Predicting the Time-variant Probability of Failure for Concrete Sewer Pipes

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ABSTRACT

Millions of dollars are being spent worldwide on the repair and maintenance of sewer networks and wastewater treatment plants. Approximately 40% of the damage in concrete sewers can be attributed to biogenous sulphuric acid attack, which causes severe structural deterioration and ultimate structural collapse. In some cases, it is difficult or not cost effective to design a sewer pipeline system that will be free of sulphide problems. It is then useful to know what levels of deterioration of sewer pipe can be expected during its service life. The major determining factors for sulphide build-up are temperature, biochemical oxygen demand (BOD), pH and stream velocity. The rate of corrosion of a concrete sewer can be calculated from the rate of production of sulphuric acid on the pipe wall, which is in turn dependent upon the rate that hydrogen sulphide is released from the surface of the sewage stream. This paper presents a detailed analysis of structural failures of corrosion affected concrete sewer pipes during their service lives. Stochastic models for pipe deterioration are developed and the associated risks of pipe collapse are quantified. A numerical example will be provided to illustrate the proposed method with a view to prevent unexpected failures of the structure during its service life. The proposed methodology can help the management in making correct decisions concerning the intervention to ensure the safe and serviceable operation of the pipes. This will, in turn, result in better asset and capital utilization.

KEYWORDS

hydrogen sulphide, Concrete sewer pipe, Probability of failure, Corrosion.

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1 INTRODUCTION

The UK has one of the largest sewerage networks in Europe, with an asset value of about £110 billion [Hau et al. 2005]. It is also known to be one of the oldest sewerage systems in the world, with more than 40% of its network constructed prior to 1945 [Read & Vickridge 1997]. The Water Services Regulation Authority estimates that the cost of replacing this entire infrastructure requires £200 billion [OFWAT 2002]. With such high stakes, this highlights the urgent need to develop methods to predict the time-variant probability of failure and innovative solutions to the optimal management of aging sewerage infrastructure. In England and Wales, the economic regulator imposes a duty on the privatised water companies to maintain the condition and serviceability of this asset.

Most of the maintenance strategies rely on the reliable data about the pipe’s physical attributes, for example wall thickness, strength, bending modulus, etc and its failure or performance history. With incomplete sewerage databases this can place significant restrictions on the decision of the most suitable maintenance strategy. Various frameworks have been proposed to model the behaviour of underground pipelines with different types of material, using reliability-based concept. Ahammed & Melchers [1997] developed a nonlinear limit state model for the analysis of underground pipelines subjected to combined stresses and corrosion. The reliability model was assumed to be a function of 20 independent random variables in order to study their effects. Li et al. [2009] presented a methodology for predicing corrosion remaining life of underground pipelines with a mechanically-based probabilistic model by taking into account the effect of randomness in pipeline corrosion. Monte Carlo simulation was employed to calculate the remaining life and its cumulative probability distribution function.

It has been known that the degradation of concrete sewer systems can be primarily attributed to concrete corrosion induced by biogenous sulfuric acid attack, which causes severe structural deterioration and ultimate structural collapse. Such problems are rarely brought to the attention of the public until a catastrophic failure occurs. Hydrogen sulphide (H₂S) related corrosion is among the most challenging problems regarding sewer operation and maintenance because sewer systems suffering from H₂S corrosion generally require costly replacement or rehabilitation of pipes. Study on sulphide formation and its corresponding modelling as well as its effects on concrete corrosion has been performed for many years [Pomeroy 1976]. Recently, new findings of a long-term study of H₂S gas adsorption and oxidation on concrete and plastic sewer pipe surfaces have been reported [Nielsen et al. 2009]. The processes have been studied using a pilot-scale setup designed to replicate conditions in a gravity sewer located downstream of a force main. The kinetic data obtained in the pilot-scale experiments can be used for prediction of concrete corrosion in real sewer systems based on H₂S measurements from a conventional gas detector.

The mechanism of H₂S in material degradation has been reasonably understood. What is less understood, however, are the factors that affect and control the process of concrete corrosion. Furthermore, little is known, in particular quantitatively, on the effect of concrete corrosion on the remaining safe life of the pipes. Without knowing this, rational decisions on maintenance and rehabilitation of the pipes are not possible and more importantly, unexpected failures of the pipes cannot be prevented during the lifetime. Therefore, the main objective of this paper is to present a method to predict the time-variant probability of failure and the expected life for concrete sewer pipes.

2 FAILURE MECHANISM OF CONCRETE SEWER PIPELINES

Sewer pipes are deteriorating slowly or fast depending on specific local conditions and not determined by age alone. There have been numerous cases of severe damage to concrete pipes, where it has been necessary to replace the pipes before the attainment of the designed life. There are many cases in which sewer pipes designed to last 50 to 100 years have failed due to H₂S corrosion in 10 to 20 years. In extreme cases, concrete pipes have collapsed in as few as 3 years [Pomeroy 1976]. The most corrosive agent that leads to the rapid deterioration of concrete pipelines in sewers is H₂S. Approximately 40% of the damage in concrete sewers can be attributed to biogenous sulphuric acid
attack. Sulphide corrosion, which is often called microbiologically induced corrosion, has two distinct phases as follows:

1) The conversion of sulphate in wastewater to sulphide, some of which is released as gaseous hydrogen sulphide
2) The conversion of hydrogen sulphide to sulphuric acid, which subsequently attacks susceptible pipeline materials.

The surface pH of new concrete pipe is generally between 11 and 13. Cement contains calcium hydroxide, which neutralizes the acids and inhibits formation of oxidizing bacteria when the concrete is new. However, as the pipe ages, the neutralizing capacity is consumed, the surface pH drops, and the sulphuric acid-producing bacteria become dominant. In active corrosion areas, the surface pH can drop to 1 or even lower and can cause a very strong acid attack. The corrosion rate of the sewer pipe wall is determined by the rate of sulphuric acid generation and the properties of the cementitious materials. As sulphides are formed and sulphuric acid is produced, hydration products in the hardened concrete paste (calcium silicon, calcium carbonate and calcium hydroxide) are converted to calcium sulphate, more commonly known by its mineral name, gypsum [ASCE 1989].

Gypsum does not provide much structural support, especially when wet. It is usually present as a pasty white mass on concrete surfaces above the water line. As the gypsum material is eroded, the concrete loses its binder and begins to spall, exposing new surfaces. This process will continue until the pipeline fails or corrective actions are taken. Sufficient moisture must be present for the sulphuric acid-producing bacteria to survive, however; if it is too dry, the bacteria will become desiccated, and corrosion will be less likely to occur.

3 FORECASTING SULPHIDE BUILD-UP AND RATES OF CONCRETE CORROSION

3.1 Forecasting Sulphide Build-Up

In some cases, it is difficult or not cost effective to design a sewer pipeline system that will be free of sulphide problems. It is then useful to know what levels of sulphide can be expected. The major determining factors for sulphide build-up are oxygen, temperature, pH, stream velocity, BOD, organic nutrients and sulphate. The sulphide concentrations in a partly filled sewer will approach a limiting level $S_{lim}$ as follows [ASCE 2007]

$$S_{lim} = 0.0005[BOD](1.07)^{T-20}\left(\frac{P}{b}\right)\frac{(su)^{3/8}}{P_{wet}}$$

where $[BOD]$ is biochemical oxygen demand concentration (mg/l), $T$ is sewage temperature ($^\circ$C), $s$ is the slope of the pipeline, $u$ is the velocity of the stream (m/sec) and $P/b$ is the ratio of wetted perimeter of the pipe wall ($P$) to the surface width of the stream ($b$).

3.2 Forecasting Concrete Corrosion Rate

The rate of corrosion of a concrete sewer can be calculated from the rate of production of sulphuric acid on the pipe wall, which is in turn dependent upon the rate that $H_2S$ is released from the surface of the sewage stream. The moisture on the pipe wall with oxidizing bacteria is very efficient in converting all of the $H_2S$ to sulphuric acid. Under most conditions, very little of the $H_2S$ escapes entirely from the sewer. The average flux of $H_2S$ to the exposed pipe wall is equal to the flux from the stream into the air multiplied by the ratio of the surface area of the stream to the area of the exposed pipe wall, which is the same as the ratio of the width of the stream surface ($b$) to the perimeter of the exposed wall ($P'$). The average flux of $H_2S$ to the wall is therefore calculated as follows [ASCE 2007]
\[
\Phi = 0.7 (s u)^{3/8} j S_{\text{lim}} (b / P')
\]  

(2)

where \( j \) is pH-dependent factor for proportion of \( \text{H}_2\text{S} \). Concrete pipe is made of cement-bonded material, or acid-susceptible substance, so the acid will penetrate the wall at a rate inversely proportional to the acid-consuming capability \( (A) \) of the wall material. The acid may partly or entirely react. The proportion of acid that reacts is variable \( (k) \), ranging from 100% when the acid formation is slow, to perhaps 30% to 40% when it is formed rapidly. Thus, the average rate of corrosion (mm/year) can be calculated as follows

\[
c = 11.5k \Phi (1 / A)
\]  

(3)

where \( k \) is the factor representing the proportion of acid reacting, to be given a value selected by the judgement of the engineer and \( A \) is the acid-consuming capability, alkalinity, of the pipe material, expressed as the proportion of equivalent calcium carbonate.

4 PROBABILITY OF FAILURE AND EXPECTED SERVICE LIFE

To predict the probability of failure for sewer pipes, a performance-based assessment criterion should be established. In reliability theory, this criterion is expressed in the form of a limit state function as follows

\[
G(S, R, t) = S(t) - R(t)
\]  

(4)

where \( G(\cdot) \) is termed the ‘limit state function’, \( S(t) \) is the load effect in the pipe at time \( t \), and \( R(t) \) is the resistance of the pipe. The pipe will be considered to have failed if its resistance \( R \) is less than the load effect \( S \) in the pipe. The probability of pipe failure is determined by the probability of a limit state violation. With the limit state function of Equation (4), the probability of pipe (structural) failure, \( P_f \), can be obtained by

\[
P_f (t) = P(R \leq S) = P[G(S, R, t) \leq 0])
\]  

(5)

For a structural member with a known distribution function \( F_R(t) \) of ultimate strength \( R \) and density function \( f_S(t) \) for load effect \( S \), the probability of failure in Equation (5) can be written in a single integral form as follows:

\[
P_f (t) = \int_{-\infty}^{\infty} F_R(t)f_S(t)dt
\]  

(6)

For a Gaussian distribution of \( R \) and \( S \), it is possible to integrate the convolution integral in Equation (6) analytically. When both the load effect \( (S) \) and the pipe resistance \( (R) \) are normal random variables with means \( \mu_R \) and \( \mu_S \) and variances \( \sigma^2_R \) and \( \sigma^2_S \) respectively, the safety margin of Equation (4) is

\[
Z(t) = R(t) - S(t)
\]  

(7)

which has a mean and variance given by well-known rules for addition/subtraction of normal random variables:

\[
\mu_Z = \mu_R - \mu_S
\]  

(7a)

\[
\sigma^2_Z = \sigma^2_R + \sigma^2_S
\]  

(7b)

Equation (5) then becomes:
\[ P_f(t) = P(R \leq S) = P(R - S \leq 0) = P(Z \leq 0) = \Phi\left( \frac{-\mu_Z}{\sigma_Z} \right) \tag{8} \]

where \( \Phi() \) is the standard normal distribution function (zero mean and unit variance). By replacing (7a) and (7b) in Equation (8), the probability of pipe failure \( P_f \) can be determined from [Melchers 1999]:

\[ P_f(t) = \Phi\left( -\frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \right) = \Phi(-\beta) \tag{9} \]

where \( \beta = \frac{\mu_Z}{\sigma_Z} \) is known as the safety index or reliability index. If either of the variances \( \sigma_R^2 \) and \( \sigma_S^2 \) or both are increased, the term in brackets in Equation (9) will become smaller and \( P_f \) will increase, as it is expected. Likewise by reducing the difference between the mean of the load effect and the mean of the resistance, \( P_f \) increases.

4.1 Resistance of Underground Concrete Pipes

The resistance of a pipe is the strength against the operational loads which are field specific and can be determined for a given field or site. The load acting on a pipe can be determined based on Marston load theory as follows:

\[ W_d = C_d B_d^2 \gamma \tag{10} \]

Therefore the resistance (strength) of a pipe would be (Moser and Folkman 2008):

\[ R = \left( \frac{W_d}{B_F} \right) \times \frac{1}{D} \tag{11} \]

where

- \( R \) = Resistance of the pipe (N/m²)
- \( C_d \) = Load coefficient
- \( \gamma \) = Unit weight of backfill material (N/m³)
- \( B_d \) = horizontal width of the ditch at top of conduit (m)
- \( B_F \) = Bedding factor, which is defined as the ratio of total field load to equivalent three-edge bearing load that causes the same bending moment at the invert of the pipe.
- \( D \) = Inner diameter of the pipe (m)

Due to the corrosion of concrete in a sewer pipe, the wall thickness of concrete pipe will reduce with a rate presented in Equation (3). Consequently the resistance of the pipe decreases with time, which can be determined as follows

\[ R(t) = \left( \frac{C_d B_d^2 \gamma}{B_F} \right) \times \frac{1}{(D + 2ct)} \tag{12} \]

where

- \( R(t) \) = Resistance of the pipe at time \( t \) (N/m²)
- \( c \) = corrosion rate (mm per year)
- \( t \) = time in years

and the other variables are as previously defined.
4.2 Maximum Design Load in an Underground Pipe

Since the emphasis of the paper is to demonstrate how to predict the service life of sewer pipes, the maximum affordable design load of the pipe will be determined from load tests for easy practical applications. One widely used test in practice is the equivalent three-edge bearing load test. From this test, the design load for an underground concrete sewer pipe is [Moser & Folkman 2008]:

\[ F_{3\text{-edge}} = \frac{F_{\text{earth}} + F_{\text{live}} + F_{\text{water}}}{B_f} \]  

(13)

where \( F_{3\text{-edge}} \) is the applied load in three edge bearing test, \( F_{\text{earth}} + F_{\text{live}} + F_{\text{water}} \) are different types of loads that need to be considered for the pipe in the field as indicated by subscripts.

ASTM C497 (2003) defines the design load \( D_{\text{load}} \) as the three edge bearing load that produces a 0.01 inch maximum crack width in the pipe. The \( D_{\text{load}} \) is measured by the three edge bearing load per meter of inner diameter so that it provides a strength classification of pipes independent of their diameters as provided by manufacturers. In practice, it is convenient to express the maximum allowable stress of reinforced concrete pipes in terms of the design load \( D_{\text{load}} \) (American Concrete Pipe Association 2007).

Considering the \( D_{\text{load}} \) of a pipe as its maximum allowable stress (S) of Equation (13) and the resistance of the pipe (R) of Equation (12), the time-variant probability of pipe failure can be determined from Equation (9). Obviously, \( P_f \) has to be smaller than an acceptable limit to eliminate undue risk of collapse. With this constraint, the expected service life can be approximately determined by assuming that the service life of the pipe is reached when \( P_f \) is equal to the acceptable limit as shown in the example below.

Alternatively, the expected service life of the pipe can also be calculated easily based on the criterion of non-exposure of reinforcing steel, which can be simply determined by dividing the concrete cover by average rate of corrosion, i.e., Equation (3).

5 WORKED EXAMPLE

A reinforced concrete sewer pipe with a diameter of 2286 mm, wall thickness of 216 mm and concrete cover of 45 mm is laid at a gradient of 1 in 667 (0.0015). The flow is half full at a velocity of 0.60 m/sec. The sewage temperature in the pipe is 22°C and the BOD is 250 mg/l. The pH of the sewage is 7.4 (taken from Table 1 of Pomeroy [1976], where \( j = 0.28 \) for pH=7.4). The pipe is made of concrete having an alkalinity equal to 0.20 of calcium carbonate. In this study, the coefficient \( k \) which represents the proportion of acid reaction, is selected to be 0.5. The statistics of the loading \( W_g \) acting on the concrete sewer pipe are estimated to be N(400 kN/m, 10). The strength in the pipe is decreasing with respect to time due to corrosion induced reduction of the wall thickness. The maximum allowable stress by the pipe based on its D-load design value is \( S = 200 \text{ kN/m}^2 \).

With above given values, the limiting level of sulphide concentration in the pipe is 3.12 mg/l and the average rate of corrosion is 0.81 mm/year which are determined using Equations (1) and (3). From this, the probability of the pipe failure can be determined using Equations (9) and (13), the results of which are shown in Figure 1 (\( P_f \) vs. time) and Figure 2 (\( P_f \) vs. thickness).

From Figure 1 it is clear that the probability of pipe failure increases with time which makes sense both theoretically and practically. It is important to note that the shape of the probability of failure curve is similar to the well known “bath-tub” from which it can be seen that year 25 seems to be the critical turning point. Also from Figure 2, it can be seen that after the wall thickness of the pipe reduces to about 170 mm the probability of pipe failure increases sharply. This again makes sense both theoretically and practically as observed in the real world.
If the acceptable probability of failure is 0.1, the expected life for the concrete pipe subjected to corrosion is 52 years (Figure 1), where the remaining thickness is 173 mm, i.e. 20% reduction of thickness (Figure 2). On the other hand, the expected life of the concrete pipe is 55 years if the criterion of non-exposure is adopted. Despite different criteria for predicting the expected service life results from both criteria are in good agreement. It is important to note that the calculated rate of corrosion is conservative because it is based on limiting value of sulphide concentrations.

![Figure 1](image1.png)  
**Figure 1** Probability of failure vs. time.  

![Figure 2](image2.png)  
**Figure 2** Probability of failure vs. thickness.

6 CONCLUSION

A widely used reliability method is presented to predict the time-variant probability of failure for concrete sewer pipes, based on the forecasted sulphide build-up and concrete corrosion rate. The major determining factors for sulfide build-up are temperature, biochemical oxygen demand (BOD), pH and stream velocity. The rate of corrosion of a concrete sewer can be calculated from the rate of production of sulphuric acid on the pipe wall, which is in turn dependent upon the rate that hydrogen sulphide is released from the surface of the sewage stream. It has been found that the expected service life of concrete sewer pipes can be determined through average rate of corrosion either based on safety criterion or non-exposure of reinforcing steel. It can be concluded that the method presented here can...
predict the expected life of concrete pipes subjected to hydrogen sulphide-induced corrosion with reasonable accuracy.

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