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Review

Statistical failure models for water distribution pipes — A review from a unified perspective

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ABSTRACT

This review describes and compares statistical failure models for water distribution pipes in a systematic way and from a unified perspective. The way the comparison is structured provides the information needed by scientists and practitioners to choose a suitable failure model for their specific needs.

The models are presented in a novel framework consisting of: 1) Clarification of model assumptions. The models originally formulated in different mathematical forms are all presented as failure rate. This enables to see differences and similarities across the models. Furthermore, we present a new conceptual failure rate that an optimal model would represent and to which the failure rate of each model can be compared. 2) Specification of the detailed data assumptions required for unbiased model calibration covering the structure and completeness of the data. 3) Presentation of the different types of probabilistic predictions available for each model.

Nine different models and their variations or further developments are presented in this review. For every model an overview of its applications published in scientific journals and the available software implementations is provided.

The unified view provides guidance to model selection. Furthermore, the model comparison presented herein enables to identify areas where further research is needed.

1. Introduction

1.1. Need for deterioration models

The structural condition of urban water distribution infrastructures is important for the continuity and quality of the water distribution services provided by these systems. The financial investments needed for the rehabilitation, adaptation, and expansion of existing urban water systems (incl. water treatment as well as drainage and wastewater treatment) are estimated at 1% of the annual GDP in the OECD member states, rehabilitation accounting for up to half of the total needs (OECD, 2006).

Targeted research programs in e.g. Canada,[1] Australia,[2] the United States,[3] and Europe[4] also acknowledged the need for approaches to assess the deterioration and failure development of urban water distribution networks. This is because pipe deterioration may have a significant impact on some of the fundamental objectives of water distribution networks, e.g. reliability and continuity of service. It is important to be able to predict future deterioration in order to determine the optimal amount and timing of the required rehabilitation efforts. These are central inputs for technical asset management and defining the long-term budgets. Knowledge about how the structural condition of pipes develops

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[1] Several projects of the National Research Council Canada (http://www.nrc-cnrc.gc.ca/eng/achievements/highlights/2008/aging_water_systems.html).

[2] Sustainable Asset Management Program developed by CSIRO (http://www.webcitation.org/6UB8dXfP3).

[3] Aging Water Infrastructure Program of the US Environmental Protection Agency (http://www.webcitation.org/6UB8jPf2P); several projects of the Water Research Foundation Asset Management (http://www.webcitation.org/6UB8nn7tE).

[4] European Union FP5 project CARE-W (http://www.webcitation.org/6UB8sNy2c); several follow-up projects by different funding agencies: AWARE-P (http://www.webcitation.org/6UB8xroUh) and EU FP7 project i-TRUST (http://www.webcitation.org/6UB9662Zn).

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over time is key to designing and choosing replacement and maintenance strategies.

A range of software has been proposed to support water supply infrastructure asset management based on pipe deterioration models (Renaud et al., 2012; Saegrov, 2005; Cardoso et al., 2012; Kleiner and Rajani, 2010; Burn et al., 2003; Le Gat, 2009). This allows, for example, comparing rehabilitation strategies based on key performance indicators, such as "main failures" or "water resources availability" (Alegre et al., 2006). Any rehabilitation strategy can be defined by, for example, incorporating constraints such as budget or work load, while the deterioration models should represent the deterioration behavior of the pipes as realistically as possible.

Even though modeling the deterioration of water distribution and drainage systems shares some challenges such as frequently incomplete data sets, its modeling is different due to the specific characteristics of each system and to the unique characteristics of the available data. Water distribution system data contain information about when events (e.g. pipe failures) occurred while drainage system data usually provide information about the condition of the pipes at the time of the inspection. Therefore we do not include statistical sewer deterioration models into this review. In this review, only statistical pipe failure models (as defined in the next subsection) developed for water distribution systems are considered.

1.2. Aim of this review and models covered

The aim of this review is to describe and compare statistical pipe failure models in a systematic way. This is intended to support practitioners and scientists in choosing a suitable statistical pipe failure model to support pipe rehabilitation and asset management decisions as well as to identify research needs. Available reviews by Kleiner and Rajani (2001), Liu et al. (2012), and to a very limited extent also Nishiyama and Filion (2013) and St. Clair and Sinha (2012) (adding information regarding artificial neural networks and fuzzy logic models) give a broad overview of statistical pipe failure models. These reviews, however, do not provide the information needed for objective model characterization, comparison and selection as recognized by Liu et al. (2012).

Instead, we discuss statistical pipe failure models from a novel unified perspective consisting of: i) a clarification of the model assumptions independent of how the models are expressed mathematically in the original publications (Section 3.1), ii) a specification of *detailed* data assumptions for model calibration covering the structure and completeness of the data (Section 3.2), and iii) a presentation of the type of probabilistic predictions published (Section 3.3). We further provide references to illustrative applications and available software implementations as published in the literature. For the first point we mathematically reformulated the models to represent them by their failure rates. We present a novel conceptual failure rate in Section 3.1 that includes all desired properties to which the failure rates of the models can be compared to. In the second point the often only implicitly assumed data characteristics important for model calibration are discussed. The third point deals with the presented predictions for each model as obtaining pipe failure predictions is usually the major motivation for using pipe failure models and the formulation of appropriate predictive distributions requires care.

This paper is organised as follows: Section 2 describes the different types of pipe failure models; this section is important to underline why we have focused the review on the *statistical pipe failure* models. A thorough explanation of model properties is presented in Section 3, allowing the structure of the model review presented in Section 4 to be understood. The core of this review are Section 4 and Table 1; the models are critically discussed, focusing on the following model properties: structure, calibration, predictions, further developments, applications and software implementations. Section 5 contains a discussion on how the review may assist model selection and potential for future developments is identified.

Readers interested only in the model properties and assumptions may want to proceed directly with Section 4 and consult Table 1. Readers looking for details, the structure of this review and the reasons for the proposed unified perspective may also read the introductory sections of this paper (Sections 2 and 3).

2. Types of deterioration models

Deterioration models for water distribution systems can be differentiated by at least three dimensions: the smallest described entity, the type of events that are modeled, and the modeled process. The smallest entity dimension relates to whether individual pipes (pipe models) or a pipe network (network models) are described. A model can describe different events: the occurrence of failures (failure models) or the end of the lifespan (lifetime or lifespan models). Finally, models aim to represent different processes, either by mimicking physical processes (physically-based models) or by attempting to describe the data generating process (statistical models). Any combination of these dimensions is possible, although from the available literature, only a part of these combinations is covered.

This three-dimension categorization (by entity, type of event, and process modeled) differs from other reviews, which are mostly based on a model categorization originating from Kleiner and Rajani (2001) (cf. section 2.3). The new categorization aims to avoid the following drawbacks of the Kleiner and Rajani (2001) characterization: i) it is based on the mathematical formulation of a model rather than on its underlying assumptions, ii) extensions with covariates are relatively simple so that "single-variate" models can always be extended to "multi-variate models" and are not a model limitation per se as discussed in Section 3.1, and iii) the "deterministic" category refers to statistical regression models which, strictly speaking, are also "probabilistic".

2.1. Individual pipe vs. network models

Many of the earlier models describe the failure rate of a complete network (see Table 1 in Kleiner and Rajani, 2001). The network failure rate summarizes the overall condition of a network and is therefore an important performance indicator to assess the structural and operational condition (such as continuity of service) of the whole system. Predicting directly how the failure rate of a complete network changes is difficult because technical management actions are generally performed at pipe level. Furthermore, the age and material distributions of the pipe network change over time so that a simple extrapolation of the failure rate is not adequate. To consider this, it is necessary to model the behavior of the pipes individually. The system wide failure rate can then be derived by aggregating the individual predictions. For this reason, we only consider pipe-based deterioration models in further detail within this review.

2.2. Failure vs. lifetime (or lifespan) models

Both the failure behavior and the lifespan of pipes depend on deterioration processes. Models describing the lifespan are less flexible than failure models because the definition of a lifespan implies a combination of pipe deterioration and the management