Factors contributing to large diameter water pipe failure

P Rajeev, Jayantha Kodikara, Dilan Robert, Peter Zeman and Balvant Rajani look at a case study in which failure inspection data from five Australian utilities was analysed to determine the factors contributing to failures in large diameter pipes.

P Rajeev and Jayantha Kodikara
Department of Civil Engineering, Monash University, Australia. Email:
prajeev@swin.edu.au;
jayantha.kodikara@monash.edu;

Dilan Robert
RMIT University, Melbourne, Victoria, Australia.
Email: dilan.robert@rmit.edu.au

Peter Zeman
Sydney Water, Parramatta, NSW, Australia.
Email: peter.zeman@sydneywater.com.au

Balvant Rajani
Rajani Consultants, Ottawa, Canada.
Email: Balvant.Rajani@gmail.com

Water utilities in Australia operate supply and distribution networks consisting mainly of ageing cast iron and steel mains. The failure of large diameter pipes (of diameters >300mm) can be highly disruptive to both water utilities and the public they serve. Failures can have major consequences in terms of economic loss to water utilities, public safety and 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 caused by a combination of factors, but predominantly occur when pipes affected by corrosion are subjected to excessive internal and / or external loadings. Identifying the relative

Table 1
Summary of collected past pipe failure data

Table 2
Asset length data on the basis of pipe material

contributions of each factor in a specific failure (that is, physical factors and corrosion) is often a difficult task that has not yet been resolved satisfactorily.

The factors that contribute to a specific pipe failure can be categorised into three principal groups:
• Pipe geometry, material type, pipe-soil interaction and quality of installation
• Internal loads due to operational and transient pressure and external loads due to soil overburden, traffic loads, frost loads (in cold climates) and third party interference (catastrophic loads)
• Material deterioration due largely to external and internal chemical factors; this includes biochemical microbiological and electro-chemical activities that lead to corrosion

(Rajani and Kleiner, 2001). To understand in-service pipe failures, it is necessary to understand the stresses to which pipes are subjected and any degradation of the pipe's mechanical performance with time that might contribute to failure. Although there may be a range of (sometimes unknown) variables involved, the pipe failure is the result of a 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, or possibly as a combination of both. Thus, pipelines reach failure states when the pipe at a particular location loses its structural

Water utilities	Period	Pipe material	Total length of asset (km)	Total number of failures
A	2000-2012	CICL, SCL, DI, PVC & AC	3061	2871
B	1973-2010	CICL, DI, S, & PVC	779	1052
D	1998-2012	CI, DI, S, & PVC	862	1023
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

Water utility	A	B	D	E	F
Pipe material			% of pipe asset length		
CI/ CICL	- / 56.65	3.46/ -	- / 48.89	276/847	638/929
S/ SCL	- / 19.64	- / 60.08	- / 24.19	17/644	5/469
DICL	23.69	9.31	26.91	18.56	25.14
AC	0.03	27.15	-	23.93	-

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 mode	Driving factors
Longitudinal split	Internal pressure and corrosion
Piece blown out	Internal pressure and corrosion
Pinhole	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

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

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

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

capacity sufficiently with time, due to corrosion or damage.

In order to understand the pipe failure mechanisms, it is therefore necessary to establish the long-term corrosion characteristics of pipes in their buried environment. There are instances, however, where 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 predicting 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.

Statistical analysis of past pipe failure data, which uses available historical data on past failures to identify the possible factors leading to pipe failure, is one of the effective ways of studying the pipe failure mechanism, causes of failure and deterioration and so on. Unfortunately, however, in contrast to small diameter pipe failures, the failure data for large diameter pipes are significantly limited. Despite this, and paying attention to any inconsistencies that may be present in the field data collection, extracting any information that can help pipe failure prediction and asset management is valuable.

In this study, information (such as installation and failure data) on buried large diameter pipes collected from five Australian water utilities was analysed to understand the physical and environmental factors that led 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 then visualised 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 the 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 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, year the pipe was laid, and year of failure, though all the information was not always available.

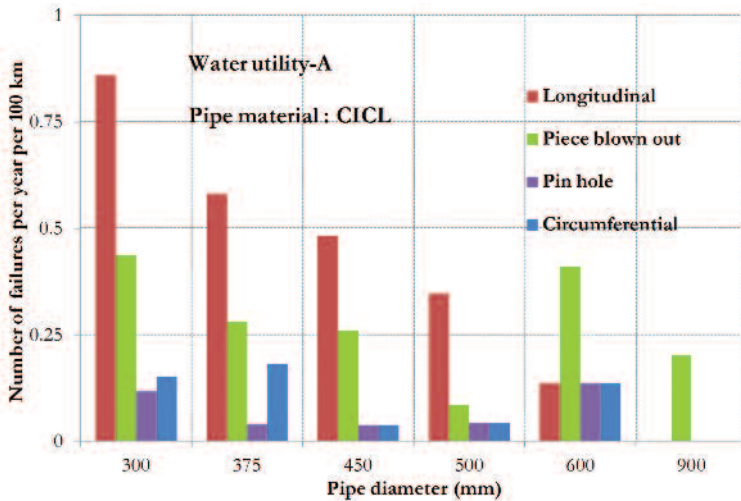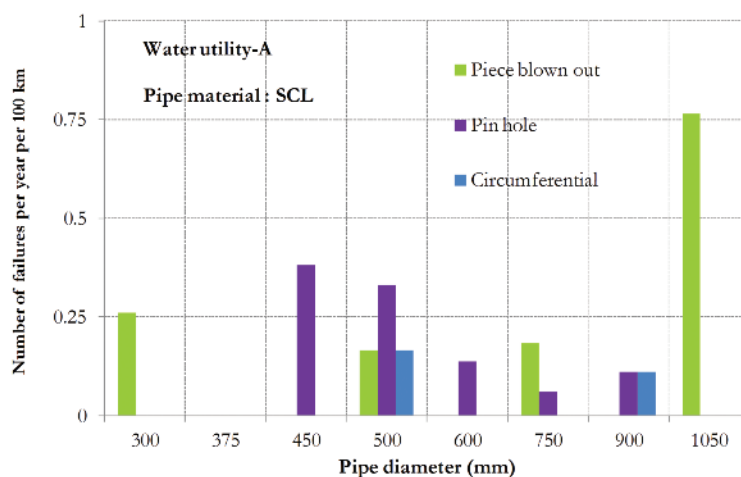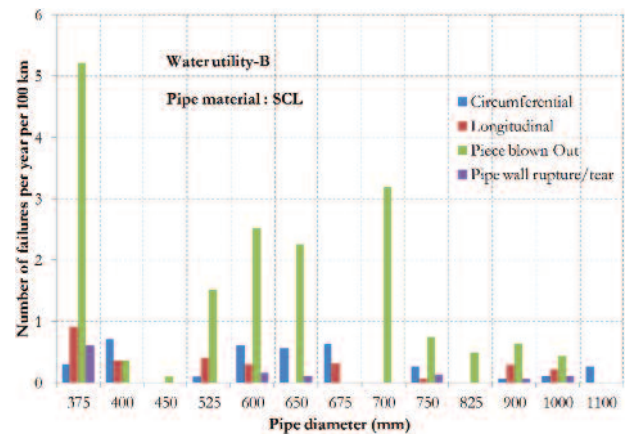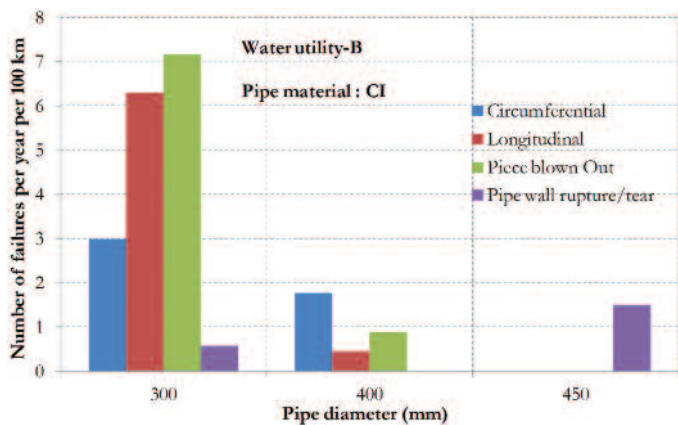It is also important to note that not

all data had the same level of detail because of the differences in data collection procedures followed by different water utilities, so direct comparison of results was not always possible. Table 1 provides a summary of failure data collected from the five water utilities (referred to here by generic names, utility A to utility F). It also shows the average failure per year (that is, the total number of observed failures per period).

In this study, analyses were performed on the data for cast iron (CI), steel (S), ductile iron (DI) and asbestos cement (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.

The collected failure data for each water utility were analysed separately and conclusions drawn on the basis of identified common trends. 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. The pipe failure inspection reports were further analysed to understand the contribution of corrosion to 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. Failure rate per year per km for a specific pipe material was determined using the total number of failures divided by the 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.

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, 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, 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 for other water utilities can be found in Kodikara et al, (2012).

Figure 1 shows histograms of failure rate versus pipe diameter based on the

Sydney Water data

Hunter Water data

(a) D=450 mm, t=21 mm

(d) D=375 mm, t=13.7 mm

(b) D=375 mm

(e) D=375 mm, t=15 mm

(c) D=500 mm, t=15 mm

(f) D=900 mm, t=8.2 mm

Sydney Water data

Hunter Water data

(a) D=300 mm, t=14 mm

(c) D=375 mm, t=13 mm

(b) D=300 mm, t=14 mm

(d) D=500 mm, t=14.2 mm

Sydney Water data

Hunter Water data

(a) D=900 mm, t=15 mm

(d) D=600 mm, t=7 mm

(b) D=500 mm, t=15 mm

(e) D=500 mm, t=15 mm

(c) D=450 mm, t=21 mm
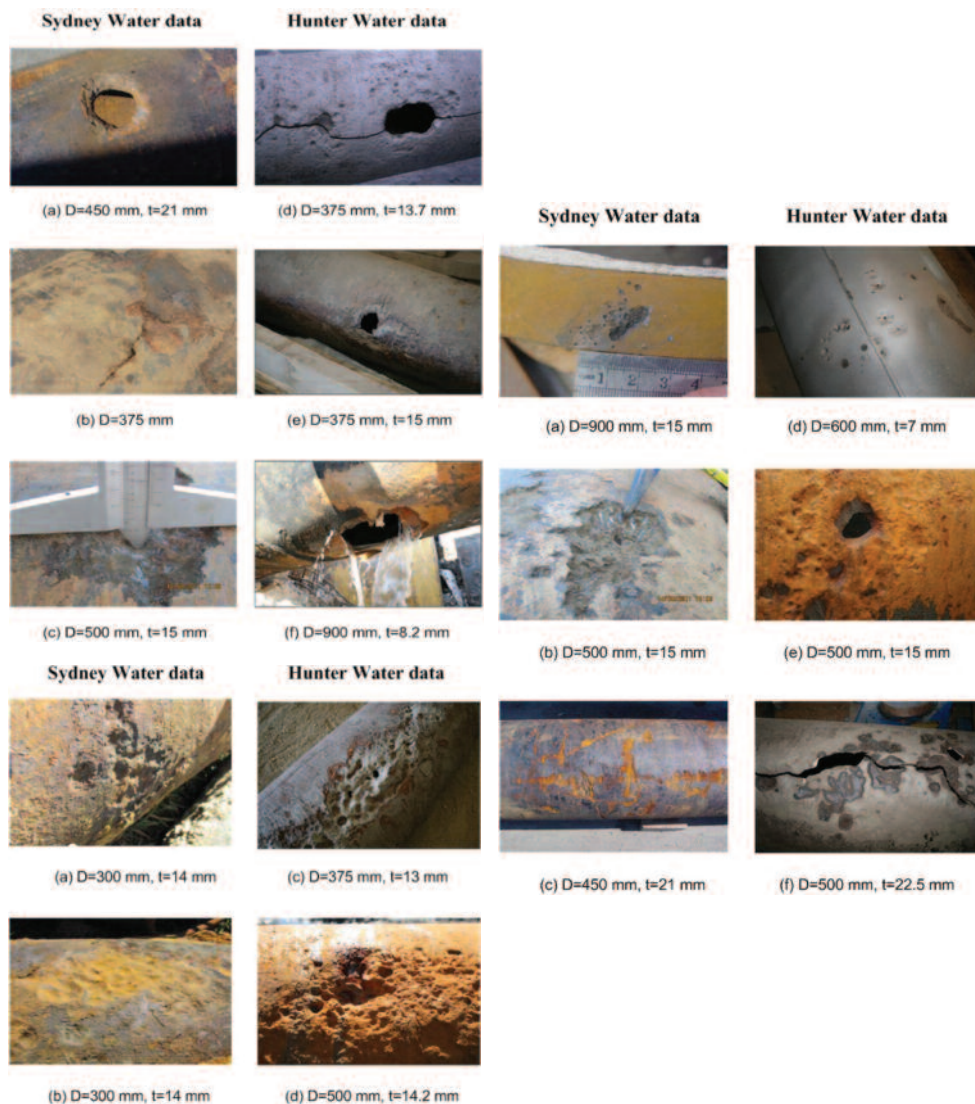
(f) D=500 mm, t=22.5 mm
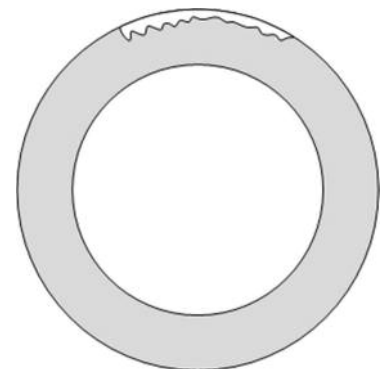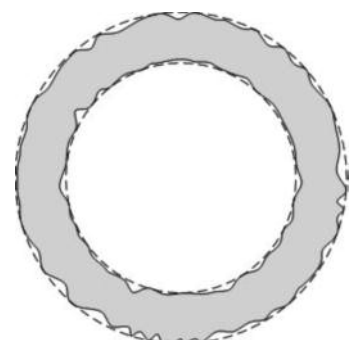
Figure 5
Observed pitting corrosion patterns

failure mode data obtained from water utility A for cast iron and steel pipes. Failures due to pieces blown out and pinholes are observed across 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 split, which is one of the dominant failure modes, is observed in cast iron concrete lined (CICL) pipes up to 600mm diameter.

The circumferential failures are also observed in steel pipes even at 600mm diameter, and in cast iron pipes of 900mm diameter. Usually, circumferential failures are not common in large diameter pipes due to the high moment of inertia, which restrains bending, so 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 data obtained from water utility B for CI and steel cement lined (SCL) pipes. As observed for water utility A, a large number of pieces blown out and

longitudinal split failures were observed in cast iron pipes. For steel pipes, a large number of failures were in the piece blown out mode 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 split and circumferential failure across the whole diameter range.

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 and pipe contents, heaving or movement in 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 are a sufficient amount higher than the pipe capacity.

The failure data collected were not sufficiently extensive to make conclusive statements about the causes of failure. However, a general evaluation of the data highlighted corrosion as the main cause of failure. In addition, pressure transients and ground movement were indicated as further causes. It is, however, not clear how ground movement could affect large diameter pipes, because they have much higher rigidity due to their 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 they are expected to occur in pipes on the basis of the empirical evidence. On the basis of the information collected 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 3a. This form of corrosion may be visualised as a reduction of thickness as in Figure 3b.

Patch corrosion is identified by graphitisation or a cluster of geometrically interacting pits, which can be approximated as a patch of corrosion as shown in Figure 4a. 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: single pit, multiple non-interacting pit and multiple non-interacting pit, which were commonly observed as shown in Figure 5. The diameter and thickness of the failed pipelines are shown along with the figures. The clusters of single pits that do not geometrically interact with each other are called non-interacting multiple pits, otherwise they are called interacting pits.

The single pit can be visualised

Figure 6
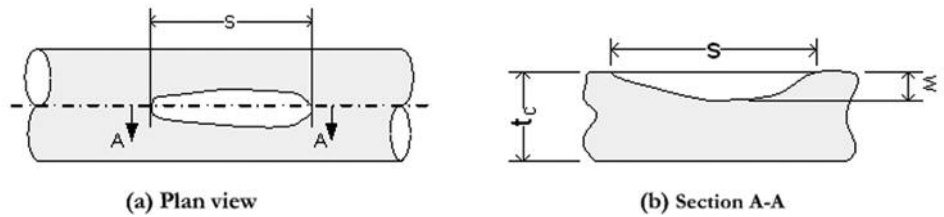Single pit (s = length of the pit, w = depth of the pit, tc = pipe wall thickness)

(a) Plan view   (b) Section A-A

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

Localised region with pitting

(a) Plan view   (b) Section A-A
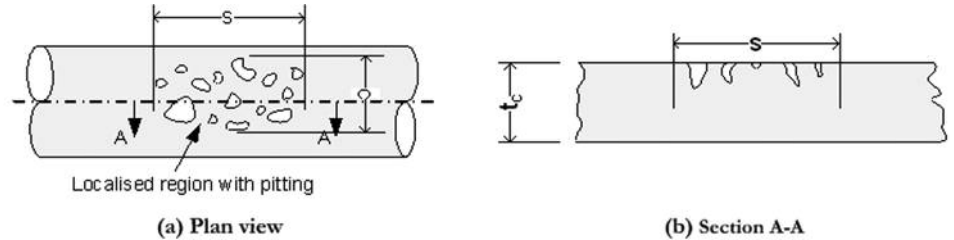
Figure 8
Schematic multiple interacting pit cluster (s = length of the pit, tc = pipe wall thickness)

(a) Plan view   (b) Section A-A
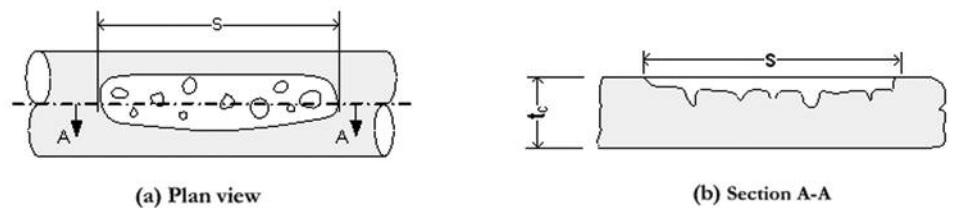
as shown in Figure 6 for analysis. Drawing from API (2007), the non–interacting and interacting multiple pit can be visualised as shown in Figure 7 and Figure 8.

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 when they 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 9a 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 its life. For more information on actual corrosion rates, influencing parameters and mechanisms related to buried cast iron pipes, see 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 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 various 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 a limited number of points (three) in NPD = 75% to 100%. It may be inferred that when the

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
R1	Corrosion and other factors	R7	Piece blown out. Failure due to corrosion.
R2	Minimal external corrosion. Failure due to other factors.	R8	Longitudinal crack seemed to follow a series of shallow pits on the external surface.
R3	Through wall corrosion. Heavy pitting corrosion.	R9	Piece blown out from collar: failure due to corrosion and other unknown factors
R4	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.	R10	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.
R5	Longitudinal piece blown out from joint collar. Significant corrosion at collar. Failure due to corrosion and water hammer (operational changes at pumping station).	R11	Longitudinal failure with a piece blown out. Failure due to corrosion and operational change.
R6	Very minor corrosion and pitting, 2 to 3mm at most. Failure was characterised by a blown out piece of pipe caused by collar fracturing: May be due to localised corrosion. The system was operated as normal. There was no pressure transient.	R12	Piece blown out. Through wall along fracture surface but only in minimal locations. Surface corrosion all around fracture. Minimal surface corrosion, except for one location with up to 6mm.

wall thickness reduced by more than 75% of its original thickness, the pipes may have failed through wall failure.

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 R3 falls on the through wall corrosion (NPD = 100%).

Summary and conclusion

In this study, the past pipe failure data and information were collected from five water utilities in Australia and analysed to identify the factors contributing to large diameter pipe failures. On the basis of the collected pipe failure data, most failures were observed in cast iron and steel pipes. Failure due to pieces blown out and pinholes are the major failure modes observed across all the utilities involved.

Corrosion is identified as a leading cause of failure, together with pressure transients and traffic load. Details of the types of corrosion observed in

failed pipes were collected from the failure inspection reports. The type of corrosion observed in a failed pipe section was characterised in 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 by collecting more accurate data in the future. ●
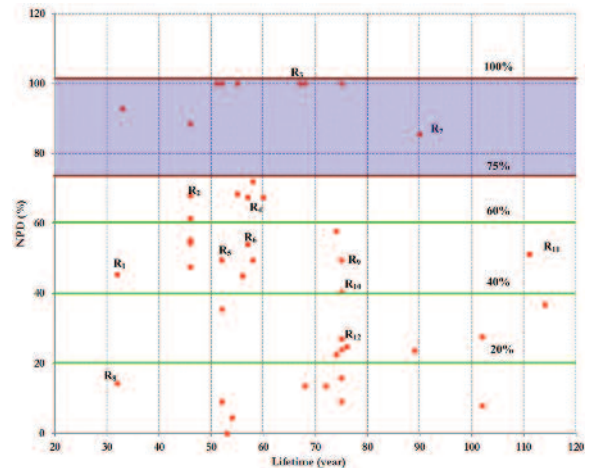

Figure 10
Normalised pit depth at failure vs age of the pipe at failure for water utility A

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

References

API (2007), Fitness-For-Service. The American Society of Mechanical Engineers, API 579-1/ASME FFS-1.

Atkinson, K, Whiter, JT, Smith, PA and Mulheron, M (2002), Failure of small diameter cast iron pipes. Urban Water, 4(3): pp263–271.

Makar, JM, Desnoyers, R and McDonald, SE (2001), Failure modes and mechanisms in gray cast iron pipe. Underground Infrastructure Research: Municipal, Industrial and Environmental Applications, Proceedings, Kitchener, Ontario, June 10-13, 2001, pp1-10.

Kodikara, J, Rajeev, P, Robert, D and Zeman P (2012), Critical review of historical information on large diameter pipe failure. Research report, Monash University, Australia.

Peterson, R and Melchers, R (2012), Long-term corrosion of cast iron cement lined pipes. Corrosion and Prevention, Paper 23.

Rajani, B and Kleiner, Y (2001), Comprehensive review of structural deterioration of water main: physically based modes. Urban Water, Vol 3, pp151-164.

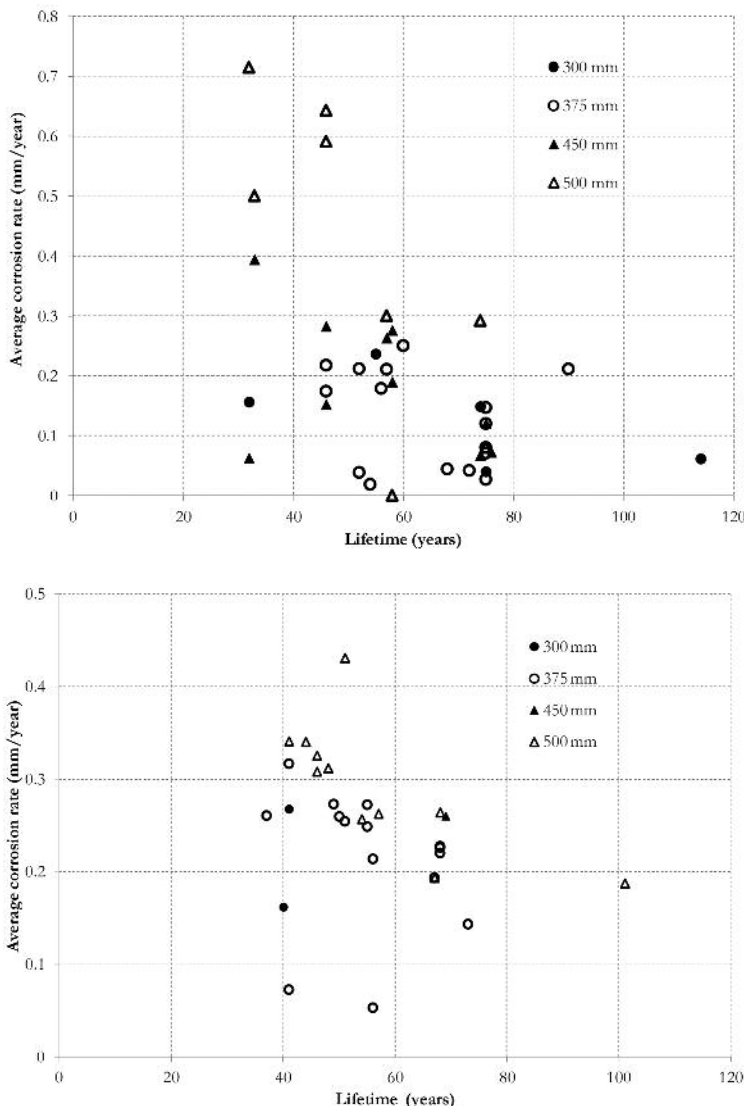*Rajani, B and Kleiner, Y (2010), Fatigue failure of large-diameter cast iron mains. Water distribution system analysis (WDSA) 2010, Tucson, AZ, USA.*