Managing water infrastructure: corrosion models for cast iron trunk mains

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Abstract

Distribution networks are critical in providing continuous potable water supplies to households and businesses. Trunk mains are the major arteries of the distribution network and convey large volumes of water over long distances. Worldwide, much of this infrastructure is made of ageing cast iron and is deteriorating at different rates. Many of these mains are beginning to approach the end of their service lives (with some already exceeding their design life) and consequently out of large populations of pipes, some are failing, although some still have considerable residual life.

Trunk main failures can have significant social, health and safety, environmental and economic impacts. It is therefore imperative to prevent the wide-scale failure of trunk mains through the implementation of proactive asset management strategies. Such approaches require accurate condition assessment data across the network in conjunction with deterioration modelling to predict how the assets' condition and performance changes over time.

This work, being part of a wider collaborative project, has outlined a deterioration modelling framework on the basis of existing physical probabilistic failure models and research focussing on residual mechanical properties, corrosion and the NDT detection of flaws. The developed deterioration model can be used to characterise individual pipes (deterministic approach), as well as the cohort/network modelling of pipes (probabilistic approach). Deterioration is assumed to be predominantly based on corrosion. Previously this has been dealt with in a rather simplistic manner. The broader work has, on the one hand,

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shown that corrosion mechanisms are rather different than previously thought and, on the other, that their effect on a given pipe can be variable. A corrosion model capable of simulating the distribution of corrosion properties of the primary defects is to be incorporated within the proposed modelling framework and the development of important aspects of this model are discussed here.

Keywords: trunk mains, modelling framework, physical probabilistic, residual mechanical properties, corrosion, NDT detection of flaws, deterministic approach, probabilistic approach.

1 Introduction

Trunk mains are the major component of a water supply network. They convey large volumes of water over long distances from reservoirs to the local distribution mains. In contrast with distribution mains, which are based on pipes of diameter around 3–8 inches (approximately 80–200 mm), trunk mains are of larger diameter, typically between 12 and 48 inches (approximately 450–1200 mm). Although cast iron mains are being phased out of water networks, a significant proportion of trunk mains network in many countries are still comprised of aging cast iron mains. This infrastructure is deteriorating at different rates depending on operational and localised conditions as well as factors such as size, quality of production and installation. Inevitability many of these mains are beginning to approach the end of their service lives (with some already exceeding their design lives). Consequently out of a large population of pipes, some are failing, although some still have considerable residual life.

Trunk main failures can have significant direct, indirect and societal costs. A major trunk main failure could have substantial flooding consequences and interrupt drinking water supplies to a large number of customers. Timely interventions that, on the one hand avoid unnecessary investment and premature renovation or replacement of these critical assets and on the other, avoid network failures and the catastrophic consequences are therefore critical. Such approaches necessitate accurate condition assessment of assets across the network in conjunction with deterioration modelling to predict the assets' condition and performance and how these change over time. However, despite the critical function of trunk mains, there appear to be few previous studies aimed specifically at modelling the in-service deterioration and corrosion behaviour of cast iron trunk mains.

The aim of the present work, which is part of a larger study to understand cast iron trunk mains, is to develop a deterioration methodology for cast iron trunk mains, building upon two pre-existing deterioration models. Both existing models are reliant on probabilistic analysis of the structural performance assessment of cast iron trunk mains but one is mainly designed to predict the likelihood of failure of trunk mains across the cohort/network of pipes whereas the other can be used to model the probability of failure of a specific section of the trunk mains based on engineering principles. This research brings together the findings from previous and current research on residual mechanical properties, corrosion and the NDT detection of flaws with both modelling

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approaches in order to produce a more robust and widely applicable model. Specifically, the focus here is on a corrosion sub-model.

2 Background

Predicting the structural deterioration of cast iron mains by analysing the historical failure data have been successfully applied in the cases of distribution mains, where there is a robustly recorded failure history [1]. However sparse failure data for trunk mains due to relatively low breakage rates has precluded conventional statistical analysis of historical events. Furthermore, distribution mains tend to be clustered within an area, such that there are many pipes with similar ages, environmental conditions and operating pressures – making it possible to be statistically relevant. Trunk mains are single pipes over long distances passing through different environmental conditions, so it is very difficult to use a simple statistical approach.

Physical/mechanical deterioration models have been developed which are capable of predicting the remaining service life and the likelihood of failure of cast iron pipes by simulation of the physical mechanism of pipe failure [2, 3]. The initial efforts have been mainly focused on deterministic models [4]. These models generally rely on a variety of background data to establish the base condition, but some of this data may not be readily available or may be very costly to acquire. Various methodologies have therefore developed over the years, employing probabilistic approaches to address the uncertainties of the physical mechanism of pipe deterioration and failure and the variability and unavailability that exist in the data and input parameters [5–10]. Although there appear to be few methodologies specifically targeting the in service deterioration and failure mechanism of trunk water mains [8, 10].

In most physically based methodologies, corrosion of cast iron has been assumed to be the predominant deterioration mechanism which is linked to structural failure. In these studies, the time dependent corrosion element of the deterioration model has either been estimated from condition assessment data of pit depth growth around the main or from one of the general corrosion models developed elsewhere in the literature. Various corrosion models have been developed over the years to simulate the corrosion mechanisms of buried metallic mains [2, 11–14]. These models have been designed to be standalone or for integration within a methodology to predict the water mains failure/remaining service life. However, few corrosion models have been verified based on the UK datasets of cast iron trunk mains. In addition, these models are based on empirical best fits to available data, but the available condition assessment data on cast iron trunk mains is believed to be of somewhat limited accuracy.

The effects of corrosion on structural capacity of cast iron pipes have been captured in various studies over the years. Experimental work carried out by Atkinson *et al.* [15] and Belmonte *et al.* [16] on cast iron distribution mains concluded that in-service corrosion induced defects (referred to as graphitisation) have lowered the pipe strength and increased the variability within the sample set compared to the pipes in the as-manufactured conditions. The relationship between the pipe strength and the corrosion pit depth measured on the fracture surface was shown to be in agreement with arguments based on either a loss-of-section model or fracture mechanics, consistent with other studies in literature (e.g. [2, 17, 18]). Recent experimental work on samples sourced from failed ex-service cast iron trunk mains concluded that unlike distribution mains, the condition of a large diameter trunk main pipe can vary significantly around the circumference and along the length of the individual pipe section and hence along the length of a collection of such pipes in the ground [19]. In addition it was found that whilst small depths of graphitisation (e.g. <4 mm) may have little effect on the strength of the samples, as the depth of graphitisation increases it can have a marked adverse impact on the pipe's strength and hence on the likelihood of brittle fracture under load. The evidence also suggested that for trunk main a fracture mechanics approach to failure analysis may be more appropriate than methods relying on knowledge of loss-of-section.

Asset management is a multi-cohort, multi-scale, multi-mechanism issue which requires where possible the most accurate condition assessment data or, where this is not possible, the best prediction from the "data cloud". The danger with this approach is that where gaps in the record exist, the temptation arises to fill these gaps with data from other industries. This must be avoided due to factors such as dissimilar operating conditions e.g. large diameter gas pipes operate under lower pressures then water mains. Instead, acknowledging the nature of this network it is possible to make predictions on the basis of the data arising from other cohorts, albeit that this data must take into account issues of location and material variability. Therefore an approach that enables the detailed investigation of particular cases (where accurate condition assessment data is available) as well as predicting the likelihood of failure across a cohort/network of pipes (on the basis of limited information) is valuable.

Graphitic corrosion of cast iron pipes is traditionally treated purely as a loss of section problem. This provides a helpful upper bound for determining the residual strength of deteriorated assets and should not be over looked, but in the current context, it has been shown that it is not always helpful and can lead to spurious results. For example, in the UK standard approach described by Dempsey and Manook [20], deepest internal and external pits are assumed to coincide, which can result in theoretical failure long before actual failure occurs. The conservative nature of this methodology is partly to compensate for the absence of other forces being accounted for.

On the other hand, a loss-of section approach does not consider the impact of stress concentration and hence an alternative model is to treat a corrosion pit as a sharp crack. Again this should not be treated as an absolute truth, as arguments based on fracture mechanics are themselves based on a number of assumptions, but again this approach is helpful as it provides a worst case scenario. Therefore, an approach that combines both models can provide upper and lower bound probabilities of failure from which a combined probability of failure can be generated.

Irrespective of the failure model considered, it must be recognised that inappropriate input data, such as that from inaccurate non-destructive testing, could lead to over- or under-estimation of the probability of failure.

3 Methodology

Figure 1 outlines the proposed modelling framework that has been developed for cast iron trunk mains as part of this project. The proposed methodology relies on surveyed condition assessment data to (1) undertake the detailed assessment of an individual pipe in a specific location; (2) enrich the model's built-in database hence capturing the temporal and spatial distribution data. The latter enables the probabilistic analysis of a cohort/network of pipes where not all of the required background data is available for establishing the baseline. Reliability analysis using Monte Carlo simulations is proposed to facilitate the probabilistic analysis. The proposed methodology therefore allows for prioritisation of the network for targeting investigation as well as deterministic assessment of the individual pipes that have been surveyed.

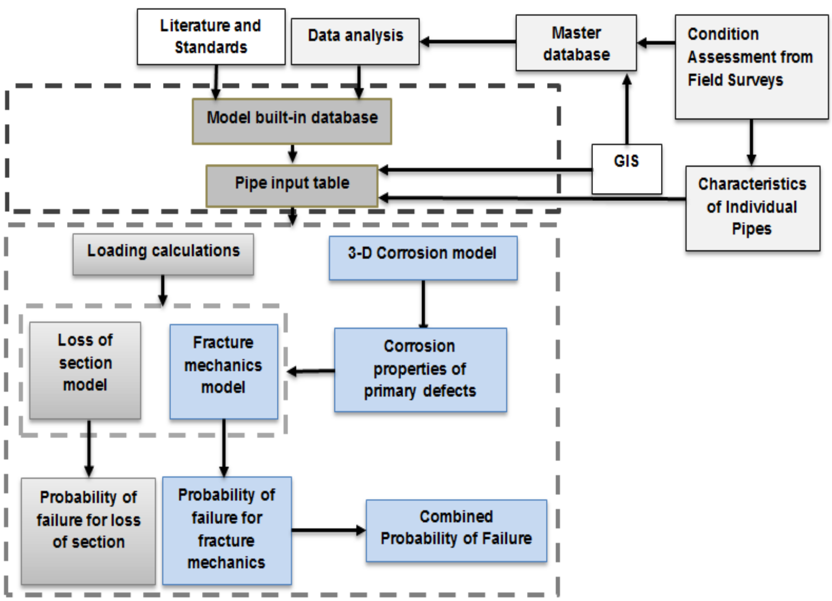

Figure 1: Proposed modelling framework for cast iron trunk mains.

The proposed methodology focuses on longitudinal fracture as this is the predominant observed failure mode in cast iron trunk mains [10]. The model therefore only considers the circumferential stresses caused by external loading as well as internal pressures. Corrosion is assumed to be the predominant deterioration mechanism. Finite element analysis of nodal forces would be employed in order to simulate the occurrence of the deepest surveyed corrosion pit (depth and width) along the thin ring. The effects of the longitudinal spread of the deepest corrosion pit along the pipe length on the pipe's residual strength would be evaluated to avoid overestimating the probability of failure due to loss of section. The proposed methodology therefore aims to incorporate the 3D properties of metal loss defects. Crucial to this methodology is, therefore, the ability to capture the most accurate condition assessment data and being able to interpret these data into the 3D properties (depth, width and length) of primary defects. A corrosion model capable of simulating the time dependent growth of the corrosion properties within the network of cast iron trunk mains is being developed as part of the wider project. This model is being developed based on examining the corrosion mechanism and rates of deterioration encountered from cast iron trunk mains recovered from the network and simulated in different environments [21].

In order to combine both loss of section and fracture mechanics models, two independent failure criteria are considered for cast iron trunk mains: combined loading analysis and fracture mechanics. The first criterion is similar to the methodology proposed by Rajani and Abdel-Akher [10] and is based on the experimental work done by Schlick [22]. Schlick's work showed that failure of cast iron pipe as a rigid structural element under combined internal pressure p (operating pressure + surge pressure) and an external ring load w (earth load + traffic load) will not occur if:

$$\left(\frac{w}{W}\right)^2 + \left(\frac{p}{P}\right) \leq 1 \tag{1}$$

where W is the crushing (ring) load that is necessary to cause failure in the absence of internal pressure, and P is the internal bursting pressure necessary to cause failure in the absence of external loading. The Schlick method of combined loading analysis defines a resistance curve for a cast iron pipe with an assumed vertical loading strength and bursting strength. Therefore, if the pipe is subjected in service to a particular pressure p, the corresponding vertical loading strength W_p or crushing load can be estimated from the pipe's resistance curve and similarly the pipe's bursting strength P_w can be estimated from the bearing load w [23]. Two factors of safety are defined for each load type i.e. internal pressure FS_p and external loading FS_w.

$$W_p = w\ FS_p \tag{2}$$

$$P_w = p\ FS_w \tag{3}$$

The second failure criterion is based on fracture mechanics i.e. that the stress field at the tip of a sharp crack can be measured by a single stress intensity factor K. K_C is defined as the critical stress intensity, also known as fracture toughness: this is a material property and cannot be exceeded. In practice, a corrosion pit is more blunt than is allowed for in fracture mechanics but, as noted, this does provide a useful lower bound. One crucial aspect of this model is the methodology to combine the two upper and lower bound probabilities of failure generated from the loss of section and fracture mechanics model. It is essential that the two probabilities combined as a final distribution in order to be used as part of asset management decision making processes.

4 Discussion

Building upon the understanding gained by working with two existing trunk mains deterioration models, and drawing on findings of other research strands of the wider collaborative project and beyond, the current study has been developing a modelling framework for cast iron trunk mains. The research is aiming to construct the individual elements of the proposed framework (Figure 1) as separate modules so each element can be withdrawn and upgraded in line with the progress in state of the art research.

Deterioration is assumed to be based on corrosion. A corrosion model capable of introducing the 3D properties (depth, width and length) of primary defects and simulating the time-dependent corrosion is to be incorporated within the proposed framework. The former is dependent on the ability to capture the accurate condition assessment data and being able to interoperate them into 3D properties of corrosion. The latter also requires the link between the corrosion mechanism as a function of material properties and environmental variations. In addition the proposed modelling framework is combining the likelihood of failure arising from two separate approaches of defining cast iron mains failure: loss-of section and fracture mechanics. This approach can provide upper and lower bound probabilities of failure from which a combined probability of failure can be generated. The combined figure can be used as part of the decision making processes.

5 Concluding remarks

The current work has outlined a deterioration modelling framework for cast iron trunk water mains. The model relies on condition assessment data to capture the 3D properties of corrosion (depth, width and length). It proposes a combined approach enabling the detailed investigation of individual sections where accurate condition assessment data is available, as well as predicting the likelihood of failure of a cohort/network of pipes on the basis of limited information which is generally available across the network. The latter enables the prioritisation of the network for targeting investigation.

In particular, it should be noted that any approach to asset management that deals with a large and/or complex network must by its very nature, use a multi-cohort, multi-scale, multi-mechanism approach. Any scheme that attempts to simplify the process must be interrogated in detail as it may lead to a masking of critical information.

Here two modelling approaches have been considered and the need to consider both approaches discussed. Improvements to failure predictions are possible through further consideration of the graphitic corrosion process and the factors that affect this.

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