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Optimal pipe replacement strategy based on break rate prediction through genetic programming for water distribution network

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Abstract

Pipe breaks often occur in water distribution networks and result in large water loss and social-economic damage. To reduce the water loss and maintain the conveyance capability of a pipe network, pipes that experienced a severe break history are often necessary to be replaced. However, when to replace a pipe is a difficult problem to the management of water distribution system. This study took part of the water distribution network of Beijing as a case and collected the pipe properties and the pipe breaks data in recent years (2008−2011). A prediction model of pipe beak rate was first developed using genetic programming. Then, an economically optimal pipe replacement model was set up. Finally, the optimal pipe replacement time was determined by the model. The results could help the utility managers to make cost-effective pipe maintenance plans.

Keywords: Pipe break rate prediction; Optimal pipe replacement strategy; Genetic programming; Water distribution system

1. Introduction

1.1. Pipe break model

Pipe breaks often occur in water distribution networks and result in large water leakage and social-economic damage, which imposes pressure on the utility managers. Great attention have been paid to pipe leakage reduction, including active leakage detection and rapid repair, replacement of the deteriorated pipes, and water pressure management. Effectiveness of pipe break prediction models on leakage reduction has been demonstrated (Xu et al., 2011a, 2011b). With the pipe break prediction models, water utility managers are able to know which pipe should have the priority to be detected, replaced or pressure-regulated. Therefore, development of reliable and robust pipe break rate prediction models has received increasing interests.

The available models can be divided into two categories. The physically based models that aim at discovering the physical mechanisms underlying pipe break (Rajani and Kleiner, 2001) so that they can be viewed as micro models. However, these models are difficult to be applied because the factors that cause pipe breaks are too different to be all investigated and precisely measured. The statistical models usually use pipes' historical break data to identify pipe break patterns (Kleiner and Rajani, 2001). Unlike the physically based models, statistical models can be viewed as macro models because the data used in these models usually cover a long time scale (years or decades). These models are advantageous at describing the rules that the historical data follows, but they are weak in explaining the underlying physical reasons. Statistical models play an important role in the prediction of pipe break rate as they are time-efficient, flexible to fit the data and cost-effective.

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According to data availability, different techniques can be adopted to develop a statistical pipe break model. Kettler and Goulter (1985) developed a rather simple pipe break model where the pipe break was linearly related to the pipe age. Shamir and Howard (1979) found an exponential relationship between pipe break rate (breaks per unit length per unit time) and pipe age.

Both the abovementioned models provided deterministic relationships between pipe breaks and pipe age. During the same period, probabilistic methods were explored to study the rules underlying the pipe break behaviors. For example, Andreou et al. (1987) developed a proportional hazards model to predict the breaks by calculating the probability of time duration between consecutive breaks. Constantine et al. (1996) proposed a time-dependent Poisson model to predict pipe breaks in a water distribution system. Bayesian diagnostic approach was applied as well to describe the pipe break phenomena by Watson et al. (2004) and Babovic et al. (2002). Other probabilistic techniques used in the pipe break model development include, but not limited to, survival analysis (Mailhot et al., 2000), accelerated lifetime model (Le Gat and Eisenbeis, 2000; Lei and Saegrov, 1998), and decision tree method (Chen et al., 2008). In these studies, the selection of the model paradigms was usually dependent on the data availability and expert knowledge.

Due to the inherent complexity of pipe breaks, understanding to the mechanisms was far from clear. Therefore, data-driven approaches were widely adopted. Artificial Neural Network (ANN) was employed by Jafar et al. (2010) and Ho et al. (2010) to analyze the pipe break behaviors for their specific cases and high model performances were obtained. Genetic Programming (GP) and Evolutionary Polynomial Regression (EPR) were also successfully used to discover the principles that pipe break behaviors followed (Xu et al., 2011a, 2011b; Giustolisi and Savic, 2009; Berardi et al., 2008). Comparisons were conducted between the two techniques and the results indicated that they had equivalent performances (Xu et al., 2011b). The advantage of GP/EPR over ANN consists in providing explicit symbolic formula in addition to data-fitting.

1.2. Optimal pipe replacement strategies

As an important component of urban infrastructure, water distribution pipe network inevitably deteriorates as time no matter how perfectly designed. Its safety and conveyance capacity decrease gradually and will not be able to meet the service standard sooner or later, thus a renewal is requested. When to replace a pipe or where to renew a network demands scientific instructions. Therefore, great effort was made to find an optimal pipe replacement strategy. The essence is to balance the maintenance cost and benefit under specific conditions. According to literature, the reported models for pipe replacement optimization can be classified into two categories. One category focuses on calculating the optimal replacement time for a pipe, and the other category aims at prioritizing the pipes in a network for replacement under certain budget.

The classical model of the first category was initiated by Shamir and Howard (1979). The model objective function was the total cost in a pipe's lifetime including the repair cost and the replacement cost. By minimizing the cost function, an optimal time to replace a pipe was obtained. The critical part of this model was the prediction of pipe break rate that was used to calculate the total repair cost. Park and Loganathan (2002) introduced the concept of critical or threshold break rate. If a pipe's actual break rate reached this critical/threshold value, it was the economically optimal timing to replace it. Kleiner et al. (1998) calculated a pipe's lifetime by considering both the structural and the functional deterioration to schedule the pipe replacement. Besides the maintenance cost, the effect of a deteriorated pipe on the whole network's water pressure was also taken into consideration in some studies, which led to the multiple objective models (Dridi et al., 2009; Halhal et al., 1997).

The second type of models focuses on prioritizing the pipes for replacement under certain investment plan. Luong and Fujiwara (2002) developed a model to assess the benefit of pipe repair and made an optimal pipe repair scheme under limited fund. The model was then improved (Luong and Nagarur, 2005) by taking into account the pipes' hydraulic criticality. Ho et al. (2010) set up an ANN model to predict the pipe breaks under the influence of earthquake, which was used to make the order of pipe replacement in a real water distribution network. De Oliveira et al. (2010) applied a density-based spatial clustering approach to define local indicators of water distribution pipe breaks, and the results were used to prioritize the pipes' replacement.

For any replacement, the quantification of cost and benefit plays a fundamental role in the determination of optimal maintenance time (Walski and Pelliccia, 1982). Another essential aspect is the estimation of pipe break rate, only based on which is the analysis of pipe replacement time reasonable. Therefore, this study first developed a pipe break prediction model and then set up a pipe replacement optimization model to calculate the optimal replacement time for the pipes in a real water distribution network.

2. Methodologies

In this study, GP was applied to develop a pipe break prediction model, and an optimization method for pipe replacement was proposed to estimate the optimal pipe replacement time. This section will briefly describe the method of GP and the pipe replacement optimization.

2.1. Development of pipe break prediction model by GP

GP is an evolutionary algorithm to find computer programs that perform a user-defined task (Babovic and Keijzer, 2000; Koza, 1992). In data mining, it proves to be a powerful tool to find the relationship between the given independent variables and dependent variable. Symbolic equations can be generated, and selected and evolved according to their fitness to the data. The goodness-of-fit is usually characterized by such index as