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Reliability-Based Maintenance Management Methodology to Minimise Life Cycle Cost of Water Supply Networks

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***Abstract*—**With a large percentage of countries' total infrastructure expenditure attributed to water network maintenance, it is essential to optimise maintenance strategies to rehabilitate or replace underground pipes before failure occurs. The aim of this paper is to provide water utility managers with a maintenance management approach for underground water pipes, subject to external loading and material corrosion, to give the lowest life cycle cost over a predetermined time period. This reliability-based maintenance management methodology details the optimal years for intervention, the ideal number of maintenance activities to perform before replacement and specifies feasible renewal options and intervention prioritisation to minimise the life cycle cost. The study was then extended to include feasible renewal methods by determining the structural condition index and potential for soil loss, then obtaining the failure impact rating to assist in prioritising pipe replacement. A case study on optimisation of maintenance plans for the Melbourne water pipe network is considered in this paper to evaluate the practicality of the proposed methodology. The results confirm that the suggested methodology can provide water utility managers with a reliable systematic approach to determining optimum maintenance plans for pipe networks.

***Keywords*—**Water pipe networks, maintenance management, reliability analysis, optimum maintenance plan

I. Introduction

THE water sector accounts for a nearly 10% of Australia's infrastructure industry. Billions of dollars are spent by the public and private sectors maintaining and upgrading Australia's water infrastructure [1]. The American Water Works Association [2] released a report detailing that more than one million miles of pipes are nearing the end of their useful life and in need of replacement. In a more recent report, the combined costs of pipe replacement and expected expansion has been reported to be more than US$1 trillion over the next 25 years [3]. Statistics from the Water Services Association of Australia [4] shows that due to aging water infrastructure, Melbourne has as many as 50 breaks per 100 km in 2009-10, compared to 22.4 in Adelaide, 28.4 in Sydney and 37 in Brisbane. According to the Australian Infrastructure Statistics [1] Australia has 318,731 km of water and wastewater networks (not including rural sewerage), which is estimated that US$0.46 billion per year is spent on scheduled upgrade of these networks, while a further US$ 0.14 billion per year is attributed to unscheduled rehabilitation in response to failures. The problem being investigated in this research is how to minimise the total life cycle cost (LCC) of a water network by optimising the pipe maintenance plan that takes into account structural risk factors.

In this study, risk is taken into account by estimating pipe reliability (and/or probability of failure), the optimal time to minimise the risk and prevent unexpected failures of pipes subject to external loadings and pipe material degradation can eventually be estimated.

Due to budget limitations, systems must be set in place to prioritise repair and replacement of water pipes at the optimal time. While models to find the optimal maintenance method for water pipelines are still in their infancy when compared to other major infrastructure sectors such as civil engineering structures including bridges and buildings, the optimum design approaches for pipe structural systems are continuously being refined and evolved [5].

The structural calculations for this research are for a mild steel (flexible) underground main drain water pipe in a residential area, the water is travelling by gravity and therefore there is no internal pressure on the pipe. The reliability with respect to time due to corrosion induced excessive deflection, ring bending strain and buckling will be estimated. These failure modes are considered in the Australian Standards AS2566.1 [6], as the primary modes of failure for underground flexible pipes. Methods of probabilistic reliability analysis, such as, First Order Reliability Method (FORM), Second-Order Reliability Method (SORM), First Passage Probability and Monte Carlo simulation (MCS), are readily available in literature [7] and [8]. The FORM method will be used in this study to predict the reliability of pipelines due to above-mentioned time-dependent multiple failure cases. The central focus of a pipe reliability based management strategy is typically to ensure that life cycle costs are minimised while achieving required performance and reliability. Currently, various optimisation methodologies are used in literature, such as Genetic Algorithm (GA), Fuzzy Set Method (FSM), Ant Colony Optimisation Approach (ACOA), Shuffled Frog Leaping Algorithm (SFLA), Linear Programming (LP) and Dynamic Programming (DP) [9]. It is commonly believed that there is no available solution technique that can provide 100% guarantee to minimise the total risk and cost, therefore this research will employ a

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systematic approach to minimising the LCC of an underground pipe in a network.

To optimise the maintenance plan for the pipe in question an objective function, which aims to minimise total life cycle cost, has been determined that sums the total cost of maintenance activities and pipe replacements over a 300 year period. It uses the probability of failure as a constraint where if the Pf is above an acceptable level then an intervention activity must occur. This information will determine which maintenance plan will have the lowest life cycle cost over 300 years. After the optimal maintenance plan has been selected, a systematic process to determine feasible renewal methods and prioritisation is conducted.

II. Pipe Service Life and Failure

In recent decades there have been many attempts in literature to relate the likelihood of water pipe failure to the characteristics of the pipes and environmental conditions. In practice, it can be difficult to determine the condition of underground pipes as the buried infrastructure is concealed below the surface and are subjected to different and changing corrosion processes [10].

Rostum [11] suggests that factors that affect the likelihood of water pipe failure include the pipe material, the year it was installed, corrosion, diameter, length, soil conditions and nearby activity such as construction. The most common factors which influences the pipe failure most are pipe leaking, blockage, excessive deflection, buckling, wall thrust or stress, bending stress and bending strain, etc. [12]. Kleiner and Rajani [13] state that pipe failure is most likely to occur when there is a combination of environmental and operational stresses acting on a certain part of the system that has been adversely effected by material corrosion, changing environmental conditions, poor tradesmanship or engineering flaws. Fitzgerald [14] stated that precise and thorough crack and failure reports need to be provided to help establish effective methods of failure reduction, however as leak and failure data is rarely recorded, it is therefore difficult to determine how certain pipes failed in the past [15]. Common variables involved in deterioration process of water systems, can be grouped into structural, environmental, hydraulic and maintenance [11].

Pipe Material: The material of water pipes is the most important factor in regards to a pipe's strength, specifically its ability to resist internal and external loads. The material of pipe determines how effective a pipe is at resisting corrosion. Kettler and Goulter [16] investigated the correlation of certain pipe materials and their rates of failure and how the pipes failed, for example, longitudinal split, joint, or circumferential failure.

The highest percentage of pipe systems in the world are made up of flexible pipes including cast iron, ductile iron and mild steel, these pipes also have the longest existing failure records, with typical rates of 39 breaks per 100 kms in Canada [17]. Makar [18] suggests that due to being installed in from 1870s to the early 1970s this is partly due to the age of the pipes. However, cast irons brittle nature and proneness to corrosion is the primary causes of failure. Many researchers have focused on analysis of failures of grey cast iron pipes [8], [15].

Corrosion: Corrosion is the foremost factor in the deterioration of iron pipes [19] and has a detrimental effect on many types of pipe materials including concrete. O'Day [20] stated that galvanic corrosion is the principal reason for the external deterioration of iron pipes. Galvanic corrosion causes the pipe to crack part way through letting water escape. If undetected, a second or third cracking occurrence can take place, this process will continue until the leak is identified or that the water pipe fails completely [21]. Tee et al. [12] state that the effect corrosion has on the excessive deflection, buckling, wall thrust and bending is significant in the failure of flexible buried pipes. However, additional wall thickness, linings and external coatings that are thought to protect pipes from corrosion have been proven to be ineffective where pipes are joined together [18]. Karaa and Marks [22] stated that unlike internal corrosion, external corrosion is a vital factor to incorporate into predictive models as its strength changes from pipe to pipe as soil conditions vary.

Pipe Diameter: Throughout literature it is agreed that there is an undesirable correlation between failure rate and diameter of the pipe [16], [23]. Due to reduced pipe strength, reduced wall thickness and less reliable joints, smaller pipes have a higher frequency of failure [16]. Rajani and Tesfamariam [15] found that the growth rate of a single corrosion pit is almost certainly more detrimental to small diameter pipes than those with a large diameter. Additionally in another study, [24] concludes that the impact of external loads has a greater effect on large diameter mains while soil loss in bedding support adversely affects small diameter pipes more. In a study on Australia utility company pipes, Rajeev et al. [25] found that pipes with a smaller diameter a more prone to longitudinal bending induced circumferential failures while larger diameter pipes experience mainly longitudinal cracking and shearing due to higher water pressure.

Pipe Length: Soil bedding and external loads can differ along the length of a long pipe, and therefore a longer pipe is possibly subject to changing conditions. However, Skipworth et al. [26] suggest that pipes with a shorter length may demonstrate higher failure rates, as there are more connections in the network, as the joint is considered a point of weakness.

Pipe Age: Early examples in literature conclude that there isn't a proven relationship with pipe failure and its age [20]. However, in later studies Kettler and Goulter [16] found that there was a relationship between the age of a pipe and its rate of failure. Goulter and Kazemi [27] later argue that age should not be the single factor used for evaluating the pipe condition. In a quantitative study of performance of water distribution systems, Butler and West [28] reported that average leakage figures in water network systems in the U.K. with an age of 50 years, was about 30%. This same measure for two water distribution systems in Germany and three in Holland, with average system age of 20 and 25 years, were in the range from 2% to 15%.

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III. Reliability Analysis of Buried Pipes

Reliability analysis is a method to determine the probability of pipe failure. These methods have become readily available in literature; however, it is still a rather theoretical practice for utility managers as conditions for different pipes in a network can vary drastically. A pipe network may have different soil conditions, groundwater level, failure rates and external loadings and therefore should be separated into specific segments for a reliability analysis [29].

The most common causes of pipe failures in Australia are attributed to excessive ring deflection, ring bending strain and pipe buckling; this is due a depletion of physical strength attributed from loss of pipe thickness [30]. For mild steel pipes this reduction in thickness is cause by corrosion making the pipe more susceptible to failure caused by external pressures applied by the soil and loads from the surface. A failed pipe can have disastrous consequences, possibly causing property damage, loss of water and even death, this is why performing maintenance or replacing a pipe before it fails is so essential. In the literature, a shift has been made from bulk pipeline maintenance plans to scheduling maintenance for individual pipes that are predicted to be reaching an unsafe condition and intervene before failure.

Due to the uncertainty associated with soil and steel properties and corrosion factors, a probabilistic approach can be employed for the analysis of pipeline reliability. In this approach certain parameters are treated as random variables and the different failure criteria are expressed in a probabilistic manner as a probability of failure [31]. First Order Reliability Method (FORM) will be used in this study to estimate the structural reliability of flexible buried pipes to predict the probability of failure for different failure modes, specifically, corrosion induced deflection, ring strain and buckling.

Corrosion of flexible buried metal pipes: Underground flexible pipelines undergo differing amounts of corrosion due to destructive soil conditions based on specific material properties, corrosion is the most common form of structural deterioration for pipes, and needs to be mitigated as much as possible [32]. Corrosion results in the loss of nominal pipe wall thickness overtime, however this rate is not constant over the entire service lifespan of the pipe. The initial rate of loss is high due to the material being porous and having poor protection properties [32]; however, Sadiq et al. [33] proved that corrosion appears to be a self-inhibiting process and therefore slows down over time. While corrosion is rarely uniform over the entire pipe, producing deep corrosion pits, for this study corrosion will be assumed to be uniform and time dependent. Kucera and Mattsson [34] proposed a widely accepted power law corrosion model, determining the pit depth over time, which can be expressed as:

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

where Dt is pit depth, T is exposure time, k is the multiplying constant and n is the exponential constant, these constants are random variables obtained from tests and site data that can be used as an approximate value only [32].

Excessive ring deflection: Ring bending stiffness (SD) is an indication of a pipes ability to resist deflection [6]. Ring bending stiffness has an influence on the deflection, strain and buckling performance of a buried flexible pipe, and can be calculated by:

$$\mathrm{SD} = \frac{EI}{(D-t)^2} \times 10^6 \tag{2}$$

$$\mathrm{I} = \frac{(t-D)^3}{12} \tag{3}$$

where SD is the ring bending stiffness, D is outside diameter, t is pipe thickness, E is the random variable for Young's modulus of mild steel and I is the 2nd moment of inertia which changes with pipe thickness [6]. However, flexible pipes become unsafe when they deflect past the critical long-term vertical pipe deflection (Δy_{cr}), which according to [6], for non-pressure pipes is 5%. A flexible pipes ability to support load is typically assessed by measuring the deflection from its initial shape, deflection can be defined as the change in diameter that results from an applied load [12]. To calculate deflection the Australian Standards use a further modified form of Watkins, modified Iowa formula that uses the ring bending stiffness (2) in the denominator, the formulation for vertical deflection can be expressed as:

$$\Delta y = \frac{K \times 10^3 (w_g + w_{gs} + w_q) D}{8 \times 10^{-6} \times SD + 0.061 \times E'} \tag{4}$$

where Δy is the pipe vertical deflection, K is bedding constant, w_g is dead load due to soil = γH, where γ is the random variable for weight of soil and H is height of soil above pipe, w_{gs} is superimposed dead load, w_q is load intensity and E' is the soil modulus [6].

Ring bending strain: Deflection of the pipe results in ring-bending and ring-compression strains. Ring-compression strains are generally small compared to ring-bending strains (ε_b) and therefore have not been considered in this reliability analysis, ring-bending strain can be calculated with [6]:

$$\varepsilon_b = \mathrm{Df}\left(\frac{\Delta y}{\mathrm{D}}\right)\frac{\mathrm{t}}{\mathrm{D}} \tag{5}$$

where ε_b is the predicted long-term ring bending strain. According to the Australian Standards critical ring-bending strain (ε_{bcr}) for a pipe with t > 8mm is 0.001208.

Equation (5) shows that for a given deflection and pipe diameter, ring-bending strain increases linearly with pipe wall thickness. The shape factor (Df) adjusts strain values to account for pipe ring shape, where pipe ring shape is an ellipse; the shape factor is approximately 3 and can by calculated as [6]:

$$\mathrm{Df} = \frac{3.33 \times 10^{-6}\left(\frac{\mathrm{SD}}{\mathrm{E'}}\right) + 0.00136}{1.11 \times 10^{-6}\left(\frac{\mathrm{SD}}{\mathrm{E'}}\right) + 0.000151} \tag{6}$$

where Df is the shape factor.

Pipe buckling: External loads lead to pipe wall

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compression and buried pipes have a tendency not only to become oval, but also to buckle. Unless this tendency to buckle is checked, satisfactory values for deflection and ring-bending strain do not themselves indicate the design is satisfactory. The total actual buckling pressure (q_b) must be less than the critical buckling pressure (q_{cr}). The calculations for actual and critical buckling pressure are as follows [6]:

$$q_b = \gamma(H - Hw) + (\gamma L + 0.623\gamma\left(\frac{D}{2}\right) + w_{gs} + w_q \quad (7)$$

where qb is the pipe buckling pressure, Hw is the height of water and γ_L is the density of water.

$$q_{cr} = (SD \times 10^{-6})^{\frac{1}{3}} (E')^{\frac{2}{3}} \times 10^3 \quad (8)$$

where q_{cr} is the allowable buckling pressure.

Probabilistic reliability analysis: There are many widely accepted forms of probabilistic reliability analysis including First Order Reliability Method (FORM), Second Order Reliability Method (SORM), Monte Carlo simulation (MCS) and Hasofer-Lind and Rackwitz-Fiessler algorithm (HL-RF), for this study FORM will be used for determining structural dependability of underground mild steel pipes.

The fundamental purpose of probability based infrastructure design is to determine whether a structural member satisfies multiple performance criteria while considering the uncertainties in the relevant related random variables [35]. The association among the basic random variables and deterministic constants is known as the limit state function Z(X). For this study the limit state functions will be determined from the failure modes previously discussed (deflection, ring strain and buckling.) The limit states for underground flexible pipe failure are as follows:

$$Z(X) = \Delta y_{cr} - \Delta y \text{ (deflection)}$$
$$Z(X) = \varepsilon_{bcr} - \varepsilon_b \text{ (bending strain)}$$
$$Z(X) = q_{bcr} - q_b \text{ (buckling)}$$

where Δy_{cr}, ε_{bcr} and q_{bcr} are the critical values and Δy, ε_b, and q_b are the actual values for pipe deflection, ring-bending strain and buckling.

The probability of failure (P_f) for each limit state can be calculated using:

$$P_f = P[Z(X) < 0] = \Phi\left[\frac{0-\bar{Z}}{\sigma(Z)}\right] = \Phi(-\beta) \quad (9)$$

where Z(X) is the limit state, the mean $\bar{Z}$ and standard deviation σ(Z) are a function of the random variables which are soil and pipe material properties. ϕ is the cumulative standard normal distribution function and β is the reliability index [12]. The standard deviation of a structural function can be difficult to determine, therefore an approach is to find the square root of the variance ($\sqrt{\text{Var}}$) of the function. This can be determined as [36]:

$$\sigma(Z) = \sqrt{\text{Var}(Z)} \quad (10)$$

$$\text{Var}(Z) = \sum_i^n \sum_j^n C_i C_j \text{ cov}(Xi,Xj) \quad (11)$$

where $C_i = \frac{\partial Y}{\partial X}|\mu_{x1}, \mu_{x2}, \ldots, \mu_{xn,}$. If the X_i are independent, $\text{cov}(X_i, X_j)=0$, if $i \neq j$ and $\text{cov}(X_i, X_j)= \text{Var}(X_i)$ if i=j. Therefore the variance of the limit state can be calculated by:

$$\text{Var}(Z) = C1^2 \text{ Var } \mu 1 + C2^2 \text{ Var } \mu 2 + \cdots Cn^2 \text{ Var } \mu n \quad (12)$$

As discussed previously a pipe can be described as a series system model. The probability of failure for a series system ($P_{f,s}$) can be estimated as:

$$Max[P_{f,i}] \leq P_{f,s} \leq 1 - \prod_{i=1}^{n}[1 - P_{f,i}] \quad (13)$$

where $P_{f,i}$ is the probability of failure due to the ith failure mode of, deflection, ring strain or buckling and n is the number of failure modes, which is this case is 3.

IV. Risk Cost Optimisation

The proposed approach detailed in this study defines a systematic procedure to assess the risk of failure, optimise the total life cycle cost and determine feasible renewal options that aid in reducing the subjective and sometimes-reactionary techniques employed by water utility companies. The problem is treated as a multi-objective problem focusing on minimising cost while considering risk constraints.

The optimal life cycle cost can be determined on a spread sheet program such as excel, where after determining the year at which the probability of failure passes a level deemed to be unacceptable, maintenance is performed and the pipe is rehabilitated to a percentage of its original state. Therefore the interval between maintenance activities becomes shorter, and it can be determined graphically the optimal number of maintenance activities before replacing the pipe, that gives the lowest life cycle cost over an extended period involving multiple pipe replacements.

The basis of this study is to determine the optimal number of maintenance activities to perform on a selected pipe in a network before replacement to minimise the objective function, which in this case is total life cycle cost (LCC) over a specified time frame. The LCC of a structure includes the sum of the maintenance costs and replacement costs over the specified time period. The optimal time to perform an intervention activity is when the probability of failure (9) determined from the reliability analysis becomes equal to or above an acceptable level. The USA Army Corps of Engineers suggested acceptable values for probability of failure, with a reliability index (β) of 3 for above average performance and 4 for good performance [37]. This study will use a reliability index of 3 as an acceptable level for probability of failure. The objective function - total life cycle cost (C_{LCC}) can be calculated as:

$$C_{LCC}(T) = \sum_{i=1}^{T} Cm(i) + \sum_{i=1}^{T} Cr(i) \quad (14)$$

If $P_f \geq P_{f,a}$ – perform intervention activity where Cm is

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maintenance cost, Cr is replacement cost, i = 1, 2, 3, … T year, and $P_{f,a}$ is acceptable probability of failure. The terms on the right side of (14) are the costs in the year they actually occur therefore the costs need to be converted into present values by the equation $(1+r)^T$. Where r is the discount rate and T is the year of intervention. The discount rate depends on the inflation rate and depreciation of money.

Life cycle cost: Life cycle cost is an assessment method for asset management optimisation. Taking into account all the costs involved, in not only a single pipes service life but the costs of maintaining and replacing a pipe in a network for an extended period of time. With having an estimate of the optimal intervention year from the reliability analysis, asset managers can determine a maintenance and replacement strategy that minimises the LCC over a predetermined time period, for this study 300 years was used.

Maintenance cost: Maintenance cost is determined for an underground pipeline by determining the future value of each maintenance activity performed on the asset over the predetermine time period. To determine the maintenance cost, this research will use a regression model determined by [38], which took into account 2526 records of pipe repair data in Australia between 2000 and 2010. Maintenance cost can be calculated as:

$$Cm = a + b \times D^c + d \times u^e + f \times D \times u \qquad (15)$$

where the parameters of the repair cost are as presented in Table I.

TABLE I
PARAMETERS FOR REPAIR COST [38]

Material of Pipe	a	b	c	d	e	R^2
AC, CICL, DICL, UPVC	877.201	0.066	1.849	0.233	-0.146	0.99
MSCL	659.143	0.023	2.063	-0.002	19.399	0.89

where D is the pipe diameter, and the decision variable u is the depth of the pipe where '1' indicated a depth of ≤1.5m, and '2' indicated depth > 1.5m, a, b, c, d, e and f are coefficients estimated using the regression model. Where if u is the independent from D, f is equal to 0.

Replacement cost: The replacement cost includes the cost of the pipe itself plus the cost of installation. The installation cost would include all aspects of the works, including design, pipe and reinstatement materials, installation and removal costs (plant & equipment), traffic management, project management, contractor profit and overheads.

The replacement costs used in this research have been obtained from costs used in a similar job completed by a Tier 1 Australian construction company in the year 2015. The cost for replacing one pipe was equal to US$140,226.

V. Selection and Prioritisation of Renewal Methods

Performing maintenance on underground pipelines is essential to prolonging service life before replacement, however if maintenance activities become too frequent then it may become more economical to replace the pipe. Buried pipeline renewal methods can be grouped into four main categories: replacement, structural, semi structural and non-structural lining methods [2].

The Water Resource centre [39] suggested a simple procedure to determine renewal methods taking into account the condition index and the possibility of soil loss. The structural condition index (CI) for an underground pipeline can be calculated from regression on available data set. As per data set given in [29], structural condition index can be calculated by:

$$CI = 0.0003T^2 - 0.000T + 1 \qquad (16)$$

where T = age of the underground pipeline (in year) which corresponds to the intervention year obtained from the risk-cost optimisation. The year (T) will be the intervention year determined from the reliability analysis.

Determining soil loss is important as losing soil underneath and surrounding the pipe can increase its likelihood to failure. The potential for soil loss can be calculated from the following table, which takes into account the level of groundwater and type of soil.

TABLE II
SOIL LOSS TABLE [39]

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

After the condition index and possibility of soil loss have been calculated the following table details the most likely applicable renewal method. As this study is focusing on a gravity main drain, semi-structural liners are not considered [39]. This renewal method table is not a guaranteed method of how the pipe will be renewed as each scenario will be different, however it gives the user a good estimate before they inspect the pipe on the given intervention year.

TABLE III
ESTIMATED RENEWAL METHOD [39]

Condition 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

VI. Impact Assessment and Prioritisation

For a series of pipes in a network many pipes may have the same structural condition index and soil conditions; however, they may not have the same likelihood of failing or the same consequence of failure. Therefore to determine which pipes have a higher priority to replace, the weighted impact factor (I_w) and failure impact rating (R_{imp}) can be determined.

The weighted impact factor (I_w) takes into account six major factors to rank the impact of an underground pipes

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failure on the local community. The formulation for impact factor is as [40]:

$$I_w = 0.2f_l + 0.16(f_s + f_z + f_d + f_f + f_q) \quad (17)$$

where each factor is given a rank between 1 and 3, 3 having a high degree of impact where 1 will have minimal impact. All factors in (17) are defined as follows:

1. Location factor, f_l: Impact based on how the location of the failed pipe would impact the local community and environment. Factors taken into account are land use, traffic intensity, access for repair, or close to critical establishments.
2. Soil factor, f_s: Soil support factor where silts and sands are rated 3 where as high plasticity clays are safer at 1.
3. Pipe size factor, f_z: A pipe with size less than 900 mm is given a low rating 1 while greater than 1800 mm are given a 3.
4. Buried depth factor, f_d: The deeper a pipe is buried the more difficult it is to assess its condition, a low rating of 1 is for pipes buried less than 3 m and a rating of 3 for pipes deeper than 10 m.
5. Functionality factor, f_f: This factor depends on what function the pipe has, whether it is a water or waste water pipe and the location of the pipe. For example a pipe entering a treatment facility is more critical than a drain pipe.
6. Seismic zone factor, f_q: Based on an areas level of seismic activity where a low seismic area such as Melbourne is rated a 1 and a high seismic area is rated a 3.

The weighted impact factor will give a failure impact rating (R_{imp}), as presented in Table IV.

TABLE IV
WEIGHTED IMPACT FACTOR – FAILURE IMPACT RATING [39]

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

TABLE V
RENEWAL PRIORITY [39]

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

Once the failure impact rating has been determined it can be combined with the structural condition index to give a guide for renewal priority to aid the decision making process in Table V.

VII. APPLICATION OF THE METHODOLOGY

The case study used in this research has been based on a newly instated pipe in a network on a suburb of Melbourne in Australia. The new pipe is a DN1150 MSCL (Mild Steel Cement Lined) buried under standard residential road load conditions. According to the Australian Soil Resource System (ASRIS) the soil in the area is medium clay.

The purpose of this study is to determine a maintenance strategy that provides the service owner with the optimal number of times to perform maintenance on the DN1150 MSCL pipe before replacement, to minimise the total life cycle cost C_{LCC} over a 300-year period. This process involves determining the combined series of probability of failure for each failure mode, an intervention year is then determined at the point where the probability of failure exceeds an acceptable limit, which was advised by the USA Army Corps of Engineers, will be taken as a reliability index of 3 for above average performance [37]. The pipe is then repaired to a certain percentage of its original state, for this study 70% is used, as there has been no research performed in this area and it is a conservative figure. With each maintenance activity the time between intervention periods becomes shorter and replacement becomes a more realistic alternative. The life cycle cost for this research is not only for one pipes service life but the combined costs of all the maintenance and replacements over a 300 year period. After determining the optimal number of maintenance activities before replacement to give the lowest life cycle cost, the renewal method and prioritisation can be established. As previously described this research will use the Water Resource centres [39] method for estimating a feasible renewal method and prioritising pipe maintenance and replacement.

VIII. RESULTS AND DISCUSSION

The pipe is a thin walled DN1150 mild steel cement lined (MSCL) pipe with 1200 mm outside diameter (OD), 10mm thickness (t), buried in a 2.941 m trench. There are 5 random variables taken into account for this research, the soil and pipe material properties and corrosion constants, these are; soil density (γ_s), soil modulus (E') and Young's modulus of elasticity of steel (E), these values were obtained from the study conducted by [37]. The corrosion constants were acquired from [32] suggesting the use of values for multiplying constant (k) and exponential constant (n). The deterministic values were taken from the Australian standards [6] and manufacturers standards [30].

The probability of failure for the limit states due to corrosion induced deflection, ring bending strain and buckling with respect to time have been predicted using FORM method based on the parameters and basic random variables in Tables VI and VII. The results (Figs. 1-4) indicate that excessive ring bending strain is by far the most critical failure mode where as buckling has the lowest probability of failure, this is due to the plastic nature of flexible pipes. The occurrence of any failure

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mode will constitute as a failure of the system. Therefore the probability of failure will be determined using (13) and the result is shown in Fig. 4.

TABLE VI
PARAMETER VALUES FOR DETERMINISTIC VARIABLES

Description	Value
Deflection constant, K	0.1
Depth of pipe, H	2.941m
Vertical design load due to surface dead load , wgs	0.58 kPa
Vertical design load due to surface live load, wq	8 kPa
Outside pipe diameter, D	1.2m
Height of water, H_w	1.2m
Density of water, γ_L	9.81 kN/m

TABLE VII
STATISTICAL PROPERTIES OF RANDOM VARIABLES

Material Properties	Mean (μ)	Cov (%)	Distribution
Soil density, γ_s	18 kN/m^3	1	Normal
Soil modulus, E'	1 mPa	5	Normal
Steel modulus, E	210×10^6 kPa	1	Normal
Multiplying constant, k	0.066	56.1	Normal
Exponential constant, n	0.53	26.4	Normal

Considering a probability of failure with a reliability index of 3 as the acceptable limit for safe service life [37], the first maintenance intervention was determined to be 55 years after pipe installation.

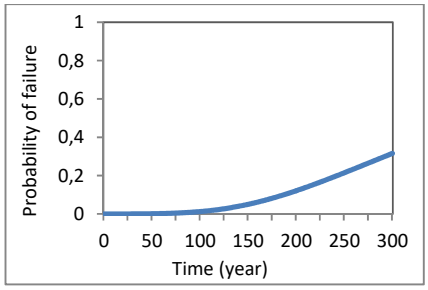


Fig. 1 Probability of failure due to corrosion induced deflection using FORM

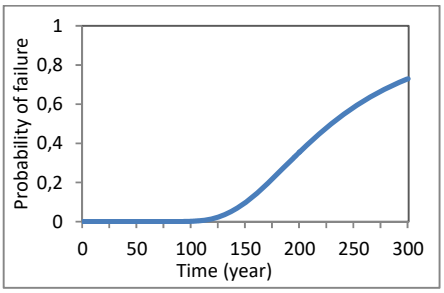


Fig. 2 Probability of failure due to corrosion induced ring-bending strain using FORM

Maintenance plan: In this study there were 4 scenarios used, 1, 2, 3 and 4 maintenance activities before a pipe is replaced. These were named maintenance plans 1, 2, 3 and 4, respectively. As previously discussed the first intervention year was when the series system probability of failure reached the unacceptable level, maintenance was then performed and the pipe was instated to 70% of its original strength, therefore shortening the period before the next intervention. As shown in (14), the total LCC is the sum of the maintenance activity costs and replacement costs over a total service period, for this study 300 years was used to give a more accurate representation of the maintenance strategy over a longer time period with multiple pipe replacements.

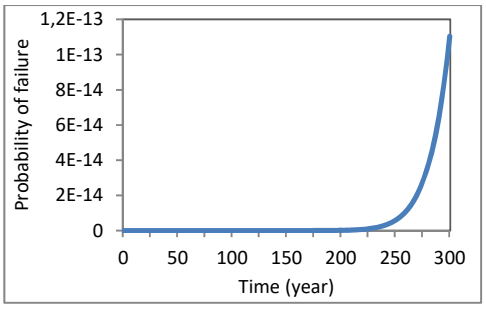


Fig. 3 Probability of failure due to corrosion induced buckling using FORM

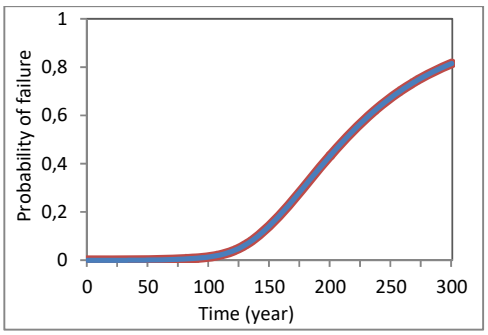


Fig. 4 Series system probability of failure

As Fig. 5 shows, two maintenance activities, named maintenance plan 2, before pipe replacement gives the lowest LCC, a total of $ 554 million over the 300 year period, this value may seem high, however it has been converted into present value using the equation $(1+r)^T$ taking the discount rate (r) as 3% [41]. This can be observed graphically in Fig. 6. Based on this maintenance strategy Table VIII depicts the maintenance and replacement schedule including the present value cost.

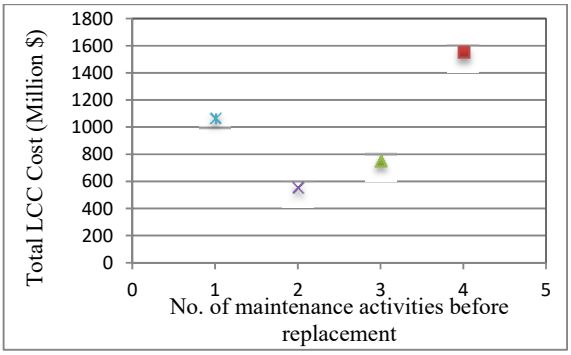


Fig. 5 Total life cycle cost

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TABLE VIII
INTERVENTION SCHEDULE – MAINTENANCE PLAN 2

Year	Activity	Cost (Million $)	Sum (Million $)
2015	Initial Cost	0.14	0.14
2070	Maintenance	0.24	0.38
2109	Maintenance	0.76	1.14
2136	Replacement	5.01	6.16
2192	Maintenance	8.86	15.02
2231	Maintenance	28.07	43.09
2258	Replacement	184.62	227.71
2314	Maintenance	326.38	554.09

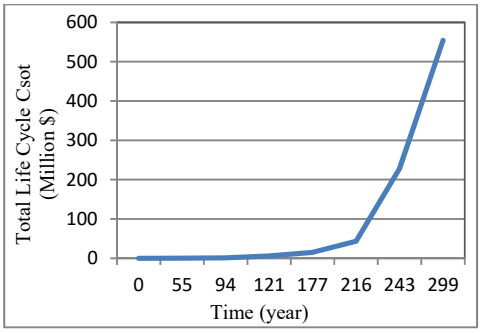


Fig. 6 Total LCC curve – Maintenance plan 2

Asset renewal method and prioritisation: After the maintenance plan is determined the study is extended to determine an appropriate and feasible renewal method for the intervention activities up until the first replacement. It was determined from ASRIS that the area is predominately clay based, and due to there being no information available on ground water level it was assumed to be at the same line as the pipe. Based on these details it was determined that the possibility of soil loss was medium and combined with the condition index a proposed renewal method was given, this can be viewed in Table X.

The rehabilitation methods for a gravity main drain can be classified as:

Non structural – used for pipes not under hydrostatic load, involves a non structural liner to improve flow, resist corrosion or to seal minor cracks on pipe surface.

Structural – A structural liner, capable of carry soil and live loads and is independent to the pipe itself, therefore bonding is not required [42].

After a renewal method is selected the weighted impact factor (I_w) can be determined using (17) with the factors from Table IX, this will give a failure impact rating (R_{imp}) from Table IV and then substituted into Table V to give the renewal priority. The underground pipe renewal method and priority is summarised in Table X.

TABLE IX
WEIGHTED IMPACT FACTORS

f_l	2
f_s	1
f_z	2
f_d	1
f_f	2
f_q	2

TABLE X
RENEWAL METHOD AND PRIORITY SUMMARY

	Year	CI	Soil loss	Implication	Method	R_{imp}	Renewal Priority
Maintenance 1	55	1.9	Med	Fair condition, minimal risk	Non Structural	3	Low
Maintenance 2	94	3.6	Med	Poor condition, moderate risk	Structural	3	High
Replacement	121	5.8	Med	Failure imminent	Replacement	3	Immediate

Parametric Study: A parametric study has been carried out to analyse the effects of using a different percentage of reinstatement strength after performing maintenance. As there has been no study that has determined the percentage of a rehabilitated pipes strength compared to its original state, this parametric study will give utility companies two more options of maintenance plans. The life cycle cost optimisation was performed using pipe reinstatement strength percentages of 90% and 50% and the results and maintenance plans have been determined (Tables XI and XII).

TABLE XI
INTERVENTION SCHEDULE – 90% - MAINTENANCE PLAN 4

Year	Activity	Cost (Million $)	Sum (million $)
2015	Initial install	0.14	0.14
2070	Maintenance	0.24	0.38
2120	Maintenance	1.06	1.44
2165	Maintenance	3.99	5.43
2205	Maintenance	13.02	18.44
2241	Replacement	111.70	130.14
2297	Maintenance	197.47	327.60

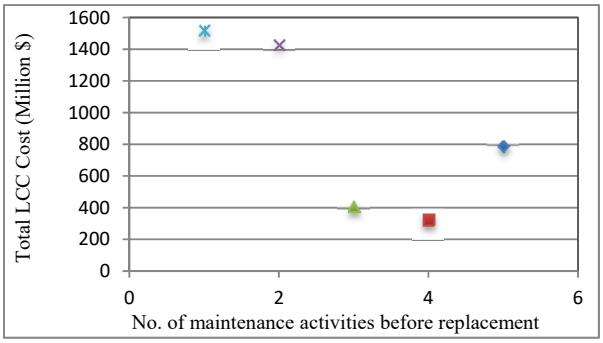


Fig. 7 Total life cycle cost – 90% reinstatement strength

As Figs. 7 and 8 show, with a reinstatement percentage of 90% the optimal approach is to perform maintenance 4 times before replacement as the pipe has a longer service life between needing rehabilitation. However a period of longer than 300 years for this reinstatement strength would give a more accurate representation as maintenance plan 1 and plan 2 are outliers. A pipe with a reinstatement strength percentage of 50% obviously has the highest life cycle costs due to needing

to be replaced more often, and the total life cycle cost graph shows that it is cheapest to only perform maintenance on the pipe once before replacement.

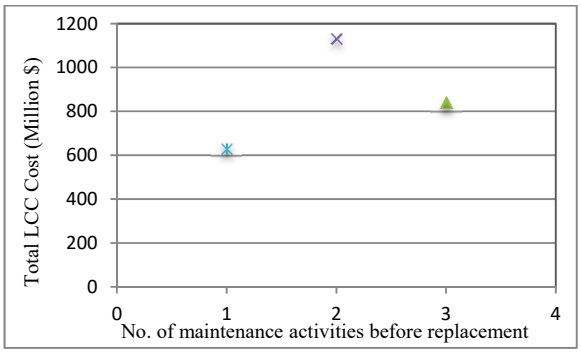


Fig. 8 Total life cycle cost – 50% reinstatement strength

TABLE XII
INTERVENTION SCHEDULE – 50% - MAINTENANCE PLAN 1

Year	Activity	Cost (Million $)	Sum (Million $)
2015	Initial Install	0.14	0.14
2070	Maintenance	0.24	0.38
2098	Replacement	1.63	2.01
2154	Maintenance	2.88	4.89
2182	Replacement	19.53	24.42
2238	Maintenance	34.52	58.94
2266	Replacement	233.87	292.81
2315	Maintenance	336.17	628.98

IX. CONCLUSION AND RECOMMENDATIONS

This research presents a systematic approach to determining the optimal maintenance plan for an underground flexible pipe. The approach used has two main components, firstly to determine the structural reliability of the pipe, then to determine the life cycle cost of each proposed maintenance plan. The structural reliability was determined by calculating the probability of failure due to corrosion-induced deflection, ring bending strain and buckling. The probability of failure was calculated by determining the reliability index using limit state functions obtained from the Australian Standard for Buried Flexible Pipelines [6]. The maintenance plan is the number of times that a pipe is rehabilitated before it is replaced and this was optimised by determining which plan has the lowest life cycle cost. To aid the asset manager further, based on the optimal intervention time, structural condition index and the possibility of soil loss, appropriate and feasible renewal methods and pipe prioritisation have been determined.

The case study used in this research has been based on a newly instated pipe in a network on a suburb of Melbourne in Australia. It was determined from the reliability analysis that the pipe will require maintenance after 55 years in the year 2070 and the renewal method will be a non structural lining. Under the assumption that the pipe will be reinstated to 70% of its original condition, the next intervention year will be 94 years after it was first installed in the year 2109, and it is estimated that the pipe will need a structural lining. Maintenance plan 2 was determined to have the lowest life cycle cost therefore it will be replaced for the first time in the year 2136, 121 years after it was installed. The total life cycle cost after 300 years for maintenance plan 2 is $554 million; this value has been calculated to its present value in the year 2314. A parametric study was undertaken using different values of percentage of reinstatement strength, 90% and 50% were used to give the decision maker some additional guides to maintenance plan selection.

The limitations of this research are as follows:

1. The corrosion constants, multiplying constant k and exponential constant n are highly uncertain and are typically determined from a regression analysis and data from specific soil conditions.
2. The random variables used in the study were kept to pipe and soil material variables; however, it would be more accurate to assume more of the deterministic constants were random such as pipe height.
3. Predicting future costs is not straight forward as inflation rate will change over time, and therefore having a constant discount rate is not ideal.
4. It was assumed that the pipe would be reinstated to 70% of its original strength after rehabilitation works; this value is extremely dependant of tradesman craftsmanship and soil conditions and therefore it is a conservative estimate.

It is hoped that the proposed methods for determining an optimal maintenance plan will assist utility managers in their decision-making however some recommendations for future research are as follows:

1. Determine a more accurate method for determining the percentage of strength of a rehabilitated pipe compared to its original strength.
2. Develop an automated tool to implement the developed risk cost optimisation procedure in the research, to allow utility managers to determine optimal maintenance plans for multiple pipes with ease.

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