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RISK-COST OPTIMIZATION AND RELIABILITY ANALYSIS OF UNDERGROUND PIPELINES

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ABSTRACT

The safety of infrastructure facilities such as buried pipelines is the primary objective of engineering design. Due to their low visibility, condition assessment and rehabilitation of underground pipelines are frequently neglected until a catastrophic failure occurs. Time, reliability and cost are the crucial aspects of any underground pipeline projects. Providing an acceptable level of service and overcoming these critical 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 the reliability and deciding when interventions are needed to prevent unexpected failures of underground pipelines subject to externally applied loading and pipe material corrosion during their whole service life at the minimal cost. The probability of system failure with respect to time due to corrosion induced deflection, buckling, wall stress/thrust and bending stress-strain has been estimated and then the study has been extended to minimize the risk and life cycle cost using genetic algorithm. The proposed risk-cost optimization approach can help the management in making correct decisions concerning the intervention year and renewal methodology. An example is presented to validate the proposed method with a view to prevent the unexpected failure of flexible sewer pipes by prioritizing maintenance based on failure severity and system reliability.

NOMENCLATURE

a = Final pitting rate constant;
b = Pitting depth scaling constant;
c = Corrosion rate inhibition factor;
D = Mean diameter of pipe;
D_f = Shape factor;
D_L = Deflection lag factor;
E = Modulus of elasticity of pipe material;
E' = Soil modulus of reaction;
F_y = Tensile strength of pipe material;
H = Height of the soil above pipe invert;
H_w = Height of water above top of pipe;
ID = Inside diameter of pipe;
K = Bedding constant;
k = Multiplying constant;
M_s = Secant constrained soil modulus;
n = Exponential constant;
OD = Outside diameter of pipe;
P_s = Live load/ traffic load;
R = Effective radius of pipe;
R_w = Water buoyancy factor;
S_h = Hoop stiffness factor;
T = Time in year;
t = Thickness of pipe wall;
y_o = Distance from centroid of pipe wall to the furthest surface of the pipe;
γ_s = Unit weight of soil;
γ_w = Unit weight of water;
Φ_s = Capacity modification factor for soil.

1. INTRODUCTION

The sustainable management and renewal of the underground sewer networks pose a wide range of difficulties due to increasing fear of failure risk and requirements to comply with environment and accounting regulations and limited renewal budgets. Many challenges have faced by water industry during placing or maintenance the underground sewer pipeline networks. The most common challenges are found as leaking, blockage, buckling, wall thrust and deflection behaviour of pipe under hydrostatic pressure, poor design detailing and installation practices during placing the pipes, insufficient corrosion protection procedures, pipe material deterioration, scouring underneath the ground level, frost heave action and insufficient understanding of the material limitations [1]. A vital failure criterion of sewer 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. It is assumed that the loss of wall thickness through general corrosion which affects much of the circumferential wall thickness is uniform or near so [2]. The size of the resulting pipe wall thickness undermines the pipe resistance capacity which in turn reduces the factor of safety of the whole sewer 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 sewer maintenance is based on performance indicators such as structural integrity, hydraulic efficiency and system reliability. Currently, achieving an optimum solution of reliability-based design and maintenance strategy for sewer distribution network has become an issue of great concern in order to save considerable amount of allocated budget, for example which pipes to renew as well as when and how to renew them (i.e. the most effective maintenance strategy, which could be a patch repair, overlay, partial depth replacement and overlay, total replacement, etc.). Much attention has recently been given to reliability of sewer distribution networks in conjunction with the optimization to achieve maximum benefits with the minimum cost [3]. The long-term planning of the renewal of sewer distribution networks requires the ability to predict system reliability as well as assess the economic impact.

The main objective of this study is to analyse the reliability of underground flexible sewer pipes using first order reliability method (FORM) and to present a reliability-based model of risk-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 a sewer pipe network, including the costs of design, construction, maintenance, repair, rehabilitation, replacement and costs of failure.

2. CORROSION OF 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. In this paper, the research will focus on metal pipes. Metal pipe corrosion pit is a continuous and variable process. Under certain environmental conditions, metal pipes can become corroded based on the properties of the pipe materials, the soil surrounding the pipe wall, water or wastewater properties and stray electric currents. The corrosion pit depths can be modelled with respect to time as shown in Equations (1) and (2) [2, 4].

The corrosion pit depth,

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

Due to the reduction of wall thickness given by Equations (1) and (2), the moment of inertia of pipe wall per unit length, I and the cross-sectional area of pipe wall per unit length, A_s become

Moment of inertia, $I = (t - D_T)^3 / 12$ (3)

Cross-sectional area, $A_s = t - D_T$ (4)

Equations (3) & (4) show that I and A_s are time dependent variables.

3. FORMULATION FOR PREDICTION OF PIPE FAILURE

All types of underground sewer pipes whether flexible or rigid, rely on the backfill properties to transfer the loads into the bedding. As a result, all pipes should be installed as designed to perform as expected. In this paper, the failure criteria of flexible pipes are characterized by:

- Excessive deflection;
- Actual buckling pressure greater than the critical buckling pressure;
- Actual wall thrust greater than the critical wall thrust and
- Actual bending stress and strain greater than the allowable stress and strain.

3.1 DEFLECTION

Deflection can be defined as the change in inside diameter that results when a load is applied to a flexible pipe. Deflection is normally quantified in terms of the ratio of the horizontal increase in diameter (or vertical decrease in diameter) to the pipe diameter. The deflection can be calculated as follows [5, 6]

$$\Delta y = \frac{K(D_L W_c + P_s)D}{\frac{8EI}{D^3} + 0.061E'} \tag{5}$$

The critical deflection for flexible pipe is determined as 5% of inside diameter of pipe.

3.2 BUCKLING

Buckling is a premature failure in which the structure becomes unstable at a stress level that is well below the yield strength of the structural material [7]. The actual buckling pressure, P_a can be calculated as follows [7]

$$P_a = R_W \gamma_s + \gamma_W H_W + P_s \tag{6}$$

The critical buckling pressure is calculated as follows [6]:

$$Pcr = \frac{1}{FS}\sqrt{\left(32RwB'E'\frac{EI}{D^3}\right)} \tag{7}$$

where FS = design factor, B' = empirical coefficient of elastic support

$$B' = \frac{1}{1 + 4e^{-0.213H}}$$

3.3 WALL THRUST

Thrust or stress on the sewer pipe wall is determined by the total load acting on the pipe including soil, traffic and hydrostatic loads. If only dead load is involved during installation, the long-term material properties are considered throughout the calculation of wall thrust analysis. However, if both dead and live loads are present (typically any vehicular load with 2.4 m of cover or less), two wall thrust analyses are required: (a) accounts both the dead and live loads and employs the short-term material properties throughout the procedure, (b) accounts only the dead load and employs the long-term material properties. Then the higher value is used for the subsequent reliability analysis [8].

The critical wall thrust,

$$T_{cr} = F_y A_s \phi_p \tag{8}$$

The actual wall thrust,

$$T_a = 1.3(1.5W_A + 1.67P_s C_L + P_W)(\mathrm{OD}/2) \tag{9}$$

where soil arch load,

$$W_A = (P_{sp})(VAF)$$

The geostatic load,

$$P_{sp} = \gamma_s(H + 0.11 \times 10^{-7}(\mathrm{OD}))$$

The vertical arching factor,

$$VAF = 0.76 - 0.71((S_h - 1.17)/(S_h + 2.92))$$

3.4 BENDING STRESS AND STRAIN

An estimation of the bending stress and strain should be done to ensure that they are within material capability. For the safety of the sewer pipe, the bending stress should not exceed the long-term tensile strength of the pipe material and the longitudinal bending strain should not exceed the allowable strain of 5% for polyethylene pipe and 0.15% to 2% for other flexible pipes [9]. Bending stress and strain can be calculated using Equations (10) and (11), respectively [8].

Bending stress,

$$\sigma_b = 2D_f E \Delta_y y_0 SF/D^2 \tag{10}$$

Bending strain,

$$\varepsilon_b = 2D_f \Delta_y y_0 SF/D^2 \tag{11}$$

where SF = safety factor.

4. RELIABILITY ANALYSIS

The First Order Reliability Method (FORM) has been applied in the current methodology to assess the reliability of underground flexible sewer pipes based on corrosion induced excessive deflection, buckling, wall thrust and bending stress or strain. For acceptable values of probability of safety of the structures, USA Army Corps of Engineers (USACE) suggested that the estimated reliability index should be at least 3.0 for above average performance and 4.0 for good performance [7]. In the proposed method, the limit state functions $Z(X_i)$ for the aforementioned failure modes (deflection, buckling, wall thrust and bending stress or strain) can be developed (critical value minus actual value) such that positive values of Z indicate no failure or safe region and negative or zero values of Z, indicates failure or unsafe region. $Z(X_i)$ is a function of random variables which are soil and pipe properties. It is assumed that the variables X_i are mutually independent and that their mean values $\bar{X}_i$ and standard deviations $\sigma(X_i)$ are known. Using the conventional rules for manipulating random variables, the mean value $\bar{Z}$ and standard deviation $\sigma(Z)$ of the limit state function Z can be approximated by

$$\bar{Z} \approx Z(\ X_1, X_2, X_3, \ldots\ldots\ldots\ldots\ldots, X_n\ ) \tag{12}$$

$$\sigma^2(Z) \approx \sum_{i=1}^{N} \left[\frac{\partial Z}{\partial X_i}\sigma(X_i)\right]^2 \tag{13}$$

where N denotes the total number of variables. The linearization implicit in Equation (12) is the first-order part of the conventional structural reliability approach. The derivatives $\partial Z/\partial X_i$ can be evaluated at the point, $X = \bar{X}$. As Z is sufficiently characterized by a mean and variance, so Z could be considered to be described by a normal distribution. From the standard structural reliability theory, the reliability index is then given by

$$\beta = \frac{\bar{Z}}{\sigma(Z)} \tag{14}$$

and the probability of failure P_f for each limit state function can be evaluated by [2]

$$P_f = P[Z \le 0] = \Phi\left[\frac{Z - \bar{Z}}{\sigma(Z)}\right]_{Z=0} = \Phi(-\beta) \tag{15}$$

or, $P_f = 1/\{1 + exp(\frac{\pi\beta}{\sqrt{3}})\}$ [10]

To evaluate the relative contribution of each random variable in the limit state function $Z(X)$, sensitivity coefficient α^2 can be calculated as follows

$$\alpha_i{}^2 = \frac{\left[\frac{\partial Z}{\partial X_i}\sigma(X_i)\right]^2}{\sigma^2(Z)} \tag{16}$$

There are basically two types of system in the theory of system reliability. One is known as the series system in which the occurrence of one failure mode constitutes the failure of the whole system. The other is known as the parallel system in which the system fails only when all failure modes occur. In this study, the occurrence of either failure mode of the sewer pipe will constitute its failure. Therefore a series system is appropriate for its assessment of failures. According to the theory of systems reliability, the probability of failure for a series system, $P_{f,s}$ can be estimated by

$$Max[P_{f,i}] \le P_{f,s} \le 1 - \prod_{i=1}^{n}[1 - P_{f,i}] \tag{17}$$

where $P_{f,i}$ is the probability of failure due to i^{th} failure mode of pipe (determined by Equation (15)) and n is the number of failure modes considered in the system.

5. RISK-COST OPTIMIZATION

Sewer network system is a complex infrastructure system that has significant impact on the economic, environmental and social aspects of all modern societies. The life expectancy as well as maintenance and repair depend on the type of material used in the pipe. 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. Similarly the joint of the pipe connection is the most vulnerable point and if proper maintenance is not done this may lead to failure. The implementation of a quantitative assessment and risk-based life cycle maintenance is a very complex task due to the difficulties of assessing quantitatively the probability and the consequences of failure, especially for a large network of pipe structures.

For a given sewer distribution network, huge number of solutions can be selected through a range of decision variables and in such cases, probabilistic methods are used instead of mathematical models to search for the best solution. In this paper, the optimal maintenance of an underground sewer network has been performed through risk-cost optimization with GA.

The whole life cycle cost (LCC) has been used as an objective function in maintenance optimization. The whole LCC is the total cost of a sewer pipe network during its lifetime. In assessing the whole LCC, all relevant costs: direct, indirect, social and environmental should be considered. While project level or short-term planning would require more accurate assessment of direct, indirect, social, environmental costs, network level or long-term planning could be reasonably conducted using approximate total cost figures such as those compiled or estimated from the literature.

In this study, the LCC consists of initial cost or installation cost, maintenance cost (including repair and replacement costs) and failure risk cost [11]. The total life cycle cost $C_{LCC}(T)$ can be presented as follows [12]

$$C_{LCC}(T) = C_A(T) + \sum_{i=1}^{T} C_O(T) \tag{18}$$

where $C_A(T)$ = the initial cost or cost of acquisition, $C_O(T)$ = operation cost and T = pipe service life.

The operation cost C_O(T) can be calculated by

$$C_O(T) = C_M(T) + C_R(T) \tag{19}$$

where $C_M(T)$ is the maintenance cost and $C_R(T)$ is the failure risk.

The failure risk cost, $C_R(t)$ is influenced by the failure cost, $C_f(T)$ and the failure probability as a series system, $P_{f,s}$ (determined by Equation (17)) as follows

$$C_R(T) = C_f(T) * P_{f,s} \tag{20}$$

So based on Equations (19) and (20), Equation (18) can be rewritten as follows

The life cycle cost, $C_{LCC}(T)$

$$= C_A(T) + \sum_{i=1}^{T} C_M(T) + \sum_{i=1}^{T} C_f(T) * P_f, s \tag{21}$$

The cost terms in the right-hand side of the Equation (21) are the costs in the year they actually occur. The $(1+r)^T$ factor is used to convert the cost into its present value discounted by the discount rate of r, for the T year period. The discount rate depends on the prevailing interest rate and the depreciation of the currency or inflation rate. This rate is not a constant term and may vary over the life of the pipeline structure.

From an economical point of view, the ideal goal of risk and cost management of sewer pipe network should be minimizing the total LCC of the network. In this study, the problem of identifying the optimal intervention year is transformed into minimization of total LCC (Equation (21)).

6. SELECTION OF RENEWAL METHODS

The sewer renewal technologies are growing rapidly and becoming more efficient and cost-effective. Different renewal methods exhibit different capabilities, limitations, costs and benefits. The particular characteristics of the sewer (e.g., material, diameter, etc.) and site conditions (e.g., soil, water table, traffic etc.), along with other operational, social and environmental factors determine the applicability of different renewal methods in a particular situation. In any given scenario, some renewal methods are more applicable and cost effective than others and therefore, a systematic procedure for selecting feasible methods is needed.

The renewal methods are grouped into four main categories: replacement, structural, semi structural and non-structural lining methods. Structural liners are defined to be capable of carrying hydrostatic, soil and live loads on their own. Structural liners are expected to be independent i.e., bonding with original sewer is not required. Semi structural liners are designed to withstand hydrostatic pressure or perform as a composite with the existing pipelines. Semi structural liners could be designed as interactive or independent [13]. Semi structural liners typically are not used for gravity pipelines. Non-structural liners are used mainly to improve flow, resist corrosion, or to seal minor cracks in gravity sewers [14].

In this study, the proposed sewer maintenance strategy complements the aforementioned risk-cost optimization by identifying applicable renewal categories based on the sewer condition index and the possibility of surrounding soil loss as shown in Table 1. The possibility of surrounding soil loss is assessed on a high, medium, or low scale according to the soil type and the groundwater level as shown in Table 2 [13]. The condition index (CI) can be calculated from the regression model [15] as follows

$$CI = 0.0003T^2 - 0.0003T + 1 \quad (22)$$

where T = age of the sewer (in year) which corresponds to the intervention year obtained from the risk-cost optimisation. The renewal methods are selected based on detailed analysis of possible defects, as indicated by the condition index and the possible scenarios of soil loss. For example, a sewer with condition index 3 and high possibility of soil loss will need replacement or the use of a structural liner to carry loads and stabilize deformation. At a minimum, a semi structural liner that can withstand hydrostatic pressure is required.

Table 1: Selection of renewal categories based on condition index and soil loss possibility [13]

Cond. Index	Possibility of soil loss		
	Low	Medium	High
2	Non-structural or semi-structural	Non-structural or semi-structural	Semi-structural, structural or replacement
3	Non-structural or semi-structural	Semi-structural or structural	Semi-structural, structural or replacement
4 and 5	Structural or replacement	Structural or replacement	Structural or replacement

Table 2: Possibility of soil loss based on soil type and groundwater level [13]

Soil Type	Groundwater level		
	Below sewer	Same line with sewer	Above sewer
Clay	Low	Medium	High
Gravels and low plasticity clay	Low	Medium	High
Silt and sand	High	High	High

7. WORKED EXAMPLE

An underground sewer network under a heavy roadway subjected to hypothetical operating conditions is taken as a numerical example to validate the proposed risk-cost optimization maintenance strategy. The sewer network consists of approximately 860 km (534.06 miles) of sanitary sewers and 755 km (468.86 miles) of storm sewers. The sanitary sewers of length 500 km and 360 km were constructed in 1989 and 1994, respectively whereas the storm sewer pipes of length 255 km and 500 km were constructed in 1999 and 2003, respectively. The sanitary sewers were constructed on clay whereas the storm sewers were built on sand and the whole sewer pipes were above the groundwater level.

For simplifying the problem, all the pipes in the network (both sanitary and storm) are presumed as large size steel sewer pipes with an outside diameter of 1.21 m and initial wall thickness of 0.021 m. The network is subjected to corrosion and its corrosion rate is modelled using Equation (1). The sewer pipe and soil parameters are listed in Table 3. There are 9 random variables (elastic modulus of pipe, soil modulus, soil density, live load, deflection coefficient, corrosion coefficients, pipe wall thickness and height of the backfill) where the mean and coefficient of variation are listed in Table 4. All of them are considered as a uniformly distributed, except the deflection coefficient which is log-normal distributed. It is assumed that the cost of acquisition or initial cost = £1.0 millions, the maintenance cost = £0.1 millions, the failure cost = £150 billions and discount rate = 4.2%.

Table 3: Parameter values of worked example

Parameters	Value
Buoyancy factor, R_w	1.00
Trench width, B_d	2.00 m (79 in)
Outside pipe diameter, OD	1.214 m (47.39 in)
Inside pipe diameter, ID	1.172 m (46.14 in)
Soil constrained modulus, M_s	2.02×103 kPa (292.8 psi)
x-sectional area of pipe wall per unit length, A_p	0.021 m^2/m (0.826 in^2/in)
Shape factor, D_f	4.0
Capacity modification factor for pipe, ϕ_p	1.00
Capacity modification factor for soil, ϕ_s	0.90
Safety factor, SF	1.5

Table 4: Statistical values of random variables

Basic Variables	Mean	COV* (%)	Standard Deviation (σ)
Elastic modulus of pipe, E	213.74×10^6 kPa (31.0 psi) (Normal)	1.0	2.1374×10^6 kPa (0.31 psi)
Backfill soil modulus, Es	10^3 kPa (145 psi) (Normal)	5.0	50kPa (7.25 psi)
Unit weight of soil, γ	18.0kN/m^3 (114.5lb/ft^3) (Normal)	2.5	0.45kN/m^3 (2.862 lb/ft^3)
Live load, Ps	80.0 kPa (11.6 psi) (Normal)	3.0	2.4 kPa (0.348 psi)
Deflection coefficient, K_b	0.11(Lognormal)	1.0	0.0011
Multiplying constant, k	2.0 (Normal)	5.0	0.1
Exponential constant, n	0.3 (Normal)	5.0	0.015
Thickness of pipe, t	0.021 m (0.826 in) (Normal)	1.0	0.00021m (0.00826 in)
Height of the backfill, H	3.75 m (147.6 in) (Normal)	1.0	0.00375m (1.476 in)

*Coefficient of variation

8. RESULTS AND DISCUSSION

The structural reliability of the underground sewer network is first estimated and then the risk-cost optimization is performed to predict the optimal maintenance or renewal time which takes into account the system reliability analysis and life cycle cost. The proposed maintenance strategy enables decision maker to choose a feasible renewal method based on the calculated optimal renewal time.

8.1 PROBABILITY OF FAILURE

The probabilities of failure due to corrosion induced deflection, buckling, wall thrust and bending stress with respect to time are estimated using the FORM based on the parameters and basic variables given in Tables 1 and 2. As all the random variables are considered as uniformly distributed, except the deflection coefficient which is log-normal distributed. Thus Rackwitz-Fiessler algorithm has been applied to transform its distribution from log-normal to normal in this study.

The occurrence of either failure mode of the sewer pipe will constitute its failure. Therefore a series system is appropriate for its assessment of failures. The probability of system failure is determined using Equation (17) and the result is shown in Figure 1. The study shows that the probability of system failure at the beginning is zero and it remains unchanged until about 40 years of service life, then it gradually changes as time increases and after 50 years, the probability of sewer failure rises drastically. When the thickness of the pipe is reduced due to corrosion, the moment of inertia and the cross-sectional area of pipe wall are decreased with a resulting reduction in pipe strength.

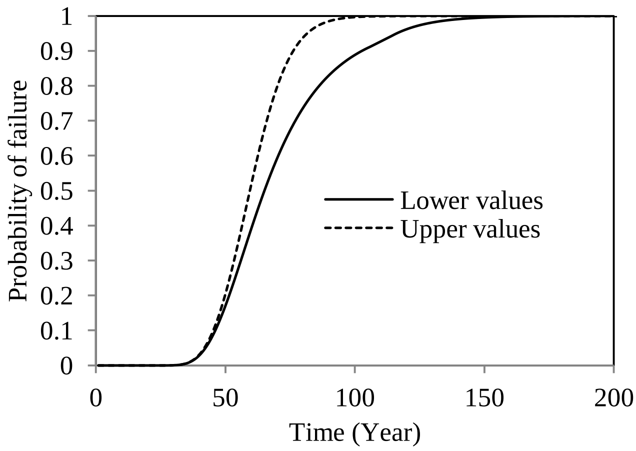

Figure 1: Probability of system failure for sewer network

8.2 OPTIMAL COST & TIME TO RENEW

As shown in Equation (20), the failure risk cost is calculated by multiplying failure cost with the probability of system failure. Once the probability of system failure has been calculated, the optimal time to repair or replace and the associated life cycle cost can be obtained from the risk-cost optimization using GA.

Figure 2 shows the convergence of total LCC obtained from risk-cost optimization and the optimal value is about £4,000 billions. The optimal LCC cost is associated with the first maintenance after 59 years of service. Therefore, based on the given data, the sanitary sewer of 500 km is required to renew in 2048, while 360 km in 2053. Similarly, the storm sewer of 255 km is required to renew in 2058 and 500 km in 2062 in order to achieve the minimum life cycle cost which takes into account the system reliability of the sewer network.

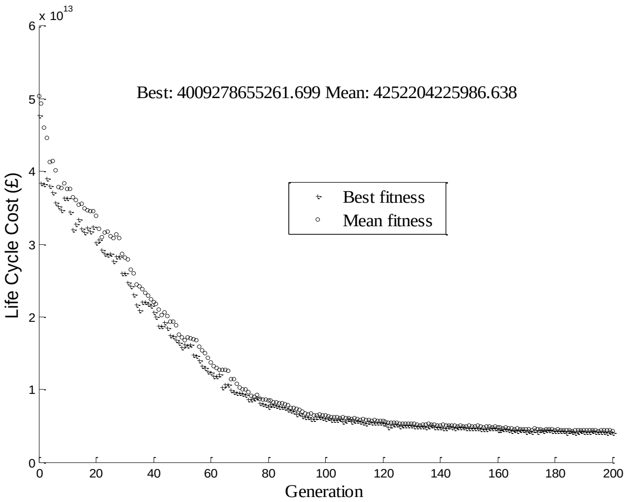

Figure 2: Life cycle cost for sewer network in GA

Next, the proposed maintenance strategy is extended to determine an applicable and feasible renewal method using Tables 1 and 2. The recorded database shows that the sanitary steel sewers are built on clay and the soil type of the storm sewers is sand. In addition, both types of sewers are above the groundwater level. Based on this information and according to Table 2, the possibility of soil loss for sanitary sewers is low whereas for storm sewers, the possibility of surrounding soil loss is high.

The condition index (CI) for the sewer network is estimated as 2.03 using Equation (22) by substituting the identified optimal time to renew (59 years) from the risk-cost optimization. Applicable renewal categories are then selected from Table 1 based on the sewer CI and the possible scenario of soil loss. The sanitary sewers of 500 km and 360 km are required to renew using non-structural or semi-structural lining method based on the estimated CI of 2 and low possibility of soil loss. On the contrary, due to high possibility of soil loss and the sewer CI of 2, the storm sewers of 225 km and 500 km are renewed using semi-structural or structural liners. Alternatively replacement is recommended when the repair cost is greater than the cost of replacing the pipes.

9. CONCLUSIONS

This paper presents a novel integrated approach for systematizing the maintenance of underground sewer networks. The approach integrates two main criteria in the planning process: structural reliability and whole life cycle cost. The probability of system failure due to corrosion induced deflection, buckling, wall thrust and bending stress is estimated and then the study is extended to minimize the risk and life cycle cost through risk-cost optimization using GA. The proposed maintenance strategy also enables decision maker to select appropriate renewal methods based on the identified optimal time to renew, sewer condition index and the possibility of surrounding soil loss. A numerical example is presented to validate the proposed maintenance strategy with a view to prevent the unexpected failure of flexible sewer pipes by prioritizing maintenance based on failure severity and system reliability. Thus, the proposed methodology can help the management in making correct decisions concerning the intervention to ensure the safe and serviceable operation of the underground pipes. This will, in turn, result in better asset and capital utilization.

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