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An integrated assessment approach to prevent risk of sewer exfiltration

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ABSTRACT

Regular inspection, assessment, and rehabilitation are necessary to maintain the performance levels of sewer pipelines. The primary objective of this research is to develop a causality-based model by incorporating twenty-two sewer defects, including erosion voids. The Decision Making Trial Evaluation Laboratory (DEMATEL) was used to study the causality relationship between the defects, based on a designed questionnaire, to conclude the influencing and influenced distress. The results suggested that 59% of the sewer structural and operational defects were influencing ones. Besides, the existing state of the sewer pipelines was evaluated on a scale from 1 (Excellent) to 5 (Critical) by integrating the DEMATEL technique with the Quality Function Deployment (QFD) method. The QFD-DEMATEL model was implemented on a case study to compare the model's classifications of the pipelines' states with the actual ones. Based on the comparison, the average accuracy and true negative rate (TNR) of the classifications were 74% and 79% respectively. Also, the average invalidity percentage (AIP) was 41.32%, causing the validity percentage to exceed 50%. The integrated approach keeps decision-makers informed about their sewer pipelines to prioritize pipelines rehabilitation. Thus, defective sewers are reduced and so are the exfiltration cases.

1. Introduction

Sewer pipelines are indispensable infrastructure components in urban cities (Kaddoura et al., 2017; Duchesne et al., 2013; Vahidi et al., 2016). They transfer sewage from residential, commercial, institutional and industrial resources to wastewater treatment plants (Baah et al., 2015; Selvakumar et al., 2004). However, defects such as cracks, fractures, holes, and breaks will exfiltrate sewage to the surroundings (Ellis et al., 2004; Selvakumar et al., 2004) and hence expose soil, water and the public at large to negative implications (Jaganathan et al. 2010; Costa et al., 2016).

An old study stated that exfiltration in the United States (US) reached up to 30% of the system's flow. However, this number increased to 50% in local areas (US Environmental Protection Agency [EPA], 1989). By that time, the overall sewer network's condition in the US was graded C (American Society of Civil Engineering [ASCE], 1988). With the recent D + grade of the sewer network in the US (ASCE, 2017), the exfiltration rate is expected to be significant. The Washington Suburban Sanitary Commission estimated 839 sewer overflows annually with 2.5 billion gallons of untreated water flowing into the surrounding environment (District of Columbia Water and Sewer Authority, 2004).

Several studies (Gallay et al., 2006; Verlicchi et al., 2012; Meffe and Bustamante, 2014) stated that wastewater that exfiltrates from defective sewer pipelines could result in severe health consequences (e.g. *Salmonella typhi*) due to the contamination of drinking water resources. Sewage contains high levels of suspended solids, pathogenic micro-organism, toxic pollutants, floatables, nutrients, oxygen-demanding organic compounds, oil, grease (US EPA, 2001; Selvakumar et al., 2004), and contaminants of emerging concern (CEC) (Roehrdanz et al., 2017). Moreover, other researchers pointed out that exfiltration causes the water quality standards (WQS) to exceed and/or impact human health through the discharge of pathogens; especially for people residing near lakes or rivers (Selvakumar et al., 2004). Leaky sewers close to surface water could endanger aquatic life forms and their habitats and debilitate the attraction of waterways (Selvakumar et al., 2004). Fish that live in polluted water can carry bacteria "on their scales and in their flesh" and later transfer it to humans, resulting in significant chances of a *Salmonella typhi* infection (Ray, 2002).

Cases of groundwater contamination by sewer related exfiltration have also been reported in several studies. For instance, Bishop et al. (1998) outlined that a total of seventeen sewer-related groundwater contamination incidents in Wales and England led to 3000 reported cases of gastroenteritis infection and 50 cases of typhoid infection between the 1920 s and the 1990 s. Furthermore, Hunt et al. (2010) studied sewer source contamination of drinking water in several areas in

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Wisconsin in the US. Based on the 33 sampled wells, 18 tested positive for human enteric viruses. Furthermore, in Rastatt (Germany), the presence of pharmaceuticals and artificial sweeteners were observed, and the mean concentration for 50% of the samples, analyzed over five years, was between 14 ng/l and 702 ng/l (Wolf et al., 2012). The war that began in Yemen in 2015 resulted in the malfunction and collapse of the sewer system, which polluted the drinking water. As a result, 5000 cholera cases were reported daily (Vox, 2017). In fact, more than 360,000 suspected cases of the disease were reported, and 1800 victims had already died.

Given the seriousness of sewage exfiltration from defective sewer pipelines, periodic sewer inspection and rehabilitation is required to maintain satisfactory performance, as pipelines are subject to deterioration. Davies et al. (2001) explained the three stages in which sewer pipelines collapse. According to the authors, the first stage is when cracks are formed due to poor construction practices or overloading disturbance. Due to the presence of groundwater and cracks in the pipeline, infiltration/exfiltration in the system is initiated due to the hydrostatic pressure, which washes out the soil around the pipeline (Jaganathan et al., 2010; Davies et al., 2001). Therefore, the side support is lost, which expedites the deformation of the pipeline, leading to collapse and exfiltration of sewage.

In infrastructure asset management, sewer pipelines are inspected via Closed Circuit Television (CCTV) cameras that are inserted in the system and controlled by an operator. The camera records the inner surface of the pipeline and detects present distress (Feeney et al., 2009). The videos are reviewed by an expert who grades the pipeline according to the detected defects and based on industrial protocols such as the Water Research centre (WRc) and Pipeline Assessment Certification Program (PACP). Nevertheless, the grades supplied by these protocols do not represent the actual state of the pipeline, as they rely on peak and mean scores, which could flatten the observed data (Daher, 2015). Besides, they exclude the assessment of the erosion void defect in sewers, which expedites the propagation of critical sewer structural defects.

Several researchers developed models that assessed the condition of sewers using inspection information and distress observations. For example, Kaddoura et al. (2017) proposed a model that investigated the state of the pipeline by taking the deformation into consideration, along with surface damage, settled deposits, and infiltration defects. The primary technique utilized in their evaluation was the Multi-Attribute Utility Theory (MAUT). Each defect consisted of at least one utility curve that was developed according to protocols and specifications. Although the model provided reliable results, it did not take into consideration many of the sewer defects that could be found in inspection reports. In another work, Daher (2015) adopted the fuzzy expert system, Analytic Network Process (ANP), and Hierarchal Evidential Reasoning (HER), to assess sewer assets including manholes, pipelines, and pipeline joints. Each structural and operational defect was represented by a fuzzy membership function and was then defuzzified into one crisp index representing the condition of the pipeline. Nevertheless, the model lacked the erosion void defect that causes other defects to propagate (Davies et al., 2001). Angkasuwansiri and Sinha (2014) assessed sewer pipelines by suggesting a performance index that took into consideration the structural and operational degradation of the pipeline. Two methods were separately adopted in their assessment: the fuzzy expert system and the weighted average method. Similar to previous research, the authors did not incorporate the erosion void defect and many of the input variables are difficult to obtain (Kaddoura et al., 2017).

Despite the advancements in inspection technologies and condition assessment models, sewer conditions are still degrading in an unanticipated manner. The misinterpretations of the distress observations and the limitations of some current practices hinder rehabilitation plans (Daher, 2015). Therefore, the paramount objective of this research is to develop a causality-based assessment model for sewer pipelines by integrating the Quality Function Deployment (QFD), and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods. The objective is accomplished after a) evaluating the structural (including erosion void) and operational sewer defects based on severity measures; b) classifying the influencing and influenced sewer defects, and c) aggregating the influence power weight of each distress in the calculation of the sewer pipelines' grades using a scale that goes from 1 (Excellent) to 5 (Critical). The proposed model will enhance the assessment of sewer pipelines and will keep decision-makers informed about the state of the pipelines to plan preventive maintenance in order to avoid sewage exfiltration (Roehrdanz et al., 2017).

2. Methods

2.1. QFD

The QFD technique is utilized to convert customer needs into technical requirements in each stage of product development (Sullivan, 1986). It is conducted to attain several quality issues' objectives (Chan and Wu, 2002), such as:

1- To improve the quality of the design.

2- To provide planned quality control charts before the initial production run.

The method was initially developed in Japan in 1966 by Yoji Akao but was not formalized in quality control planning until 1972 (Costa et al., 2000). Since then, the QFD approach spread rapidly across Japan and the US (Costa et al., 2000). The QFD is a Total Quality Management (TQM) concept as it requires the inclusion of the customer needs into the project design targets, apart from the essential projects' requirements (Dikmen et al., 2005). It focuses on implementing the voice of the customer after assessing their needs, which are usually determined through interviews, surveys and/or focus groups to ensure their satisfaction (Dikmen et al., 2005).

The formulation of the QFD approach starts with the determination of the product policy and the end-user needs. Therefore, design requirements are established to form the "WHAT's," which in turn establishes the component characteristics "HOW's" of the product design. A matrix is then constructed to study the relationship between the HOW's and the WHAT's (Costa et al., 2000). After that, the absolute weights are determined by aggregating the HOW's and WHAT's through the use of the factors in the matrix established earlier. Consequently, the House of Quality (HOQ) is then finalized; a general representation is shown in Fig. 1.

The QFD utilization was restructured to suit its application in the infrastructure condition assessment. Thus, in the context of this research, each component was considered as follows (Alsharqawi et al., 2015):

- WHAT's was the condition severity. In this research, five different severities were considered: Excellent, Good, Fair, Poor, and Critical. These severities reflected the asset's condition.
- HOW's represented the defects considered in each asset under assessment in a percentage form, as shown in Table 1. The table describes each defect and grade and their definitions. The grades range

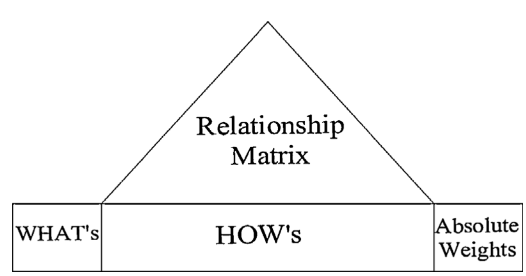

Fig. 1. HOQ General Representation.