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Risk-based prioritization and its application to inspection of valves in the water sector

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ABSTRACT

Isolation valves facilitate the effective operation and maintenance of water supply networks, but their sheer number presents a significant asset management challenge. If left unmanaged, valve reliability issues can become widespread. Inspections provide a means of increasing reliability, but a survey of industry practices indicated that some utilities did not have such a program in place. To improve asset management and reduce business risk exposure, such utilities need an effective means of commencing inspection programs. From a theoretical perspective, risk concepts provide a means of optimizing maintenance effort. However, in the face of poor data on reliability or condition, pragmatic approaches to risk-based prioritization are needed. One such approach, risk indexing, is considered in this paper. Background on the research is presented, including the application of risk-based inspection concepts within the water sector. The development of a risk indexing scheme is then investigated, drawing on two industry workshops in which the analytical hierarchy process was used to set relative weights. It is concluded that risk indexing provides the basis for a rational prioritization process in the absence of data on valve reliability or condition.

1. Introduction

Water utilities are today faced with the challenge of delivering required levels of service with limited funds in the face of an ageing asset stock and increasingly stringent standards and customer expectations [1]. One aspect of this is to manage isolation valves. Isolation valves are installed to facilitate the operation and maintenance of a water network, but present significant difficulties because of the size of the asset stock. For example, data reported by the American Water Works Association indicates that 338 water utilities operate an aggregated 202,158 miles of pipe with 2,776,059 gate and 150,531 butterfly valves. This equates to *ca.* 15 valves per mile of water main, with an average of approximately 9,000 valves per utility [2–5]. The challenge of managing these assets is increased by the spatial distribution of the valves and the heterogeneity of the asset stock [6].

Like all mechanical assets, the physical state or '*condition*' of valves changes over time as components deteriorate. The rate of deterioration is asset and context-specific, being influenced by factors such as the type of valve, the quality of the installation, the external and internal environment the valve is exposed to and the operating and maintenance regime. As valve condition deteriorates, failures due to fatigue, corrosion and wear-out start to occur. There is thus a driver for water utilities to understand valve condition at the individual asset level and across the network. Information on asset condition is collected by undertaking inspections, which is a key input into physical asset management [7,8]. Physical asset management aims to provide sustained services at a cost and level of risk that is acceptable to customers and the broader community [1,7,8].

In 2006, the Water Services Association of Australia (WSAA) held a workshop to formulate a program of research to address gaps in asset management capacity. One priority identified was the need to develop specific guidance on condition assessment and inspection processes for water main valves. The Water Research Foundation (Water RF) in the USA and WSAA subsequently co-sponsored a major research project aimed at meeting this need [6,9]. This paper draws from this research project, focusing specifically on the challenge of prioritizing inspections within utilities that have poor data on valve condition and reliability. For example, one large utility who provided information for a case study had not undertaken maintenance on any isolation valves for over 15 years, and did not have a comprehensive database for these assets. Issues with data included that the inventory of valves was not complete, assessment of asset importance and risk had not been made, condition of valves was unknown and maintenance schedules were not allocated [6].

The context and focus of the work presented herein is significantly different to that of related research previously described in the literature, including in this journal. For example, while Walski discussed the role that valves play in maintaining water distribution system reliability and emphasized the need to manage valves

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effectively [10,11], the practicalities of dealing with a backlog in maintenance was not considered. Similarly, risk-based approaches to the scheduling and prioritization of maintenance tasks, including inspections, have generally been considered within the context of relatively good estimates of reliability and costs [e.g. 12,13]. Various papers address risk-based inspection for assets within safety critical systems (e.g. reactors) [14,15], applications that imply a level of rigor that would not be justified for valving within a water supply system. In other studies, the systems analyzed have been simple enough to allow explicit analysis of all valves individually [13], which is not possible across a water supply network in the absence of good data. Prioritization procedures have also been developed that involve a detailed consideration of specific assets. For example, Stewart [16] presents a risk ranking procedure for bridges that uses the expected cost of failure as a risk measure. Other procedures have been developed that are applicable across a system of assets. For example, Brito and de Almeida developed a multi-attribute decision model for ranking sections of gas pipelines in terms of risk [17]. Their assessment procedure included a process to incorporate subjective perceptions of decision makers regarding risk, an approach that is paralleled in this study. However, their procedure again implies a more detailed consideration of assets than is possible given the context of this paper.

In summary, while the literature provides useful insights into risk-based prioritization procedures, the focus and intended application of existing research is significantly different to the context of the research described herein. More specifically, an approach was needed that would allow utilities to commence inspection programs in the absence of data on asset reliability or condition. With this focus in mind, the remainder of this paper is structured as follows. Background information on the research context is first given, followed by a mathematical representation of risk-based inspection and its practical interpretation. Pragmatic approaches to risk-based prioritization are then outlined, and the development of a risk indexing scheme investigated. The approach taken uses expert opinion mobilized through the application of the analytical hierarchy process. A synthesis of this approach is provided in the conclusion.

2. Research context

Isolation valves are generally only needed during specific events such as to isolate a pipe burst or undertake pipeline maintenance. As such, the failure of a valve may only become evident when there is an operational demand for its use. This increases the time taken to undertake planned and reactive maintenance, thereby increasing costs. In the case of a burst, failure of a valve to operate on demand can also increase failure consequences by prolonging social and commercial disruption, increasing damage to property and other assets and increasing the number of customers who lose water.

Valves generally fail due to the corrosion of internal components, deterioration of seals and the internal build up of deposits [18]. A pragmatic approach to valve inspection is thus to undertake an in-service or functional test (commonly referred to as '*valve exercising*') to determine if the valve is in an operational state [10]. Ideally, this involves operating the valve '*stop-to-stop*', though some utilities only practice partial closure due to operational risks [6]. Periodic exercising of valves also ensures moving components remain free, so valve exercising also increases reliability [6,19].

2.1. Industry practice

A review of valve inspection practices was undertaken as part of the research presented in this paper. Information obtained from industry partners in the UK, Australia and the USA indicated that some utilities have scaled back or abandoned their valve inspection and exercising programs. Furthermore, of 25 utilities who answered a web-based survey, seven indicated there was no routine inspection program in place for valves [6]. If left unmanaged in this way, reliability issues can become widespread across a network [20,21]. It can be anticipated that the more unreliable the valve stock, the higher the probability that additional effort will need to be expended to isolate any given burst or undertake maintenance on a pipeline. Given the additional costs and consequences involved, there is thus a driver for utilities to undertake inspection programs to improve overall reliability.

When commencing such a program, it is highly desirable for utilities to target initial inspections where they are likely to provide the most valuable information and/or mitigate the greatest risks. Unfortunately, the number of valves, their spatial distribution and the differences in environmental and operational factors across a network all mean that it can be challenging to design an inspection program to achieve this end.

3. Theoretical basis of risk-based prioritization

As part of effective asset management, a water utility must balance the cost of performing inspection and other maintenance activities against the cost and impact of not performing them [6,7]. Such decisions are often facilitated by adopting a risk-based framework [17,22–24]. In asset management, risk is defined as the product of the likelihood (or probability) of an asset failure and the severity of the failure consequence [25–27]. Risk defined in this way has been used to develop inspection programs for a range of purposes [28–31]. More generally, risk-based inspection is a standard maintenance practice that focuses on failure modes initiated by material deterioration and controlled primarily through inspections [25,32]. In the context of water sector asset management, the basic elements that need to be addressed in the development of such a program are [7]:

1. The assessment of the risk introduced by potential asset failures.
2. The identification of the degradation mechanisms that can lead to failures.
3. The selection of effective inspection techniques that can detect the progression of degradation mechanisms.
4. The development of an optimized inspection plan.

The later stage is important because inspection and subsequent repair/replacement of assets is carried out subject to budgetary constraints and the level of such activities influences the total cost of operating the network.

3.1. Risk as a basis for optimization

Ideally, an inspection program would be optimized to give the greatest benefit relative to costs across the entire population of assets. The use of risk concepts for optimizing inspection programs can be justified from a theoretical basis if a number of simplifications are made. To this end, let n be the number of assets and, for each $i=1, \ldots, n$, let x_i be a 0–1 valued decision variable which indicates whether or not asset i is to be inspected. Suppose that we have reasonable estimates of the probability p_i of failure of asset i; the probability q_i of failure of asset i given that it has been inspected; the consequence c_i of failure of asset i; the cost d_i of inspecting asset i; the cost e_i of repairing asset i and the expected benefit b_i of repairing asset i for each asset ($i=1, \ldots, n$). Since we are assuming only probabilistic knowledge about some of the variables describing the system, we consider a sequence of trials over an ensemble of