Reliability-based management of underground pipeline network using genetic algorithm

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Abstract: When the residual ultimate strength of buried pipeline has exceeded the limit due to external loadings, failure becomes imminent and overall reliability is reduced. Therefore, the concerned industry has to plan how to operate and maintain the system within budget constraints. This paper is concerned with estimating reliability and deciding when and how interventions are needed to prevent unexpected failures of flexible buried metal pipelines subject to externally applied loadings and corrosion at minimal cost. The probability of failure due to corrosion induced excessive deflection with respect to varying time has been estimated in this study. Then intervention year for maintenance is determined and the most appropriate renewal solution is identified by minimising failure risk and whole life cycle cost using genetic algorithm. An example is presented to validate the proposed method with a view to prevent unexpected failure by prioritising maintenance based on failure severity and pipeline reliability.

Keywords: probability of failure, reliability, optimisation, pipeline network, genetic algorithm, life cycle cost, condition index, renewal priority.

1 Introduction

The world is moving towards adopting more proactive and optimised approaches to manage underground pipeline systems in a more sustainable way. Different management approaches exhibit different capabilities, limitations, costs and benefits. The particular characteristics of the buried pipes (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 method of management strategy in a particular situation [1]. For example, in some cases, the maintenance costs on a system can exceed the initial costs. Therefore, asset managers need to be able to develop the optimal strategy regarding inspection as well as maintenance works or rehabilitation works [2]. 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. Different research show that the vast majority of existing underground pipeline systems focus primarily on managing day-to-day operational activities, e.g., issuing and tracking work orders, mapping and data management, logging service requests, cost estimating, etc., and optimum long-term management planning for the pipeline network is limited [3]. This scarcity is mainly attributed to the lack of systematised, standardised and quantitative models, e.g., deterioration, risk, prioritisation and optimisation models and the lack of adequate reliable data to support the application of such models. However, finding the optimal strategy is not easy and the wrong maintenance strategy may result in excessive risks, costs and losses. Optimisation 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 [4]. To address these problems, several countries have developed or initiated the development of pipe management systems to optimise the inspection and maintenance of deteriorated pipe structures. Different optimisation approaches have been implemented in the different buried pipe management systems ranging from simplified economic models to advanced Markovian decision processes [5].

Due to uncertainty associated with the rate of failure and behaviour of buried pipeline system, the probabilistic pipe reliability methodology has been applied in optimisation process in this study. According to Sarma and Hojjat [6], a few researchers have presented probabilistic reliability models for life cycle cost optimisation of pipe structures. Numerous potential failure modes are found in a buried pipe structure system. Therefore, it is important to have a method by which the most critical failure modes can be identified. The critical failure modes are those contributing significantly to the reliability of the system at the chosen level. The failure criterion adopted in this paper is due to loss of structural strength of pipelines which is influenced by corrosion through reduction of the pipe wall thickness. The chosen dominating failure mode in flexible buried metal pipeline system is time-dependent corrosion induced excessive deflection. Then, an optimisation algorithm, genetic algorithm (GA) has been developed to optimise the management strategy. Life cycle cost (LCC) of pipeline network has been used as an objective function in this process. LCC consists of initial cost or installation cost, maintenance cost and failure risk cost of the system. The propose management option has yield a performance according to the risk involved and cost of the activities throughout the service life. The proposed maintenance strategy will enable the decision makers to select appropriate renewal methods based on the identified optimal time to renew i.e. repair or replace.

2 Problem formulation

In this study, the LCC is used as an optimisation objective with effects of pipe failure according to Eq. (1). The total life cycle cost can be presented as follows:

$$\mathrm{C}_{\mathrm{LCC}}(T) = C_A + \sum_{i=1}^{T} C_O(i) \tag{1}$$

where C_A = the capital cost; $C_O(i)$ = operation cost; and i = 1,2,3,…..,T years. The operation cost $C_O(i)$ can be calculated by Eq. (2) as below:

$$C_O(i) = C_M(i) + C_R(i) \tag{2}$$

where $C_M(i)$ is the maintenance cost and $C_R(i)$ is the failure risk cost. The failure risk cost, $C_R(i)$ is influenced by the failure cost, $C_f(i)$ and the failure probability, P_f. The faillure risk cost can be estimated as below:

$$C_R(i) = C_f(i) \cdot P_f \tag{3}$$

Based on Eqs. (2) and (3), Eq. (1) can be rewritten as follows:

$$C_{LCC}(T) = C_A + \sum_{i=1}^{T} C_M(i) + \sum_{i=1}^{T} C_f(i) * P_f \tag{4}$$

The cost terms in the right-hand side of Eq. (4) 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 years period. The discount rate depends on the prevailing interest rate and the depreciation of the currency or inflation rate which is not a constant term and may vary over time. From an economical point of view, the ideal goal of risk and cost management of pipe network should be minimising the total LCC of the network. In this study, the problem of identifying the optimal intervention year is transformed into minimisation of total LCC (Eq. (4)).

The time-dependent corrosion depth (D_T), moment of inertia (I) and cross-sectional area (A_s) of thin walled buried pipe can be estimated as below [7], [8]:

$$D_T = kT^n,\ I = (t - D_T)^3/12 \text{ and } A_s = t - D_T \tag{5}$$

where k = multiplying constant, n = exponential constant and t = thickness of pipe wall.

Actual deflection (Δ_y) and allowable deflection (Δ_a) can be predicted as below [9], [10]:

$$\Delta_y = \frac{K(D_L W_c + P_s)D}{\left(\frac{8EI}{D^3} + 0.061E'\right)} \text{ and } \Delta_a = 5\% \text{ of diameter of pipe} \tag{6}$$

where D = mean diameter of pipe, D_L = deflection lag factor, E = modulus of elasticity of pipe material, E' = Soil modulus of reaction, K = Bedding constant and P_s = live load and W_c = soil load.

For this failure mode, limit state, $Z(X)$ ($\Delta_a - \Delta_y$) < 0 represents failure state, $Z(X) > 0$ indicates a safe state and the limit state boundary at $Z(X) = 0$. The probability of failure for excessive deflection can be predicted as Eq. (7) [11]:

$$p_f = P[Z(X) < 0] = \Phi\left[\frac{0 - \bar{Z}}{\sigma(Z)}\right] = \Phi(-\beta) \tag{7}$$

where Φ = the cumulative standard normal distribution function (zero mean and unit variance) and $\beta = \bar{Z}/\sigma(Z)$ is known as the safety index or reliability index.

3 Renewal methods and condition index

The buried pipelines renewal methods can be grouped into four main categories: replacement, structural, semi structural and non-structural lining methods [2]. 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 underground pipeline 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. Semi structural liners typically are used for non-gravity pipeline system. Non-structural liners are used mainly to improve flow, resist corrosion, or to seal minor cracks in gravity pipelines [12]. The maintenance strategy can be implemented by identifying applicable renewal categories based on the underground pipeline condition which is called condition index or mean structural pipe grade. The purpose of the condition index is to objectively rate or scale the current condition of buried pipes based on several physical, environmental, and operational factors, which provide the basic terminology and framework [13].

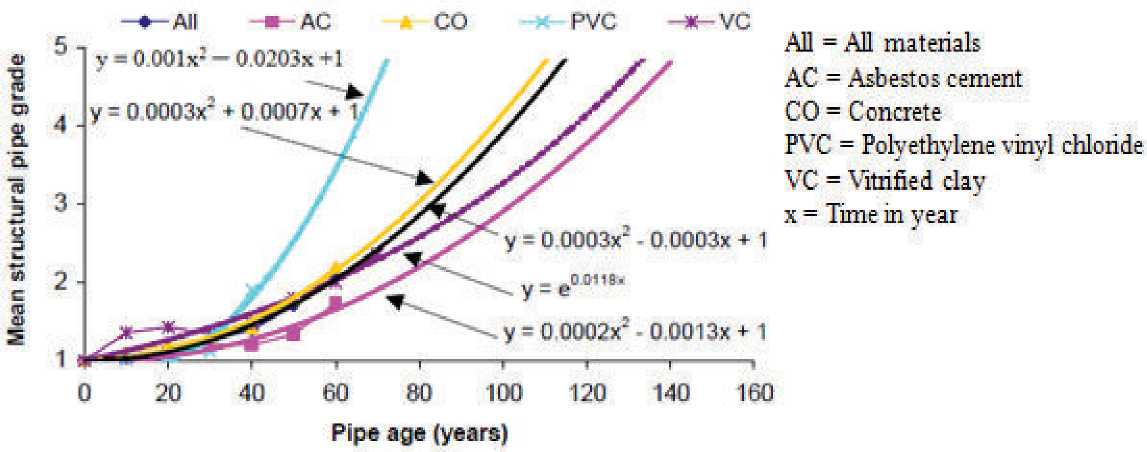

Fig. 1: Underground pipeline deterioration models using MIIP [12] dataset

The mean structural pipe grade or structural condition index (*CI*) for underground pipeline can be calculated from the regression model in Fig. 1 as follows [13].

$$CI = 0.0003T^2 - 0.0003T + 1 \tag{8}$$

where T = age of the underground pipeline (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 (Tab. 2 and 3) [13]. For example, an underground pipeline 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.

4 Impact assessment and prioritisation

The criterion used to renewal of pipes is the degree of impact of an underground pipeline failure. The impact assessment ranks the pipe segments in unit length in terms of six major factors: location, embedment soil, burial depth, pipe size, functionality and seismic zone. The assessment generates a ranking of impact for the underground pipeline system. Each of the six factors is assigned a degree of impact defined by low, medium or high [4]. A weighted impact rating (I_w) formula is used to combine the influence of each of the six factors for each pipe segment within the system as below.

$$I_w = 0.2 f_l + 0.16(f_s + f_z + f_d + f_f + f_q) \tag{9}$$

where f_l = location factor, f_s = embedment soil factor, f_z = size factor, f_d = burial depth factor, f_f = underground pipeline function factor and f_q = seismic factor. Although these factors do not change dramatically from year to year, periodic updating may be necessary. The failure impact rating can be assessed based on Tab. 1 with respect to I_w values [4].

Tab. 1: Failure impact rating

Weighted impact factor, I_w	Failure impact rating, R_{imp}
1.00	1
1.01 – 1.60	2
1.61 – 2.20	3
2.21 – 2.80	4
> 2.81	5

For all of the factors listed above, the low value is 1 and high value is 3. Medium degree of impact falls between the high and low extremes and is assigned a value of 1.5. Once the weighted impact rating is determined for individual pipe segments, the impact assessment can then be used in a number of ways in the decision-making process. The impact ratings can be used in combination with the physical condition index of a pipe to prioritise rehabilitation or replacement work and the future inspection frequencies. For the pipe segments with the same physical condition index/rating, those with higher impact ratings would be considered first for rehabilitation and lowest impact ratings would be considered no renewal required, as shown in Tab. 4.

Tab. 2: Possibility of soil loss based on soil type and groundwater level

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

Tab. 3: Selection of renewal categories based on condition index and soil loss possibility

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

Tab. 4: Renewal priority

Structural condition index	Implication	Failure impact rating (R_{imp})	Renewal priority
5	Failed or failure imminent	1 to 5	Immediate
4	Very poor condition High structural risk	5 1 to 4	Immediate High
3	Poor condition Moderate structural risk	4 to 5 1 to 3	Medium Low
2	Fair condition/ Minimal structural risk	1 to 5	Low
1 or 0	Good or excellent condition	1 to 5	Not required

The possibility of surrounding soil loss, a very important parameter to assess the renewal process is determined on a high, medium, or low scale according to the soil type, groundwater level and condition index, as shown in Tabs. 2 and 3 [13]. Finally, the renewal priorities are predicted based on CI, I_w and R_{imp} values as metioned in Tab. 4.

5 Numerical example

An underground pipeline network under a heavy roadway subjected to hypothetical operating conditions where some sections of the networks has passed under commercial/business areas and some parts has crossed residential areas, are taken as a numerical example to validate the proposed risk-cost optimisation management strategy. The underground pipeline network consists of approximately total 775 km of sanitary underground pipelines, made from steel and ductile iron, constructed in 1940. The underground pipelines and soil parameters are listed in Tabs. 5 and 6. The pipes are circular and buried in a mean trench width of 2 m. The backfill material has a mean unit weight of 18 kN/m^3 and mean soil modulus of 2 MPa. There are 9 random variables with the mean and coefficients of variations are listed in Tab. 6.

The underground pipelines consist of six types of pipeline sections as A – F, as mentioned in Tab. 5. The whole network constructed above ground water table. It is presumed that the whole underground pipeline network located in a high seismic vulnerable zone area. The cost data are presented in Tab. 7 for the whole pipeline sections (A – F). Note that in Tab. 7, the capital cost, maintenance cost and failure consequence cost are presumed based on MELBOURNE WATER report [14], typical 12.5% of capital cost and DAVIS ET AL. [15], respectively. The typical discount rate (UK) = 5% is considered in this example. The pipes in the network are consisted of medium size steel and ductile iron pipes. The network is subjected to corrosion and its corrosion is presumed as uniform over the pipe sections.

Tab. 5: Pipe materials and location properties

Pipe section	Material	Location	Embed-ment soil	Length (km)	Mean diameter (mm)	Thick-ness (mm)	Soil height above pipe invert (m)	Traffic load, kPa
A	Steel	Commercial	Clay	150	500	8	2.0	100
B	Ductile iron	Commercial	Clay	100	600	8	2.0	100
C	Steel	Residential	Sand	110	600	9	2.1	100
D	Steel	Residential	Sand	225	480	7.5	2.5	90
E	Ductile iron	Residential	Sandy Gravel	85	350	7	2.2	100
F	Ductile iron	Commercial	Sandy Gravel	115	500	8	1.8	100

Tab. 6: Statistical properties

Symbol description	Mean value	Coefficient of variation (%)	Distribution
Elastic modulus of steel pipe	210 GPa	1.0	Normal
Elastic modulus of ductile iron pipe	170 GPa	1.0	
Soil modulus, E_s	2 MPa	5	Normal
Unit weight of soil, γ	18.0 kN/m^3	2.5	Normal
Traffic load (Live load), P_s	See Tab. 5	3.0	Normal
Deflection coefficient, K_b	0.11	1.0	Lognormal
Multiplying constant, k	0.3	10.0	Normal
Exponential constant, n	0.6	5.0	Normal
Thickness of pipe, t	See Tab. 5	1.0	Normal

Tab. 7: Cost data for pipe network

Pipe section	Operation cost	Maintenance cost	Failure cost
A	£100000	£20000	£100m
B	£50000	£10000	£80m
C	£70000	£8000	£90m
D	£100000	£15000	£140m
E	£30000	£8000	£70m
F	£55000	£7000	£85m

5.1 Pipeline reliability

The probabilities of buried pipe failure due to corrosion induced excessive deflection, with respect to time are estimated based on the parameters and basic variables given in Tabs. 5 and 6. The failure probabilities are predicted using First Order Reliability method and results are shown in Figs. 2 – 7. 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. All the random variables are considered as uniformly distributed, except deflection coefficient which is log-normally distributed. Thus Rackwitz-Fiessler algorithm has been applied to transform its distribution from log-normal to normal in this study.

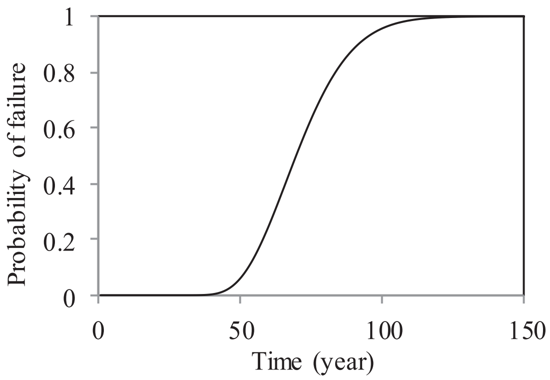

Fig. 2: P_f for pipeline section A

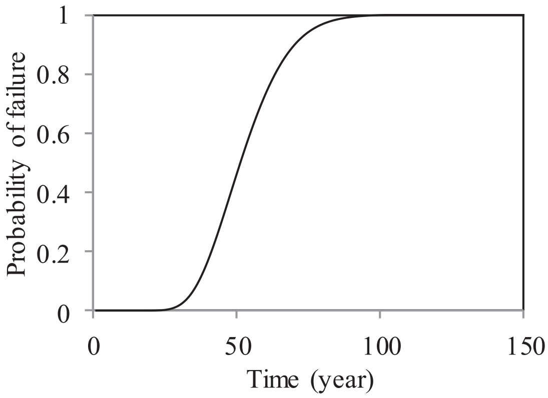

Fig. 3: P_f for pipeline section B

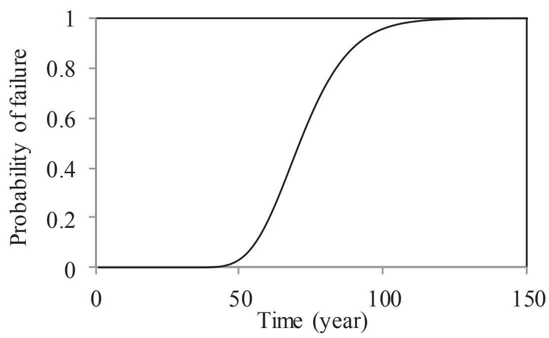

Fig. 4: P_f for pipeline section C

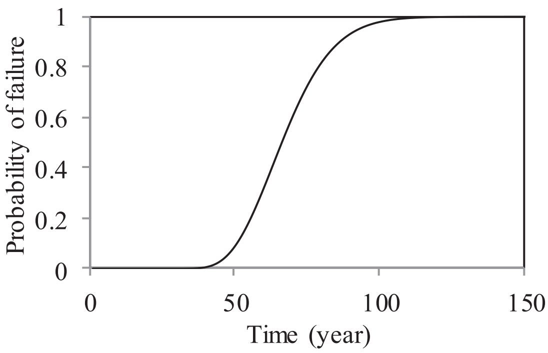

Fig. 5: P_f for pipeline section D

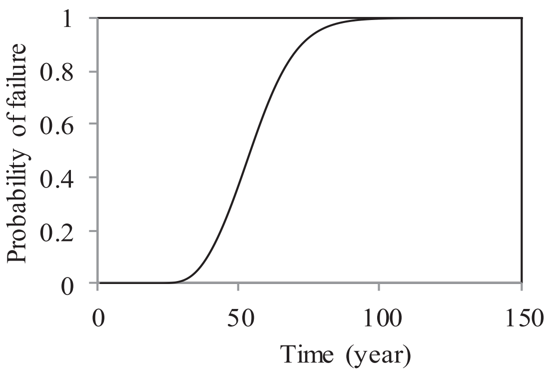

Fig. 6: P_f for pipeline section E

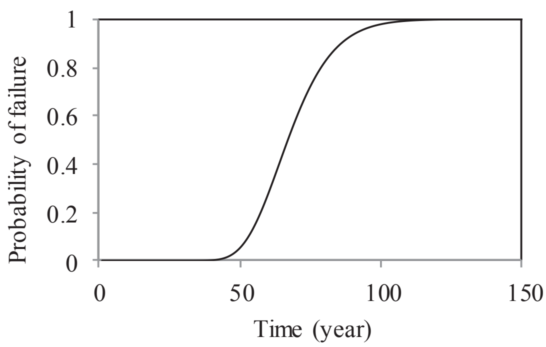

Fig. 7: P_f for pipeline section F

The study shows that on average the probability of pipe failure at the beginning is close to 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 failure rises drastically. Failure probability as shown in Fig. 2 – 7 has been used for the subsequent risk-cost optimisation for cases A – F.

5.2 Optimum renewal cost, time and priority

As shown in Eq. (4), 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 optimisation using GA. Figs. 8 – 13 show the best and mean convergence values of total LCC obtained from risk-cost optimisation by applying 150 generations in GA. The best value for each pipeline section is considered as the optimal LCC as shown in Tab. 8. The optimal LCC cost is associated with the first maintenance of the pipeline.

Next, the proposed maintenance strategy is extended to determine an applicable and feasible renewal method using Tabs. 2 – 4 [13]. The recorded database shows that the sanitary steel and ductile iron underground pipelines are built on clay and sand or sandy gravel. Based on this information and according to Tab. 3, the possibility of soil loss for sanitary underground pipelines is low for sections A and B whereas, for sections C – F, the possibility of surrounding soil loss is high. The *CI* for the underground pipeline network is estimated as shown in Tab. 8, using Eq. (8) by substituting the identified optimal time to renew from the risk-cost optimisation. Applicable renewal categories are then selected from Tab. 3 based on the *CI* and the possible scenario of soil loss.

It is obtained from the proposed risk-cost optimisation that the pipeline sections A, B and C are required to renew using non-structural or semi-structural lining method based on the estimated *CI* and low possibility of soil loss. On the contrary, due to high possibility of soil loss and $CI > 2$, the sections D and E are needed to renew using semi-structural or structural liners. Finally section F should be renewed with structural liners or replacement. Alternatively, replacement is recommended when the repair cost is greater than the cost of replacing the pipes.

Based on the underground pipeline's inventory information and alignment, the renewal assessment has been carried out considering all six major impact factors and results of the renewal priority based on the structural condition index and failure impact index as shown in Tab. 8. According to Tab. 8, the pipes which are in fair or minimal structural risk condition needs low renewal priority and on the other hand, pipe with highly structural risk condition requires immediate rehabilitation or replacement for safety of the network.

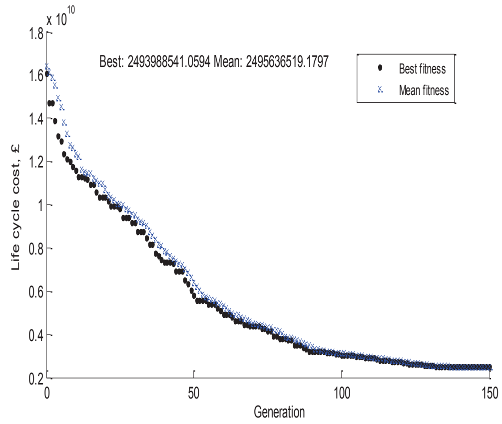

Fig. 8: LCC for pipeline section A from GA

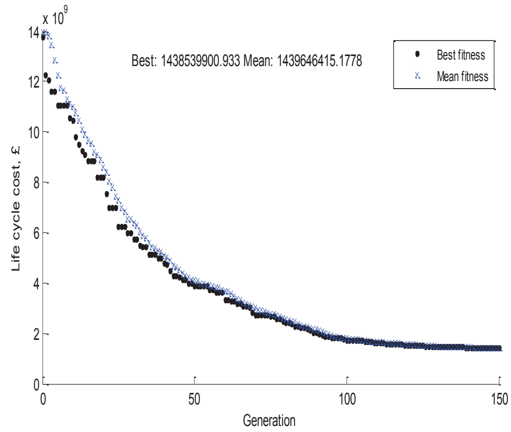

Fig. 9: LCC for pipeline section B from GA

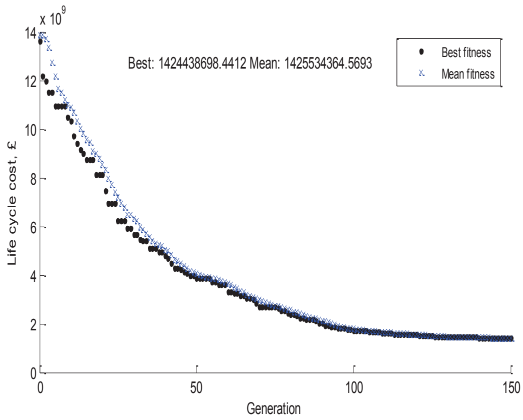

Fig. 10: LCC for pipeline section C from GA

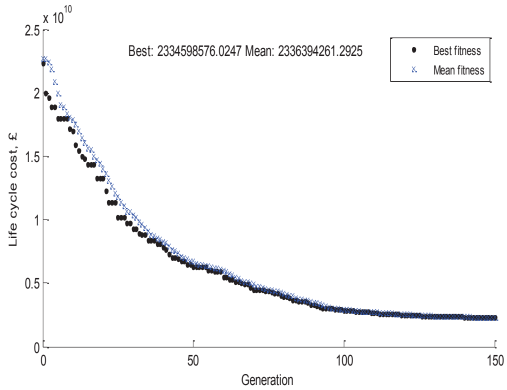

Fig. 11: LCC for pipeline section D from GA

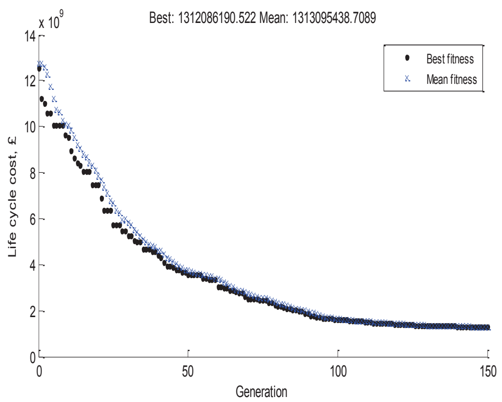

Fig. 12: LCC for pipeline section E from GA

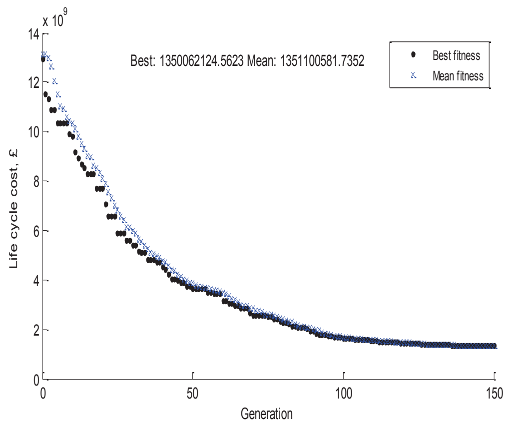

Fig. 13: LCC for pipeline section F from GA

Tab. 8: Results of pipeline network optimisation

Pipe section	Optimum Life cycle cost (£b)	Renewal time (year)	Structural Condition index (CI)	Renewal priority	Renewal methodology
A	2.4	62	2.2	Low, minimal structural risk	Semi-structural, structural
B	1.43	63	2.3	Low, minimal structural risk	Semi-structural, structural
C	1.4	66	2.25	Low, minimal structural risk	Semi-structural, structural
D	2.33	62	2.2	Medium, poor condition	Semi-structural, structural or replacement
E	1.3	72	2.5	Medium, poor condition	Semi-structural, structural or replacement
F	1.35	88	3.5	Immediate, high structural risk	Structural or replacement

6 Conclusion

This paper presents a novel approach for managing underground pipeline network. The proposed approach is integrated with two main criteria in the planning process: pipe reliability and life cycle cost. It follows that a rigorous decision process should find a balance between the risk of failure and the cost to mitigate it. The proposed management strategy also enables decision maker to select appropriate renewal methods based on the identified optimal time to renew, pipe condition index and the possibility of surrounding soil loss. Note that if historical data and current pipe thickness are available, then the real data can be used instead of corrosion model in the proposed approach to estimate pipe reliability and to determine the optimum management strategy. The proposed technique can help in making the appropriate decisions concerning the intervention to ensure the reliable and serviceable operation of the underground pipelines.

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