Measurement 46 (2013) 1–15

Contents lists available at SciVerse ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Review

# State of the art review of inspection technologies for condition assessment of water pipes

Zheng Liu *, Yehuda Kleiner

*Institute for Research in Construction, National Research Council Canada, 1200 Montreal Road, Ottawa, Ontario K1A 0R6, Canada*

## ARTICLE INFO

*Article history:*
Received 28 December 2011
Received in revised form 18 April 2012
Accepted 30 May 2012
Available online 16 June 2012

*Keywords:*
Pipe condition assessment
Distress indicator
Deterioration
Non-destructive inspection

## ABSTRACT

This paper reviews the state-of-the-art of inspection techniques and technologies towards condition assessment of water distribution and transmission mains. Pipe condition assessment is the determination of its current condition, including structural health, impact on water quality, and hydraulic capacity. The collection and analysis of relevant data and information is the first and a paramount step to detect and monitor critical indicators to prevent or mitigate catastrophic failures. The technologies include conventional non-destructive inspection and advanced sensor techniques for condition monitoring. This paper focuses on the inspection techniques and technologies for structural deterioration of water pipes. Technologies like smart pipe, augmented reality, and intelligent robots are also briefly discussed and summarized.



**Contents**



* Corresponding author. Address: 1200 Montreal Road, Building M-20, Ottawa, Ontario, Canada K1A 0R6. Tel.: +1 613 993 3806; fax: +1 613 993 1866.
*E-mail addresses:* zheng.liu@nrc-cnrc.gc.ca (Z. Liu), yehuda.kleiner@nrc-cnrc.gc.ca (Y. Kleiner).


http://dx.doi.org/10.1016/j.measurement.2012.05.032

## 1. Introduction

The structural deterioration of water mains and their subsequent failure are complex processes, which are affected by many factors, both static (e.g., pipe material, size, age, soil type) and dynamic (e.g., climate, cathodic protection, pressure zone changes). Condition assessment is critical to the management and maintenance of water transmission and distribution systems. The physical mechanisms that lead to pipe breakage are often very complex and not completely understood. The facts that most pipes are buried, and relatively little data are available about their breakage modes contribute to this incomplete knowledge.

The US EPA defines pipe condition assessment as "the collection of data and information through direct and/or indirect methods, followed by analysis of the data and information, to make a determination of the current and/or future structural, water quality, and hydraulic status of the pipeline". The assessment of the structural condition of water mains and decision making on pipe renewal involves several elements [1]:

- Inspection of the pipe to discern distress indicators.
- Interpretation of distress indicators to determine pipe condition.
- Empirical/statistical modeling of historical failures (mainly in small-diameter distribution mains).
- Development of pipe deterioration models, which in conjunction with knowledge about pipe current condition will enable the forecast of future failure rates and consequent pipe residual life.
- Physical/mechanistic modeling of the pipe in the soil.
- Understanding of pipe failure modes and their associated frequencies, including observable or measurable signs that point to these modes and to potential existence of deterioration mechanisms.
- Assessment of failure consequences.
- Scheduling pipe renewal so as to minimize life-cycle costs while meeting or exceeding functional objectives of water distribution (quantity, quality, reliability, etc.).

A distress indicator is defined as the observable/measurable physical manifestations of the aging and deterioration process [2]. Each distress indicator provides partial evidence for the condition of specific pipe components, which varies with pipe materials. Distress indicators can be acquired by various means, as described in the following section. An inferential indicator refers to the potential existence of a pipe deterioration mechanism without actual knowledge if this potential has actually been realized. Many of the environmental indicators, such as soil type and groundwater fluctuations, are inferential in nature. The inferential indicators do not provide direct evidence about pipe deterioration but rather indicate the potential thereof. These indicators and means to acquire them are also discussed in the next section.

A review of sensor technologies for buried sewer inspection was published by Duran et al. in 2002 [3] and relevant information is also available in other reports [4–6]. Our paper reviews the state-of-the-art technologies for water main inspection and detection of structural deficiencies. This paper focuses on pipe inspection technologies, while a companion paper provides a review of advanced sensor technology for pipe condition monitoring [7].

Condition assessment methods can be roughly categorized into direct and indirect methods [8]. Direct methods include automated/manual visual inspection and non-destructive testing. Pipe sampling is also included in this category. Indirect methods include water audit, flow testing, and measurement of soil resistivity to determine the risk of deterioration. Generally, the direct methods generate the pipe distress indicators while the inferential indicators are obtained by indirect methods. Table 1 shows the potential to apply an inspection technology to different pipe materials. Detailed descriptions of these methods are presented in the following section.

## 2. Direct methods for pipe inspection

### 2.1. Visual inspection

#### 2.1.1. Closed-circuit television (CCTV) inspection

Closed-circuit television is a well-adopted technique for the inspection of the pipe's inner surface. CCTV inspection is mainly applied to sewers and stormwater pipes. For the inspection of water pipes, CCTV is commonly used for