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Evaluating emerging structural inspection technologies for high-risk cast iron water mains

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ABSTRACT

Structural inspection is an important component of asset management and involves quantifying current asset condition and remaining life. Research is being conducted across a wide range of fields to develop structural inspection technologies that can reduce costs and improve effectiveness for multiple industrial and infrastructure applications. Some of these technology developments may be transferable to the structural inspection of water mains, while others may not be feasible for water mains if they do not address appropriate structural issues and/or are not as cost-effective as competing methods. To help guide agencies in addressing the most important issues relevant to high-risk water mains, the U.S. Environmental Protection Agency (EPA) initiated a project to develop a protocol to strategically evaluate the feasibility of structural inspection technologies for use on large-diameter cast iron water mains. The protocol is intended to be used for periodic expert panel reviews for evaluating the prospects of proposed innovations to pipe inspection technologies. This paper provides an overview of the potential failure modes, mechanisms, and distress indicators for large-diameter cast iron water mains; briefly discusses structural inspection technologies; and presents the screening protocol. The screening protocol evaluates the feasibility of accessing the water main for inspection, the detection of specific anomalies, and the cost of technology development and utilization. A trial application of the protocol on eight technologies is provided as well. It is recommended that agencies interested in supporting structural inspection technology development use this protocol as a screening measure to determine if a proposed technology is applicable to large-diameter cast iron water mains based upon its ability to detect key distress indicators and to be implemented at a reasonable cost.

1. Introduction

Cost-effective structural inspection can be an important component of effective condition assessment and asset management of water conveyance infrastructure. Structural inspection involves collecting data about meta-stable and/or transient indicators of the condition of the pipe. The data are used as inputs for estimating the current and future condition of the pipe.

Cost-effective structural inspection can provide value to water utilities in three primary ways. First, it can help the utility prevent catastrophic failures in their deteriorating water mains, which they cannot afford to replace at present (Royer, 2005). Secondly, it can help the utility reduce the amount of pipe perceived to need replacement, which may enable them to replace only the pipes that are structurally deteriorated to the point that their probability of failure is unacceptable. Finally, by enabling the utility to more promptly identify pipes that are deteriorating at an accelerated rate, it may help the utility reduce water main deterioration through targeted actions, e.g., leak repair, retrofit cathodic protection, and/or spot rehabilitation to mitigate the conditions causing accelerated deterioration.

The benefits provided by structural inspection technologies are important for water utilities that must strategically select water mains for replacement since they cannot afford to replace their entire aging infrastructure. No references are readily available outlining how much utilities would be willing to pay for condition assessment versus replacement costs, but rehabilitation and maintenance activities are typically cheaper and less disruptive than replacement and can extend the asset life for years before replacement is needed (Baird, 2010).

These technologies can be improved by identifying failure modes and indicators that are of most concern; improving technology performance (e.g., efficiency of detecting critical flaws); and reducing cost (e.g., mobilization/demobilization; pipe preparation/access; data

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collection; etc.). Scientific and engineering research is being conducted to develop and improve these technologies and to accelerate commercial implementation, but some developments are unsuccessful because they are not feasible for water pipelines, do not properly address the structural integrity issue, or are not as cost effective as competing methods.

This project reported herein was initiated by the U.S. Environmental Protection Agency (EPA) to strategically evaluate the feasibility of emerging structural inspection technologies for large-diameter cast iron water mains. The objectives of this work were to develop a screening protocol for evaluation of structural inspection technologies that could be used to provide data that can support estimates of current and future condition of the structural condition of water mains. These estimates can be used to help optimize decisions about inspection, rehabilitation, and replacement of water mains. The value of optimal renewal decision making arises from the need to: safely utilize installed infrastructure to its full life; reduce main break failures and their adverse health, safety, environmental, and economic effects; and promptly recognize and correct significant leakage or deterioration.

2. Characterization of high risk mains

Cast iron pipe has been used in the U.S. since 1804 and an American Water Works Association (AWWA, 2004) survey of 337 water utilities determined that about 35% of the U.S. water pipe network was laid with cast iron pipes made up of approximately 18% unlined and 17% lined (AWWA, 2004). The estimated total length of 900,000 miles of water pipe would indicate that there is nearly 315,000 miles of cast iron in the system in the U.S.

The structural deterioration and subsequent failure of cast iron water mains is a complex process involving numerous factors both physical and dynamic. Particularly for large-diameter cast iron pipes, the pattern of failure may be complex due to factors such as the heterogeneous nature of cast iron, variability of handling and installation, and differing soil properties along the line. Research has suggested that many failures occur as a series of multiple events rather than a single event (Makar, 2000).

Despite these complexities, effective structural inspection can be an important component in estimating the current and future condition of water mains. Some large-diameter, cast-iron, failure mechanisms have potentially critical and reliable measurable distress (e.g., corrosion, graphitization, cracks, leakage, and angled pipe joints) and inferential indicators (e.g., pipe vintage, pressure variations, pipe location, and soil issues), although the critical values that must be measured for each indicator may not be known. Therefore, it is reasonable to expect that if monitored and measured accurately, the indicators if known can help determine if failure is imminent or if an asset can operate for longer before failure.

2.1. Failure modes and mechanisms

Failure in pipes is defined here as a condition caused by collapse, break, or bending, so that a structure or structural element can no longer fulfill its purpose. Other definitions include failures where relatively small amounts of water are lost from defective joints. Failure occurs when the pipe is weakened by corrosion or other defects to an extent when it can no longer resist the imposed stresses.

Smaller diameter pipes generally have smaller moments of inertia making them more susceptible to longitudinal cracking failures. Larger diameter pipes have greater moments of inertia which creates a tendency to longitudinal cracking and shearing at the bell. Not only is the length of pipes in a typical water network of diameters less than 16-in. much greater than those greater than 16-in., but information on the break frequency (per unit length per year, per mile per year) is more readily available (Morrison et al., 2013). Although a number of utilities record failures, there is a dearth of detailed records on failures and the modes for these larger diameter pipes.

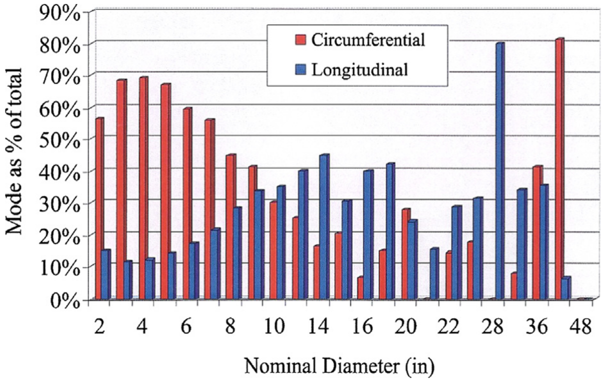

Fig. 1. Graph of failures modes to diameter (UKWIR).

The National Research Council (NRC) of Canada has undertaken detailed investigations of failures in U.S., UK, and Canada (Rajani and Kleiner, 2011; Makar et al., 2001; Makar, 2001; Makar, 1999a; Makar, 1999b; Moser, 2008) as have other organizations (Seica et al., 2002; Marshall, 2001). These reports contain numerous studies examining the failures of cast iron mains. The primary failure discussed in the reports above include: longitudinal cracking; circumferential cracking; mixed fractures; and bell splitting.

Large-diameter pipes generally have a higher moment of inertia and are less prone to circumferential failures. Although not common, there are recorded cases of circumferential cracking in large diameters (Rajani and Kleiner, 2011). The relationship of circumferential to longitudinal failure modes by diameter in cast iron pipe is illustrated in Fig. 1, which was developed from 72,000 UK water systems data records of burst failures in the period from 1992 to 1998 collected by UK Water Industry Research (UKWIR, 2011). In general, circumferential failures were more prevalent in smaller diameter mains, and, by comparison, longitudinal failures were more common than circumferential failures for mains 10 in. and larger.

Another failure mechanism is corrosion in the form of pitting and/or graphitization, which is a common but not exclusive factor in most pipe failures. Possible causes are localized corrosion cells, adverse soil chemistry, and bacteria. Pitting is the most common form and occurs quite randomly and leads to leaks rather than structural failures. Corrosion pitting thins and weakens the pipe wall to the point where the water pressure blows out the remaining, very thin pipe wall. This type of corrosion failure may produce a very small hole or a large one, depending on how localized the corrosion process has been and the pressure experienced by the pipe.

Wall thinning can also make the wall susceptible to failure from external loads (e.g., live loads, traffic loads, bending loads, etc.), but these loads are relatively small compared to internal pressures. Where the through wall perforation is small, the pipe does not structurally fail or in some cases even leak as the corrosion product can act as a stopper in the pipe wall hole (Marshall, 2000).

Graphitization, which is an important form of failure, is a corrosion process that removes some of the iron leaving a matrix of graphite flakes held together by iron oxide. Graphitization is often not discernable to the eye as it forms a substance with some strength albeit considerably reduced and with the appearance of normal cast iron.

Many potential contributory factors to pipe failure are shown in Table 1 (Al-Barqawi and Zayed, 2006). These factors are classified into three categories: physical, environmental, and operational. The factors in the first two classes could be further divided into static and dynamic (or time-dependent). Static factors include pipe material, pipe geometry, and soil type, while dynamic factors include pipe age, climate, and seismic activity. Operational factors are inherently dynamic. Many of the factors are not readily measurable or quantifiable, and the