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Research article

Risk assessment model to prioritize sewer pipes inspection in wastewater collection networks

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ABSTRACT

In wastewater systems as one of the most important urban infrastructures, the adverse consequences and effects of unsuitable performance and failure event can sometimes lead to disrupt part of a city functioning. By identifying high failure risk areas, inspections can be implemented based on the system status and thus can significantly increase the sewer network performance. In this study, a new risk assessment model is developed to prioritize sewer pipes inspection using Bayesian Networks (BNs) as a probabilistic approach for computing probability of failure and weighted average method to calculate the consequences of failure values. Finally to consider uncertainties, risk of a sewer pipe is obtained from integration of probability and consequences of failure values using a fuzzy inference system (FIS). As a case study, sewer pipes of a local wastewater collection network in Iran are prioritized to inspect based on their criticality. Results show that majority of sewers (about 62%) has moderate risk, but 12%of sewers are in a critical situation. Regarding the budgetary constraints, the proposed model and resultant risk values are expected to assist wastewater agencies to repair or replace risky sewer pipelines especially in dealing with incomplete and uncertain datasets.

1. Introduction

Wastewater collection networks are critical in the preservation of a society public health, safety, environment and economy (InfraGuide, 2004). These systems may be used at a lower level than desirable for long periods of time before appearing evidences of existing problems. Structural or hydraulic failures may be unknown for a long time until service disruptions, road collapse or basement flooding (Khan et al., 2009). Failure occurrence in weak networks can lead to pathogen exposure, pollution of groundwater, waterways and wetlands, damage to roads and buildings, and disruption of vital services. When the performance is desirable in moving wastewater from residential, commercial and industrial sources, sewer pipes ensure a clean environment and limit the ground and surface water contamination (Baah et al., 2015).

Performance of a wastewater collection network is related to the operation and maintenance (O&M) programs. Such programs should contain sufficient details to be useful to make informed decisions and strategic plans. This information is derived from activities such as closed caption television (CCTV) filming, flow monitoring and manhole inspections (Hahn et al., 2002). Make such an estimate for the total collection network is a costly and time consuming process. Budget constraints only allow annual inspection of a part of the network, usually about 10 percent each year. Thus, the development of models which can prioritize sewer pipes inspection based on their criticality and risk level is essential. This prioritization reduces the system risk level and consequently the number of emergency repairs which typically has severe adverse effects and high managing costs.

This paper develops a risk-based ranking model to prioritize sewers inspection. There are different definitions for risk assessment in the literature (e.g. Huang, 2009; Aven, 2011), but in one of the important and useful definitions, risk measure is a function of specific hazard probability and also its attributed consequences which are usually proportional to the system vulnerabilities against

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the hazards (Roozbahani et al., 2013). The proposed methodology requires the use of a weighted scoring system to calculate consequences of failure values with respect to relevant impact factors. Failure probability is calculated using Bayesian Networks (BNs), which is suitable for this purpose according to the characteristics of BNs. Recently, the utilization of graphical models, such as Networks has grown rapidly in water and environment resources modeling and management under uncertainty. Some of the features of this model include: the feasibility of developing the BN network in case of incomplete datasets, the possibility of combining the expertise opinions and available data, easy to update parameters and conditional probabilities between model variables, etc. Integration of the probability and consequences of failure values in the proposed risk analysis model is performed using Fuzzy Inference System (FIS). FIS is used to model the uncertainties in the risk assessment procedure. Finally, sewer pipes inspection is prioritized based on their criticality and estimated risk values.

2. Background

Although much research has been performed in the past to rate pipes based on conditions assessment in water and wastewater networks (e.g., Kleiner, 2001; Babovic et al. 2002; Kleiner et al., 2004; Najafi and Kulandaivel, 2005; Baik et al., 2006; Babani et al., 2008; Berardi et al., 2008; Beuken et al., 2008; Khan et al., 2009; Wang et al., 2010; Roozbahani et al., 2013; Hwang et al., 2015; Baah et al., 2015), determining consequences of failure as a main part of a risk analysis program, has not been completely considered. This is due to high uncertainty and complexities involved in evaluating failure impacts and consequences of a pipe failure, especially environmental and social impacts. However, instead of determining consequences of failures in monetary terms, agencies may also use consequences-of-failure indexes or prioritize pipe inspection based on criticality. For example, Water Environment Federation/ASCE (WEF/ASCE, 2009) categorizes sanitary sewers into three criticality groups:

- Category A: Sewers with high costs of failure and high impact on human health and environment.
- Category B: Sewers that their cost and impact of failure is smaller compared to the sewers in Category A; however, preventing a failure would still be cost-effective.
- Category C: Noncritical sewers. Cost of failure and impact on the environment and public health is minimal.

McDonald and Zhao (2001) developed a consequences assessment method for large diameter (diameter > 900 mm) sewers. Six impact factors were used in the assessment: location, type of embedment soil, burial depth, pipe size, functionality, and seismic zone. In each factor, sewers were categorized in low, medium, or high consequence classes. The overall impact of a sewer was obtained by weighted average method. Condition ratings and impact ratings were combined by decision rules to prioritize pipes rehabilitation and inspection.

Hahn et al. (1999) and Hahn et al. (2002) developed knowledge-based expert system denoted as sewer cataloging, retrieval and prioritization system (SCRAPS). This system was used to identify sewer pipes inspection priority in a wastewater collection network. In this study, the information of expert system was obtained from a group of public and private sector experts. SCRAPS analysis was performed in an expert based computer program using Bayesian Belief Network (Hugin Expert A/S, 2012). Six parameters were used to obtain the likelihood of failure: structural defects, interior corrosion, exterior corrosion, erosion, infiltration, and operational defects. Two mechanisms were used to predict the consequences of failure: socioeconomic impacts and reconstruction impacts.

Najafi and Kulandaivel (2005) predicted the conditions of wastewater collection network pipelines using neural networks. Seven factors were used for the conditions prediction: length, diameter, material, age, depth, and network type. The advantage of neural networks is the possibility of using the expert opinion, and also there is no need to identify the exact function for condition assessment. However, these networks require large data sets to learn all the possible combinations.

Baik et al. (2006) evaluated wastewater systems condition using Markov chain model. The developed model was applied in the wastewater collection network of San Diego. The considered factors include: length, diameter, material, age, and slope of sewer pipes. Markov chain approach in comparison with some methods such as nonlinear optimization has some advantages including ease of application, the accuracy of estimates, and the production of matrix based on the experts' opinions. The assumption that failure rate is not dependent on time, reduce the accuracy of analysis in the Markov chains. To use this method, data must be divided into several groups with a new Markov chain failure curve, which is difficult.

Khan et al. (2009) used Monte Carlo simulation to assess the condition of a sewer network in operation. The considered parameters were: age, length, diameter, and slope of the pipe. To determine the importance of each parameter, the parameter was studied using different probability distributions, in the case that the other parameters were fixed. Results showed that all four selected features have noticeable effect on the system performance, but the age of the pipe has the most impact compared with other factors.

Fuchs-Hanusch et al. (2012) derived the main influencing factors on the occurrence of hazards in the risk assessment process using a bivariate logistic regression analysis and presented a definition of relevant hazards causing "undesired events" responsible for deficits regarding functional requirements. Further, a vulnerability analysis to quantify hydraulic consequences of undesired events was described.

Baah et al. (2015) evaluate the consequence and risk of sewer failure using a risk matrix and a weighted sum multi-criteria decision-matrix. They developed a map incorporating risk of sewer pipe failure and consequence to facilitate future planning, rehabilitation and maintenance programs.

In previous studies conducted in the field of risk analysis of sewer networks, some important parameters have been ignored. For example, some consequences such as the sewer proximity to water wells have not been considered. In this study, both structural and hydraulic failures have been included in the model to evaluate sewer network in a suitable way and a comprehensive model has been established to assess the risk of sewers. In addition, in the mentioned researches, the exact computing of probability of failure has not been involved in the risk assessment procedure. In this paper by using of expert judgment in combination with Bayesian Networks, an accurate approach to compute this important parameter is presented and ability of the model in overcoming to data scarcity in wastewater collection networks is improved. Some recent studies reviewed applications of BNs in water and environment resources management (e.g., Malekmohammadi et al., 2009; Farmani et al., 2009; Kragt, 2009; Kragt, 2009; Stewart-Koster et al., 2010; Holzkamper et al., 2012; Keshtkar et al., 2013; Madadgar and Moradkhani, 2014).

3. Consequences and probability of failure in sewer networks

3.1. Consequences of failure

Structural and hydraulic failures in a wastewater collection