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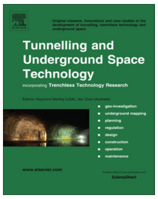

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Reliability based life cycle cost optimization for underground pipeline networks

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ABSTRACT

The safety of underground pipelines is the primary focus of water and wastewater industry. Due to low visibility and lack of proper information regarding the condition of underground pipes, assessment and maintenance are frequently neglected until a disastrous failure occurs. The reduction of pipe thickness due to corrosion undermines the pipe resistance capacity which in turn reduces the factor of safety of the whole distribution system. Providing an acceptable level of service and overcoming practical difficulties, the concerned industry has to plan how to operate, maintain and renew (repair or replace) the system under the budget constraints. This paper is concerned with estimating reliability of non-pressure flexible underground pipes subjected to externally applied loading and material corrosion during the whole service life. The reliability with respect to time due to corrosion induced deflection, buckling, wall thrust, bending stress is estimated. Then the study is extended to determine intervention year for maintenance and to identify the most appropriate renewal solution by minimizing the risk of failure and whole life cycle cost using Genetic Algorithm (GA). An example is presented to validate the proposed method with a view to prevent unexpected failure of flexible pipes at the minimal cost by prioritizing maintenance based on failure severity and system reliability.

1. Introduction

Underground pipeline network is a complex infrastructure system that has significant impact on the economic, environmental and social aspects of all modern societies. The world is moving towards adopting more proactive and optimized approaches to manage underground pipeline systems for their short and long term renewal planning in a more sustainable way. These approaches mostly aim to maximize return on investment by optimizing the allocated budget. Return on investment includes higher asset performance, lower risk of failure and lower life cycle costs. Such decisions can range from determining the optimal maintenance or inspection interval to evaluating a proposed design change. The decisions involve deliberate expenditure in order to achieve reliability, performance and other benefits. Costs involved are known but it is often difficult to quantify the potential impact of risks, the efficiency or safety and structural life expectancy. Guice and Li (1994) suggested that not only are the benefits difficult to quantify but also the objectives often conflict with each other. Finding the optimal strategy is difficult and the wrong maintenance strategy will result in excessive costs, risks or losses. Optimization models for pipeline maintenance methodologies are still in their infancy condition when compared to those in bridges, buildings and other civil engineering structures although optimum design approaches for pipe structural systems are continuously evolving and improving (McDonald and Zhao, 2001; Tee and Li, 2011).

Davies et al. (2001) pointed out that the Water Services Regulation Authority in England and Wales or OFWAT spent a huge amount of money every year on sewer replacement in the UK. According to Concrete Pipeline Systems Association (CPSA, 2008), OFWAT estimated that replacing or renovating the UK's 309,000 km sewerage and drainage network required £200 billion. The consequences of failure are multiple and may include loss of life, injury, excessive maintenance costs, user costs, environmental impacts etc. It is clear that some of these consequences are incommensurable and cannot be evaluated in monetary terms. The concept that needs to clarify is the meaning of 'optimum'. The word is often used in phrases such as the optimum maintenance strategy or the optimum performance. Woodhouse (2001) stated that in areas where there are conflicting interests, such as pressures to reduce costs at the same time as the desire to increase reliability or performance or safety, an optimum represents some sort of compromise between the demand and

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performance. It is quite impossible to achieve the ideal – zero cost and at the same time total 100% reliability or safety.

Structural reliability analysis of buried pipeline systems is one of the fundamental issues for water and wastewater asset managers. Methods of reliability analysis such as first order reliability method, second-order reliability method, point estimate method, Monte Carlo simulation, subset simulation, gamma process, probability density evolution method, etc. are available in literature (Baecher and Christian, 2003; Sivakumar Babu and Srivastava, 2010; Tee et al., 2013b; Mahmoodian et al., 2012; Fang et al., 2013a, 2013b). Recently, considerable amount of attention has been given to reliability of underground pipeline networks in conjunction with the optimization to achieve maximum benefits with the minimum cost (Moneim, 2011). The prediction of structural reliability throughout its life cycle depends on probabilistic modelling of load and strength of the system and on the use of appropriate analytical or numerical methods (Estes and Frangopol, 2001; Tee et al., 2013a).

Knowing the age of a pipeline segment, the condition of the pipe and how a pipe of that type deteriorates over time makes it possible to estimate the remaining service life of specific pipe. Unfortunately few municipalities have sufficient historical data to model the actual deterioration of underground pipes. Mailhot et al. (2000) used data from a Quebec municipality to simulate the deterioration of a sewer network from a good to poor state; Wirahadikusumah and Abraham (2003) modelled the deterioration of combined sewers using data from the city of Indianapolis; Ariaratnam et al. (2001) used data from the City of Edmonton to model sewer pipe deterioration and Micevski et al. (2002) modelled the deterioration of storm sewers for the Newcastle City Council in Australia. All the four models have predicted the pipe service life which is approximately 100–125 years. However, according to Newton and Vanier (2006), the estimated service life can range from 50 to 125 years depending upon the material and pipe diameter. In fact, the service life of a pipe can also be affected by other factors such as type of embedment soil, pipe thickness, pipe depth, pipe class (combined, sanitary, storm), level of maintenance, overburden, soil type, etc. (Ana et al., 2008; Wirahadikusumah et al., 2001). These elements are inherently conflicting, so an integrated multi-criteria approach is needed to develop renewal plans that satisfy these criteria in a balanced and optimized manner.

The sustainable management and renewal of underground pipeline networks pose a wide range of difficulties due to increasing fear of failure risk and requirements to comply with environment and accounting regulations as well as limited renewal budgets. Many challenges have been faced by water industry during installation and maintenance of underground pipeline networks. Frequent change of weather, corrosion, shrinkage and crack may reduce the pipe service life even if repair is done and the initial strength may not be achieved. A vital failure criterion of pipelines subjected to both internal and external corrosion is that the loss of structural strength which is influenced by localized or overall reduction in pipe wall thickness. Ahammed and Melchers (1994) assumed that the loss of wall thickness through general corrosion which affects much of the circumferential wall thickness is uniform or near so. The size of the resulting pipe wall thickness undermines the pipe resistance capacity which in turn reduces the factor of safety of the whole pipeline distribution system. The decision to repair or replace existing pipes is typically based on past performance indicators such as annual number of failure in a given section of a pipe network. This approach is not robust because it depends largely on what has happened in the past and what is expected to happen in the future. A better approach to scheduling pipe maintenance is based on performance indicators such as structural integrity, hydraulic efficiency and system reliability (Khan et al., 2013).

The main objective of this study is to analyse the reliability of non-pressure flexible underground pipes using First Order Reliability Method (FORM) and to present a reliability-based model of life cycle cost optimization in Genetic Algorithm (GA). Given the importance and high consequences of pipe collapse, a risk-based maintenance management methodology can be more effective by considering not only the probability of failure but also the consequences of failure. The optimization objective function of this study is the value of life cycle cost (LCC) which represents all the costs incurred throughout the life cycle of an underground pipe network, including the costs of design, construction, maintenance, repair, rehabilitation, replacement and expected costs of failure. The proposed maintenance strategy enables decision maker to decide when and how to renew the pipes (i.e. the most effective maintenance strategy, which could be replacement, structural, semi structural and non structural lining methods) at the minimum cost.

2. Corrosion of metal pipes

Buried pipes are made of plastic, concrete or metal, e.g. steel, galvanized steel, ductile iron, cast iron or copper. Plastic pipes tend to be resistant to corrosion. Damage in concrete pipes can be attributed to biogenous sulphuric acid attack (Tee et al., 2011). On the other hand, metal pipes are susceptible to corrosion. Metal pipe corrosion is a continuous and time variable process. Under certain environmental conditions, metal pipes can become corroded based on the properties of pipe materials, soil surrounding pipe wall, water or wastewater properties and stray electric currents. The corrosion pit depth (D_T) with respect to time can be modelled as shown in Eq. (1) or Eq. (2). Kucera and Mattsson (1987) first proposed a widely accepted model, a power law equation to measure D_T for atmospheric corrosion which can be expressed as follows.

$$D_T = kT^n \tag{1}$$

where k is multiplying constant (typical value 2.0), n is exponential constant (typical value 0.3) (Sadiq et al., 2004) and T is exposure time. Rajani et al. (2000) proposed a two-phase modified corrosion model to accommodate the self-inhibiting process as follows.

$$D_T = aT + b(1 - e^{-cT}) \tag{2}$$

where a is final pitting rate constant (typical value 0.009 mm/year), b is pitting depth scaling constant (6.27 mm) and c is corrosion rate inhibition factor (0.14 per year). Eq. (1) is normally used to predict D_T for steel pipe whereas Eq. (2) is used for cast iron pipe. Due to reduction of pipe wall thickness caused by corrosion, the moment of inertia per unit length, I and cross-sectional area per unit length, A_s can be defined as shown in Eqs. (3) and (4), respectively (Watkins and Anderson, 2000; Tee and Khan, 2012).

$$I = (t - D_T)^3/12 \tag{3}$$

$$A_s = t - D_T \tag{4}$$

where t is thickness of pipe. Eqs. (1)–(4) show that D_T, I and A_s are time dependent variables.

3. Flexible pipe failure modes

The dominating failure criteria of flexible pipes are characterized by limit states as follows

(a) Excessive deflection.
(b) Actual buckling pressure greater than the critical buckling pressure.