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An expert system for assessing the technical and economic risk of pipe rehabilitation options

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ABSTRACT

Cast iron (CI) pipes still make up a significant portion of many water distribution systems across the globe. A range of trenched and trenchless technologies are available to rehabilitate these pipes, but in the USA trenched replacement is still the standard approach used, despite 'trenchless' options having significant financial, social and environmental benefits. This paper focuses on the development of a decision support tool to help asset managers determine which rehabilitation technique to select, with specific emphasis given to whether to renovate or replace a group of CI pipes. The tool encapsulates expert knowledge on a range of issues, and provides an assessment of both the practical and economic feasibility of available techniques. During the tool development, it was recognized that the economic justification for renovation depended strongly on the assumed operational life of the renovated asset, which is inherently uncertain. To circumvent this, the tool calculates the minimum required service life (MRSL) for technically feasible renovation options, taking into account the life cycle costs of rehabilitation scenarios. The MRSL is the operational life beyond which renovated assets provide economic benefit in comparison to replacement options. This metric thus allows asset managers to determine if the risk of renovating pipes is worth taking when considered in light of the potential cost savings and other benefits. Overall, the tool is intended to encourage innovation diffusion in the USA and to help utilities adopt a 'risk appropriate' approach to pipe rehabilitation.

1. Introduction

Water services are provided to urban communities via extensive networks of infrastructure assets. Pipes used to transport and distribute potable water are a key part of this infrastructure. Being buried and thus out of sight, the importance of these assets is somewhat undervalued and this has led to long-term underinvestment in some countries (Marlow, Beale, & Burn, 2010). Several reports have attempted to characterize the nature and extent of underinvestment in infrastructure assets in the USA (Nolan, 2007; Slack, Johnson, & Aunkst, 2004). The impact of that underinvestment is reflected in national assessments of infrastructure. For example, the American Society of Civil Engineers (ASCE) graded water infrastructure in the USA as "D" in 2013. According to the grading used, this means that, overall, the infrastructure is considered below standard, with many elements approaching the end of their service life with a large portion of the system exhibiting significant deterioration; condition and capacity are thus both of significant concern with strong risk of failure (ASCE, 2013).

Given the financial challenges facing the sector, utilities must seek to upgrade infrastructure without imposing unaffordable tariff increases on customers. As the provision and management of buried pipes typically represents 50–75% of a utility's combined operating and capital costs (Speers, 2009; Thomas & McLeod, 1992), it is particularly important to manage the life cycle costs of these assets. However, while significant advances in infrastructure asset management have occurred over the last decade (Kaplan, Banyard, Randell-Smith, & Savic, 2010, chap. 9), managing life cycle costs remains challenging because the assets are hidden from view, spatially distributed and exposed to a wide range of deterioration processes and loading conditions (Davis & Marlow, 2008).

An additional complexity is that pipes still in use have been installed over more than a century. A range of pipe materials and jointing techniques have been used over this time. Cast iron (CI) was one of the first pipe materials to be used in many systems. While a legacy material (it is no longer installed today), many utilities still manage a significant length of such pipe. For example, Table 1 shows the length of small diameter pipe (nominal diameter of 4–8 in. or 100–200 mm) for water utilities in North America and Australia who provided input into the research detailed herein

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Table 1
Summary of small diameter (4–8 in.) CI pipe in networks.

Utility	All materials km (miles)	CI km (miles)	Proportion CI (%)
1	30,000 (18,645)	18,000 (11,187)	60
2	6351 (3946)	1928 (1198)	30
3	905 (563)	434 (270)	48
4	1456 (905)	22.5 (14.0)	2
5	20,951 (13,021)	7752 (4818)	37
6	21,839 (13,573)	6443 (4004)	30
7	3727 (2315)	2123 (1319)	57
8	9051 (5625)	7241 (4500)	80
9	6847 (4255)	3218 (2000)	47
10	8045 (5000)	805 (500)	10
11	805 (500)	494 (307)	61
12	5367 (3336)	3596 (2235)	67
13	1046 (650)	418 (260)	40
14	5393 (3352)	1289 (801)	24
15	3813 (2370)	877 (545)	23
16	100,000 (62,150)	17,000 (10,456)	17
17	53,770 (33,419)	1312 (815)	2
18	5933 (3688)	3560 (2213)	60
19	3461 (2151)	1720 (1069)	50
20	75,556 (46,958)	34,000 (21,131)	45
		Median	43

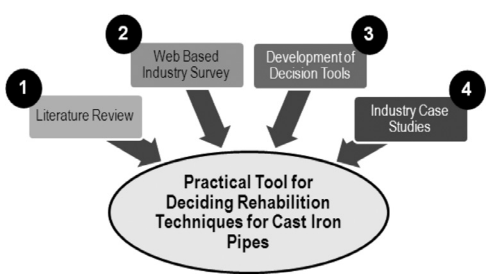

Fig. 1. Summary of CI pipe structural failure mechanisms.

(Marlow, Beale, Gould, & Lane, 2013). As can be seen, the network of some utilities is still around 60% CI pipe. As they deteriorate, CI pipes eventually start to fail structurally, affect water quality, and/or provide inadequate pressure or flow. To manage these issues, utilities conduct an annual rehabilitation program to renovate or replace a portion of their CI pipes. With rehabilitation costing hundreds of dollars per meter, this represents a significant level of investment.

Within the literature, while a significant body of work focuses on the identification of pipes requiring rehabilitation, less emphasis has been given to the subsequent decision of whether to replace or renovate pipes. This was identified as a priority research area by member utilities of the Water Research Foundation (Water RF, Denver, USA), which led to the development of a project to address perceived knowledge gaps. One objective of the research was to develop an easy to use decision support tool that helps asset managers to determine when small diameter CI water mains should be renovated rather than replaced. The research underpinning the development of this tool included a comprehensive literature review, web based surveys, interviews and the development of case studies, as shown in Fig. 1.

This paper presents information on the challenge of managing CI pipes, including information on the decision to replace or renovate them elicited through the application of qualitative research techniques. The conceptual design and implementation of the decision support tool is also outlined, focusing on the approaches used to allow practical assessment of technical and economic risk.

2. Research context: rehabilitation of cast iron PIPES

In general, the failure of small diameter CI mains (8 in. or less) results in consequences that are relatively minor and localized, though

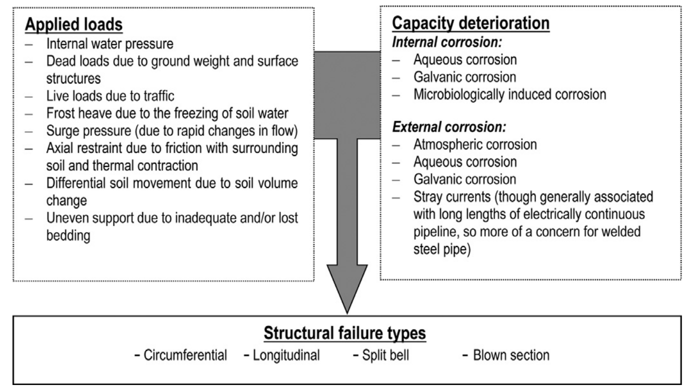

Fig. 2. Summary of CI pipe structural failure mechanisms.

this may not always be the case (Davis & Marlow, 2008; Marlow & Burn, 2008). As such, these assets are often managed reactively; *i.e.*, they are operated until failures start to occur. This approach is taken because the expected failure impacts do not justify the cost of undertaking preventative maintenance (Burn, Marlow, Moglia, & Buckland, 2007).

As noted above, CI pipe can 'fail' from a structural, hydraulic or water quality perspective. Structural failures occur when applied loads exceed the residual strength of the pipe (Makar, Desnoyers, & McDonald, 2001). This can result from an increase in applied loads (*e.g.* increase in traffic loads over time), the deterioration of the pipe's structural capacity (through corrosion) or a combination of the two factors. A summary of the most common applied loads, capacity deterioration mechanisms, and failure types for CI pipes is shown in Fig. 2. As shown, the most common structural failure types are circumferential, longitudinal, blown section and split bell failures (Hu & Hubble, 2007; Makar et al., 2001; Marlow et al., 2013; Rajani, Zhan, & Kuraoka, 1996).

Hydraulic failures occur when the pipeline is no longer able to supply water at the required flow rate or pressure. This can be due to either deterioration of the pipe's hydraulic characteristics or because of changes in demand (the pipe then being undersized with respect to normal or peak flow requirements). A reduction in hydraulic capacity can be caused by an increase in surface roughness and/or the reduction of pipe internal cross-sectional area resulting from the build-up of corrosion products, a process known as tuberculation (Benjamin, Sontheimer, & Leroy, 1996).

A water quality failure attributable to a CI pipe also occurs due to internal corrosion, which results in the discoloration of the conveyed water (Shams El Din, 1986). Corrosion can be either galvanic or microbially influenced (MIC). MIC is caused by the by-products of bacterial metabolism, *i.e.*, acid producing bacteria, hydrogen producing bacteria and iron-oxidizing bacteria (Reynaud, 2010).

2.1. Rehabilitation options

As repairs are generally inexpensive relative to the cost of rehabilitation, it is often cost effective to manage infrequent failures by repairing them. However, once an asset starts to fail repeatedly, a decision has to be made whether to continue to repair the asset or to rehabilitate it. Rehabilitation is undertaken to reduce failures (structural, hydraulic and/or water quality) and therefore improve service provided. While rehabilitation removes or reduces the potential for future failures, it can be more cost effective to implement other interventions such as:

(1) ***Pressure reduction***: pressure reducing valves are inserted to reduce operating pressure and thereby decrease bursts and leaks;