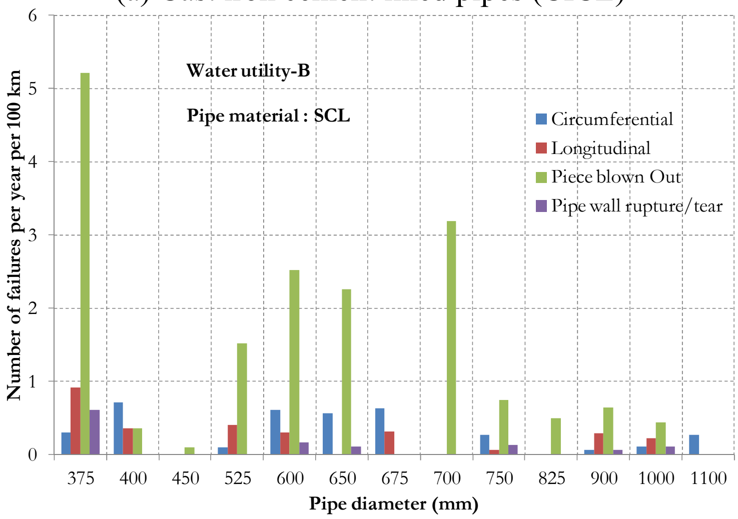


(b) Steel cement lined pipes (MSCL)

Figure 1. Histogram of failure rate based on failure mode for: (a) CICL main and (b) SCL main using the past failure data obtained from water utility-A



(a) Cast iron cement lined pipes (CICL)



(b) Steel cement lined pipes (MSCL)

Figure 2. Histogram of failure rate based on failure mode for: (a) CI main and (b) MSCL using past failure data obtained from water utility-B

Causes of failure

Buried pipes are subjected to internal water pressure consisting of static water pressure and pressure transients due to surges, external loads, self-weight of pipes and their contents, the heaving or movement of the surrounding soils and potential inertial seismic forces. External loads typically consist of earth load and traffic load. Unlike the uniform stress condition developed by internal pressures if no other external loads are acting, external loads develop non-uniform stress conditions (bending) around the pipe circumference. A pipe affected by corrosion or some other similar defect can fail if the stresses induced by a combination of the sum of all of these loads is sufficiently higher than the pipe capacity. The failure data collected were not sufficiently extensive to make conclusive statements of the causes of failure. However, general evaluation of data highlighted corrosion as the main failure cause. In addition, pressure transients and ground movements were indicated. It is, however, not clear how ground movement could affect large diameter pipes due to their much higher rigidity against bending due to higher moment of inertia. This would be another aspect where more clarity would be needed in data collection.

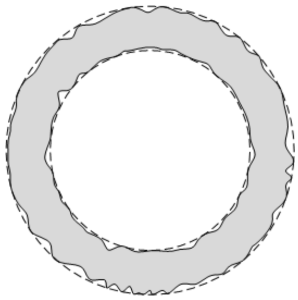
PIPE CORROSION

Utilities in Australia operate a supply and distribution network consisting of predominantly cast iron and steel pipes with ages on average greater than 60 years. As shown above, pipe corrosion is one of the major factors controlling pipe failure.

It is envisaged that pipe failure analysis should take into account actual deterioration and defects identified either through condition assessments or as expected to occur in pipes on the basis of the empirical evidence. On the basis of the collected information from utilities -A and D, corrosion patterns and the rate of corrosion as evident from failed pipes were studied. The corrosion in the pipes was mainly classified as general corrosion, patch corrosion and pitting corrosion.

General corrosion refers to reasonably uniform reduction of thickness over the surface of the pipeline wall. An example of this is shown in Figure 3 (a). This form of corrosion may be idealised in the form of a reduction of thickness Figure 3 (b).

(a)



(b)

Figure 3. General corrosion: (a) field observation and (b) idealisation of general corrosion

Patch corrosion is identified as a patch of corrosion due to graphitization or cluster of geometrically interacting pits, which can be approximated as a patch of corrosion as shown in Figure 4 (a).

Pitting is defined as localised regions of metal loss that can be characterised by a pit diameter (API, 2007). On the basis of the corrosion data obtained from the utilities, there were three different corrosion pit patterns named as single pit, multiple non-interacting pit and multiple non-interacting pit commonly observed, as shown in Figure 5. The diameter and thickness of the failed pipelines are shown along with the figures. The cluster of single pits that are not geometrically interacting with each other is called non-interacting multiple pits otherwise it is called interacting pits.

The single pit can be idealised as shown in Figure 6 for analysis. Drawing from API (2007) the non-interacting and interacting multiple pit can be idealised as shown in Figure 7 and Figure 8 respectively.

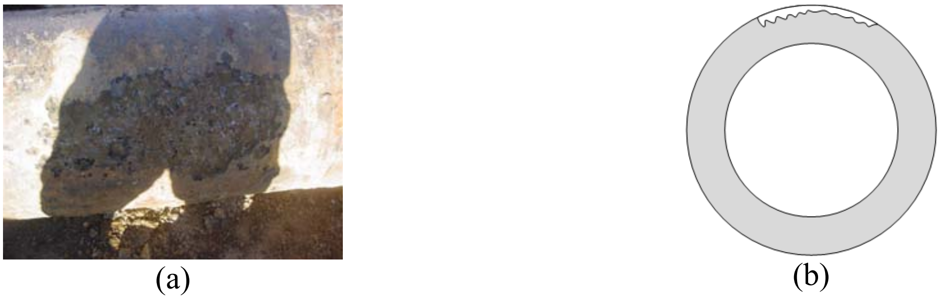


Figure 4. Patch corrosion (a) field observation and (b) idealisation of patch corrosion

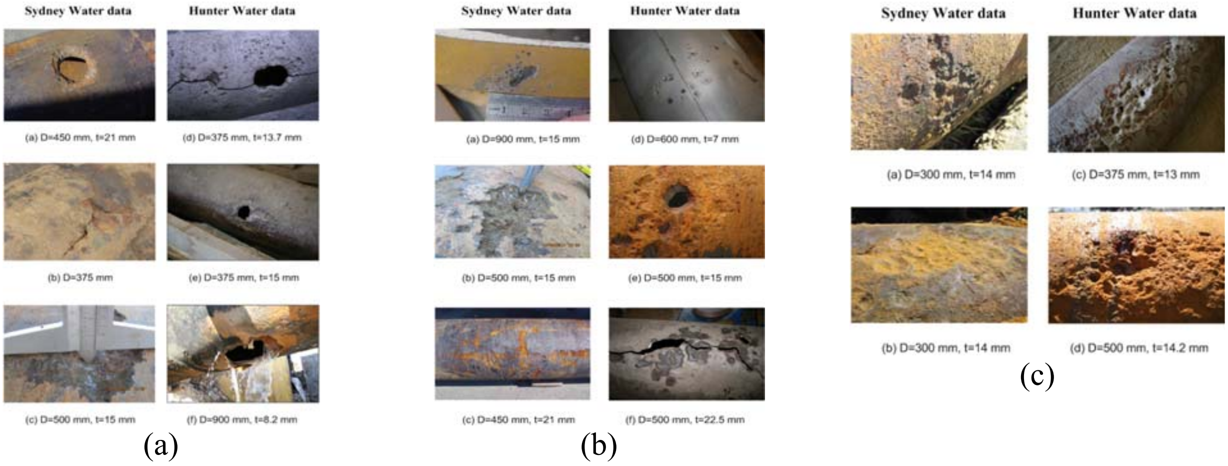


Figure 5. Observed pitting corrosion patterns

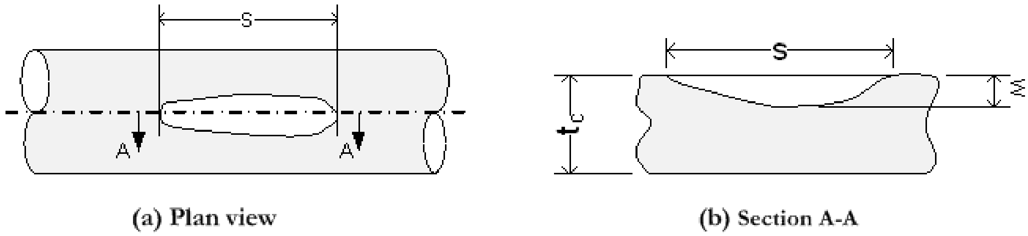


Figure 6. Single pit (s- length of the pit, w – depth of the pit, t_c –pipe wall thickness)

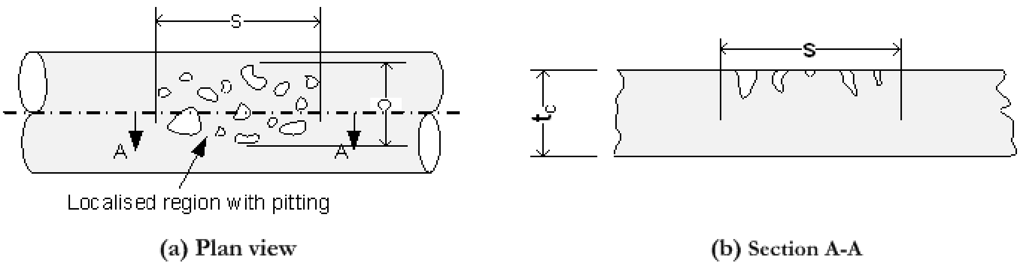


Figure 7. Schematic multiple non-interacting pit cluster (s- length of the pit)

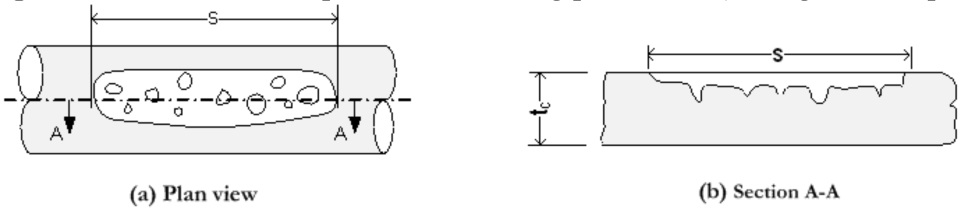


Figure 8. Schematic multiple Interacting pit cluster (s- length of the pit, t_c –pipe wall thickness)

Corrosion rate

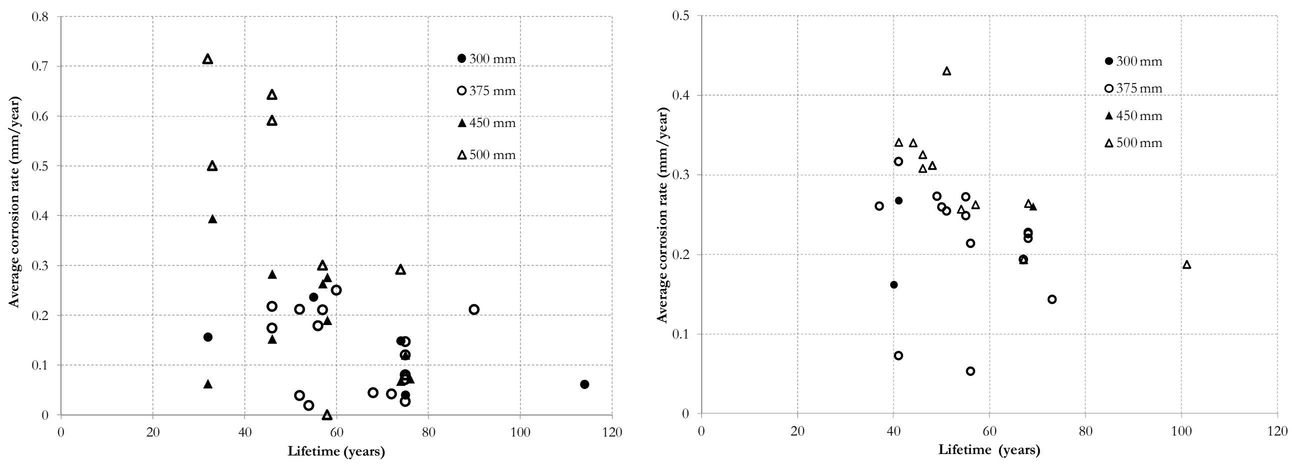
The inspection reports collected from the water utilities provided information on pipe laid year, the year of failure, and the maximum corrosion pit depth observed in the failed section. The depth of the corrosion pit was determined during the (forensic) investigations of the failed section. These data were available only from water utilities-A and -D.

An analysis was conducted on the average rate of corrosion experienced by the failed pipes over the period which the pipes were in operation. The methods used to estimate normalised corrosion rates were as follows:

- Average Corrosion Rate (ACR) - The maximum pit depths determined during the forensic investigation of the failed section are divided by the pipe lifetime (defined as the difference between the year of failure minus the year of installation) to determine the average corrosion rates over the life of the pipelines (see Figure 9.(a) for water utility -A). It should be noted that this is an average corrosion rate over the entire pipe life and is not reflective of actual corrosion rates the pipe was experiencing at various times in pipe life. For more information on actual corrosion rates, influencing parameters and mechanisms related to buried cast iron pipes, refer Peterson and Melchers (2012).
- Normalised Pit Depth at Failure (NPD) - The normalised pit depth was calculated by dividing the pit depth measured at failure by the original nominal pipe wall thickness and multiplying by 100 to give as a percentage.

Figure 9 shows ACR calculated using failure inspection reports for cast iron pipes obtained from water utilities- A and -D. The results are shown for different pipe diameters. There is significant scatter in the data, and there are some pipe failures even below 40 years featuring lower average corrosion rates at failure.

In order to examine the likely pit depths at failure, NPD is plotted against the pipe lifetime in Figure 11. As can be seen NPD= 100% means that the pipes have failed with through wall corrosion, and values less than 100% reflects the percentage of pit corrosion with respect to the original thickness. It can be seen that quite a few data points fall on the through wall corrosion level. It is also evident that a significant number of failures have occurred with less than through wall corrosion. There are limited number of points (i.e., 3 points) in NPD = 75% to 100%. It may be inferred that when the wall thickness reduced more than 75% of its original thickness, pipes may have failed through wall failure.



(a) (b)

Figure 9. Average corrosion rate vs. lifetime for: (a) Water utility-A and (b) Water utility-D

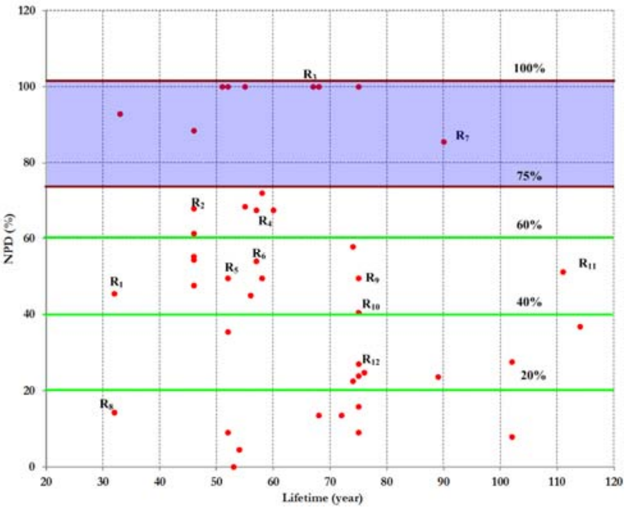


Figure 10. Normalised pit depth at failure vs. age of the pipe at failure for water utility -A

In order to examine the possible causes and modes of failure associated with NPD, a number of data points in Figure 10 are elaborated further in Table 5. For instance, the point R_3 falls on the through wall corrosion (NPD=100%).

Table 5. Detailed analysis of failure data and qualitative contribution of corrosion and other factors to failure. Table must be assessed in conjunction with Figure 10

Selected point	Cause of failure as noted in the failure inspection report	Selected point	Cause of failure as noted in the failure inspection report
R_1	Corrosion and other factors	R_7	Piece blown out. Failure due to corrosion.
R_2	Minimal external corrosion. Failure due to other factors	R_8	Longitudinal crack seemed to follow a series of shallow pits on the external surface
R_3	Through wall corrosion. Heavy pitting corrosion.	R_9	Piece blown out from collar: failure due to corrosion and other unknown factors
R_4	No signs of corrosion along the point of failure, only a thin layer of surface corrosion coming off when hit. One location of deeper surface corrosion. Failure due to water hammer resulting from pumping	R_{10}	Failure by a piece blown out. Through wall along surface fracture but only in minimal number of locations. Surface corrosion all around fracture. Minimal surface corrosion, except for one location with up to 6mm.
R_5	Longitudinal piece blown out from joint collar. Significant corrosion at collar. Failure due to corrosion and water hammer (operational changes at pumping station)	R_{11}	Longitudinal failure with a piece blown out. Failure due to corrosion and operational change
R_6	Very minor corrosion and pitting, 2 to 3mm at most. Failure was	R_{12}	Piece blown out. Through wall along fracture surface but only in minimal

	characterised by a blown out piece of pipe caused by collar fracturing: May be due to localized corrosion. The system was operated as normal. There was no pressure transient		locations. Surface corrosion all around fracture. Minimal surface corrosion, except for one location with up to 6mm.

SUMMARY AND CONCLUSION

In this study, the past pipe failure data and information were collected from five water utilities in Australia and were analysed to identify the factors contributing to large diameter pipe failures. On the basis of the collected pipe failure data, most of the failures were observed in cast iron and steel pipes. Failure due to piece blown out and pin hole are the major failure modes observed for all the water utilities. Corrosion is identified as a leading cause of failure together with pressure transients and traffic load. The details on the types of corrosion observed in the failed pipe were collected from the failure inspection reports. The type of corrosion observed in a failed pipe section was characterised into three main groups to facilitate pipe failure prediction for corroded pipes, namely uniform corrosion, patch corrosion and pit corrosion.

On the basis of the corrosion pit information reported in the failure inspection reports, the average rate of corrosion was calculated using the field observed maximum corrosion pit depth and the pipe lifetime. Examination of pit depths as a percentage of the original pipe thickness indicated that failures occurred at various pit depths, but there were fewer failures between 70% and 100% pit depths. It should also be noted that some inconsistencies were found in the analysed failure data and these observations and inferences, while based on the available data, need to be further verified and checked with collection of more accurate data in the future.

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