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EFFECT OF SOIL CORROSION IN FAILURES OF BURIED PIPELINES

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Over the last few years, several failures in transmission and distribution water/gas pipelines have been reported around the world. The failure of buried pipeline is controlled by several factors, such as pipe material, soil corrosion, internal and external loading, etc. Among these, soil corrosion makes a significant contribution towards failure mode and mechanisms in buried pipes, yet few studies have been done. Although a number of corrosion models have been developed over the years, the applicability of the model predominantly depends on the type of soil and its moisture change over time at the pipe depth. By incorporating a corrosion model, the remaining life of the pipe can be estimated on the basis of applied traffic and pressure loads, which determine the stresses in the pipe segment. Depending on the model, the estimation can show significant variability, and consequently affect the pipe renewal and rehabilitation plans that ultimately have economic impacts. Therefore, it is important for the pipeline asset owners to understand the effect of corrosion models in the remaining life calculation. This paper reviews briefly the available corrosion models and the sensitivity of each parameter in pipe corrosion pit properties and in the remaining life estimation. Finally, a comparison among the corrosion models on the basis of the remaining life estimation is provided to improve the renewal plan.

Keywords: Corrosion pit, Renewal plan, Remaining life, Asset management, Infrastructure.

1 INTRODUCTION

Pipelines are the one of the important infrastructure transporting the water and gas from one location to other. The failure of aging infrastructure is a major problem around the world. The failure of buried pipeline depends on several factors such as soil corrosion, traffic load, and pressure loads (Rajeev *et al.* 2014). In a buried pipe, the structural load carrying capacity of pipe deteriorates mainly due to external and internal corrosions (i.e., corrosion causes the reduction in pipe wall thickness that increases the pipe stress) and the external and internal loadings (i.e., traffic load and internal water/gas pressure) in the pipe, which may increase due to increase in demand with time. The pipe fails when the stress on pipe induced by internal and external loads exceeds the pipe capacity. The failure mode depends on the type of loading, level of loading, level of deterioration, type of pipe material and pipe geometry. This can be explained using the "Schlik diagram". The pipe past failure data of five major water utilities in Australia were analyzed in Rajeev *et al.* (2014), finding that corrosion is the main cause for most of the pipe failures. Further, the failure analysis of high-pressure natural gas was conducted by Hassan *et al.* (2007) and Hernandez-Rodriguez *et al.* (2007), concluding that corrosion is the major factor behind failure of buried gas pipe.

In Australia, water pipes installed after 1970 are mostly cement-lined. Therefore the effect of internal corrosion is not severe in comparison to external corrosion. However, understanding the progress of external corrosion in buried pipe is not simple, because the corrosion rate depends on soil parameters such as soil type, soil moisture content, pH and soil resistivity, and pipe material properties (Doyle *et al.* 2003, Petersen and Melchers 2012). Therefore, estimating the corrosion rate is complex because it is location dependent for buried pipe. In the past, corrosion-prediction models were proposed by several researchers, and the prediction of each model largely varies due to inherent uncertainty associated within the variable(s) in the model. Hence, an assessment of those corrosion models for a remaining-life estimation of any buried pipe network is necessary for the asset owners to perform a timely and cost-effective renewal and rehabilitation plan. In this paper, a brief review of available corrosion models and the sensitivity of models' parameters are presented. Finally, a comparison among the corrosion models on the basis of remaining-life estimation is provided.

2 CORROSION MODELS

Several corrosion prediction models have been developed for buried water and gas pipes and used by the utilities for their network renewal plan. The corrosion model for buried pipe correlates to the growth of corrosion pit geometry (mostly corrosion pit depth) over time with the surrounding soil properties. The growth of a corrosion pit significantly depends on soil condition, pipe material, and the climate of the location; therefore, there is no universal model to predict the effect of corrosion in buried pipe. For example, Doleac *et al.* (1980) proposed a power function to correlate "pit depth" with the age of pipe. Randall-Smith *et al.* (1992) concluded that corrosion pits grow at a constant rate and expressed a linear model. Kucera and Mattson (1987) derived a corrosion model to predict the pit depth of buried cast iron pipe as in Eq. (1).

$$d = K\tau^{n} \tag{1}$$

where K and n are constants normally assumed to equal 2 and 0.3 respectively. Rajani *et al.* (2000) developed a two-phase corrosion model as given in Eq. (2) to predict the pit depth over exposure time period of buried cast iron pipe in varying soil corrosivity.

$$d = a\tau + b(1 - e^{-c\tau}) \tag{2}$$

where d is the corrosion pit depth, a is the minimum corrosion rate (mm/yr), k is the petting depth constant (mm), c is the corrosion rate inhibition factor (yr^{-1}), and τ is the exposure time period. The possible range of a is 0.0042 to 0.0336, b is 1.95 to 15.6, and c is 0.01 to 0.18 for all type soils. Figure 1 shows all possible corrosion pit depths with exposure time for combination of maximum and minimum corrosion model parameters. The variability in corrosion pit depth with exposure time is significant, with considerable effect on the remaining life calculation of buried pipe that misleads the renewal planning decision making process. In this study, a detailed analysis was carried out using the corrosion model in Eq. (2):

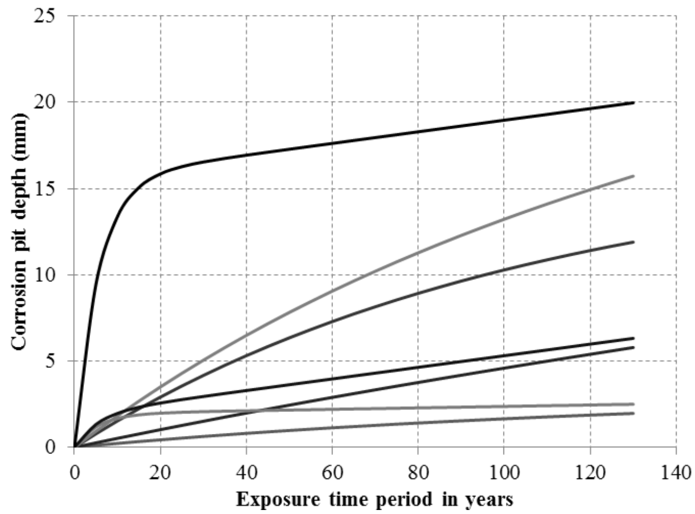

Figure 1. Possible corrosion pit depth with exposure time.

3 PIPE STRESS ANALYSIS

The level of stresses in a buried pipe depends on the internal pressure and the external loads due to soil and traffic. A range of pipe stress prediction models have been reported in the literature with varying levels of complexity. Most of the asset condition assessment tools used by utilities use stress prediction models developed using the simple 2D-ring theory. Therefore, in this study a simple stress predication model incorporating the soil effect is used and given as Eq. (3):

$$\sigma_{\max} = \frac{k \cdot q \cdot D}{2 \cdot t} + 1.5 \cdot (1-k) \frac{q \cdot D^2}{4 \cdot t^2} \tag{3}$$

where q is the uniform vertical stress due to soil and traffic loads, D is the pipe diameter, t is the pipe wall thickness, and k is the lateral earth pressure coefficient. The stress q is required to estimate from a suitable method. For the same operating conditions, pipe stress increases with reduced pipe wall thickness due to corrosion. The pipe fails when the stress reaches the ultimate stress capacity of the pipe (σ_{ult}). Therefore, a pipe's factor of safety (FoS) can be determined in terms of stresses.(Eq. 4):

$$FoS = \frac{\sigma_{ult}}{\sigma_{\max}} \tag{4}$$

4 UNCERTAINTY ANALYSIS AND ITS EFFECT IN PIPE SAFETY ASSESSMENT

The complex corrosion process in buried pipe and loadings often involve input data or parameters from field and laboratory testing and sometime expert opinion based on experience and judgment. Data associated with uncertainty need to be quantified properly during the decision making process. In this study, a probabilistic uncertainty quantification method is proposed incorporating the corrosion and stress analysis models. The variability in the estimated *FoS* with time due to the uncertainty in the corrosion model parameters are presented.

Table 1 shows the possible ranges and the most likely values of the input variables such as pipe material properties, soil properties, traffic and pressure loads, and corrosion model parameters. To perform the traditional probabilistic analysis, an appropriate probability distribution function has to be identified for each input parameter on the basis of the available data. In this study, the input parameters were assumed to follow the uniform distribution due to lack of information on input parameters. A set of random samples was drawn from an assigned distribution and the sample size was around 500. The pipe stress was calculated for each set of random variables at present and with exposure time by incorporating the random corrosion model that was also sampled. Subsequently, the *FoS* with exposure time was estimated using Eq. (4). No variability was assumed for the pipe diameter or the ultimate tensile capacity of the pipe material. The pipe material is cast iron.

Table 1. Input parameters for pipe, soil, load and corrosion model.

Parameter	**Minimum**	**Most likely**	**Maximum**
Pipe			
Diameter , D (mm)	-	600	-
Wall thickness, t (mm)	20	25	30
Burial depth, h (mm)	300	800	1500
Ultimate tensile capacity, σ_{ult} (MPa)	-	100	-
Soil			
Lateral earth pressure coefficient, k	0.2	0.4	0.6
Soil unit weight, γ (kN/m^3)	18	20	24
Load			
Traffic, W (kN)	20	40	70
Pressure, P (kPa)	300	600	1000
Corrosion model			
a	0.0042	0.009	0.0336
b	1.95	6.27	15.6
c	0.01	0.14	0.18

Figure 2 shows the variability in estimated *FoS* together with the most likely *FoS* and the critical *FoS* values with exposure time. The shaded area in Figure 3 shows how the variability in *FoS* changes with time. The most likely *FoS* is estimated using the most likely values of the parameters given in Table 1. Based on Figure 3, the possible failure can start to occur from 15 years after installation for the worst-case scenario. The pipe remains in good condition after 175 years of exposure time for most likely value of the input parameters (i.e., *FoS* > 7). The reduction in *FoS* is significantly high soon after the installation of the pipe (say, within the first 25 years of exposure time) and the rate of reduction reaches a stable stage after an initial period.

Sensitivity analysis was performed to identify the parameters that have significant influence in *FoS*. The most commonly-used Spearman's rank correlation method was used to estimate the approximate relative contribution of input parameters (Hammonds *et al.* 1994). The estimated correlation coefficients were squared and normalized to 100%. Figure 3.a shows the contribution of each input parameter to the overall variability of *FoS* over time.

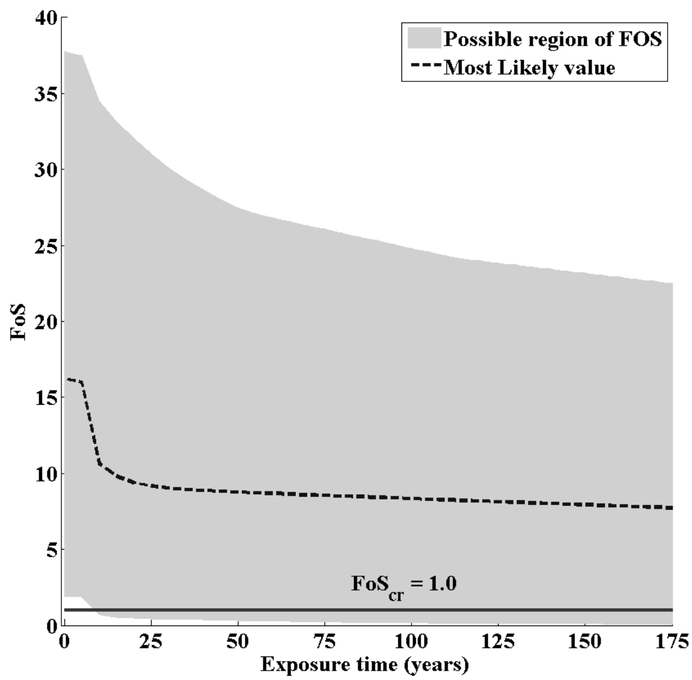

Figure 2. Declined *FoS* with exposure time together with most likely and critical *FoS.*

At the early stage, the contribution of the pipe's operational conditions and geometry (i.e., traffic load, thickness, and burial depth) are significant, and the contribution decreases with time. The contribution of soil unit weight and internal pressure has fairly low and stable over time. As shown in Figure 3.b the total contribution from the corrosion model increases with time. Constant *b* is the biggest contributor. Constant *a* has lower and stable contribution over a substantial period of time (say, 30 years), and the contribution increases when the pipe ages. At the early stage of the pipe life the constant *c* has as prominent a contribution as *b* does to overall variability; this contribution diminishes to zero as the pipe ages. The total contribution of corrosion to *FoS* increases above 50% with time. This dominance suggests that future research should invest the greatest effort in further improving and validating the corrosion model.

5 CONCLUSION

This paper studies the effect of soil corrosion on buried cast-iron pipe. A probabilistic assessment of the effect of corrosion model on the *FoS* with time was explored. Sensitivity analysis was performed and showed that the corrosion model parameters were the largest contributors to the overall variability in *FoS* when the pipe ages. Therefore more research is needed to accurately model external corrosion buried pipes.

References

Doleac, M. L., Lackey, S. L., and Bratton, G. N., Prediction of Time to Failure for Buried Cast Iron Pipe, *Proceedings of American Water Works Association Annual Conference*, Denver, CO, 21-28, 1980.

Doyle, G., Seica, M. V., and Grabinsky, M. W. F., The Role of Soil in the External Corrosion of Cast Iron Water Mains in Toronto, Canada, *Can. Geotech. J*., 40, 225-236, 2003.

Hammonds, J. S., Hoffman, F. O., and Bartell, S. M., *An Introductory Guide to Uncertainty Analysis in Environmental Health and Risk Assessment*. Oak Ridge, TN: SENES Oak Ridge, Inc.,1994.

Hassan, F., Iqbal, J., and Ahmed, F., Stress Corrosion Failure of High-Pressure Gas Pipeline, *Eng. Fail. Anal.*,14, 801-809, 2007.

Hernandez-Rodridriguez, M. A. L., Martinez-Delgado, D., Gonzalez, R., Perez Enzeta, A., Mercado Solis, R. D., and Rodriguez, J., Corrosive Wear Failure Analysis in a Natural Gas Pipeline, *Wear*, 263, 567-571, 2007.

Kucera, V., and Mattson, E., Atmospheric corrosion, in Mansfeld F, Ed.. *Corrosion Mechanics*, New York, NY: Mercel Dekker, 1987.

Petersen, R. B., and Melchers, R. E., Long-term Corrosion of Cast Iron Cement Lined Pipes, *International Conference in Corrosion and Prevention*, Melbourne, Australia, 2012.

Rajani, B., Makar, J., McDonald, S., Zhan, C., Kuraoka, S., Jen, C. K., and Veins, M., *Investigation of Grey Cast Iron Water Mains to Develop a Methodology for Estimating Service Life*, Denver, CO: American Water Works Association Research Foundation, 2000.

Rajeev, P., Kodikara, J, Robert, D., Zeman, P., and Rajani, B., Factors Contributing to Large Diameter Water Pipe Failure as Evident from Failure Inspection, *Journal of Water Asset Management International*, 10(3), 9-14, 2014.

Randall-Smith, M., Russell, A., and Oliphant, R., *Guidance Manual for the Structural Condition Assessment of the Trunk Mains*, Swindon, UK: Water Research Centre, 1992.