Statistical Modelling of External Corrosion in Buried Piping

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Abstract

The assessment of external corrosion of buried piping is a major challenge due to access restrictions. This study utilizes field data collected by the U.S. National Institute of Standards and Technology (NIST) to model the external corrosion rate using a weighted least squares (WLS) multiple regression approach. The key parameters in the model include soil resistivity, pH, moisture equivalent, and the time of exposure. The model can be used to predict the corrosion rate and probability of leak over time, and hence directly support the risk-informed decision making and management of buried piping at nuclear power plants.

1. Introduction

The integrity of buried piping is a significant concern for nuclear power plants planning to continue operating through licence extension and refurbishment. Buried pipes can range in size from a few inches to several feet in diameter and are subject to degradation both from the outside (soil side) and the inside (fluid side). Unlike aboveground piping, assessing the degradation of buried piping is very difficult due to access restrictions. The failure or leakage of buried piping can have significant economic and environmental consequences and may also have an impact on critical safety-related systems.

Because of these challenges and concerns, the industry has developed many programs and methods to not only ensure, but also improve the integrity of buried piping [1-10]. These include recommendations for preventing, controlling and mitigating the degradation through risk-informed inspection and repair activities, as well as assessing the fitness-for-service of critical pipes and segments.

The failure of buried piping is a complex phenomenon that depends on physical and electrochemical (and microbial) processes, piping and soil characteristics, as well as inspection and preventive maintenance methods. External corrosion is a common failure mechanism of buried piping in nuclear plants, and may include general corrosion, localized corrosion, such as pitting, crevice corrosion and intergranular attack, microbiologically influenced corrosion (MIC), galvanic corrosion, environmentally assisted cracking, stress corrosion cracking (SCC), and corrosion fatigue [1]. As a result, failure mitigation typically involves corrosion prevention on the exterior surface through the use of coatings and/or cathodic protection.

Most buried pipe is constructed of carbon steel, although many other materials have also been used [6]. Following the breakdown of the coating and/or the cathodic protection system, the external corrosion rate depends largely on the characteristics of the surrounding soil. The key parameters influencing the rate of degradation include soil electrical resistivity, pH value, moisture conditions, chloride concentrations, redox potential, temperature, and others [2, 11-15]. However, because of large scatter in the soil conditions and chemistry, the reliable prediction of corrosion rates has often been difficult and subject of much uncertainty [16-17]. For unprotected carbon steel, EPRI [8] suggests a corrosion rate of 0.05 to 0.5 mm/year in acidic soils and 0.08 to 1.27 mm/year in alkaline soils, depending on the pH and soil resistivity. Similarly, a wide range of 0.03 to 0.43 mm/year is recommended for pitting corrosion in carbon steel, depending on the resistivity, drainage, and air pore space of the surrounding soils [8].

This study aims to characterize the uncertainty in the external corrosion rate of buried piping through statistical modelling of field data collected by the U.S. National Institute of Standards and Technology (NIST). The model is based on weighted least squares (WLS) regression of soil conditions and chemical parameters presented in [15]. The key variables used in the model include soil resistivity, pH, and moisture equivalent, as well as the time of exposure. The developed model can be used to predict not only the corrosion rate, but also the probability of leak over time. These results, along with consequence analysis, directly support the risk-informed decision making and management of buried piping at nuclear power plants.

2. Data

The data for this study is based on [15], which summarizes the corrosion testing field data by the National Bureau of Standards (NBS) conducted between 1922 and 1940. The original study (also discussed in [16, 17]) consisted of samples of eight different alloy types (nominal 1.5 inch and 3 inch steel and iron pipes) that were buried to varying depths at 47 different sites across the U.S. The samples were retrieved from the sites at periodic intervals, with the last samples removed up to 17 years after burial (depending on the site), and measured for mass loss and corrosion penetration. In addition to the corrosion measurements, the soil and soil- (i.e., ground-) water were analyzed for various properties, including soil type, drainage, particle sizes (i.e., relative sand, silt, clay and colloid content), resistivity, moisture equivalent, air-pore space, specific gravity, volume shrinkage, pH, total acidity, as well as the concentration of soluble ions such as Na, Ca, Mg, HCO_3, Cl, and SO_4 [15].

Figure 1 shows the maximum corrosion penetration measurements as a function of time for selected four sites. Each inspection contains the results for the eight different alloys (i.e., eight separate points), which were based on a two-sample average of the maximum measured penetration in each alloy. The different alloys are not identified individually in Figure 1, because no significant or identifiable differences in the corrosion behaviour could be determined between the alloys by [15] or by our own assessment (not included here).

As shown in Figure 1, the depth of corrosion penetration increases with time and with different rates depending on the site. Naturally the key question is whether the differences in the observed corrosion rates can be explained by the underlying site characteristics.

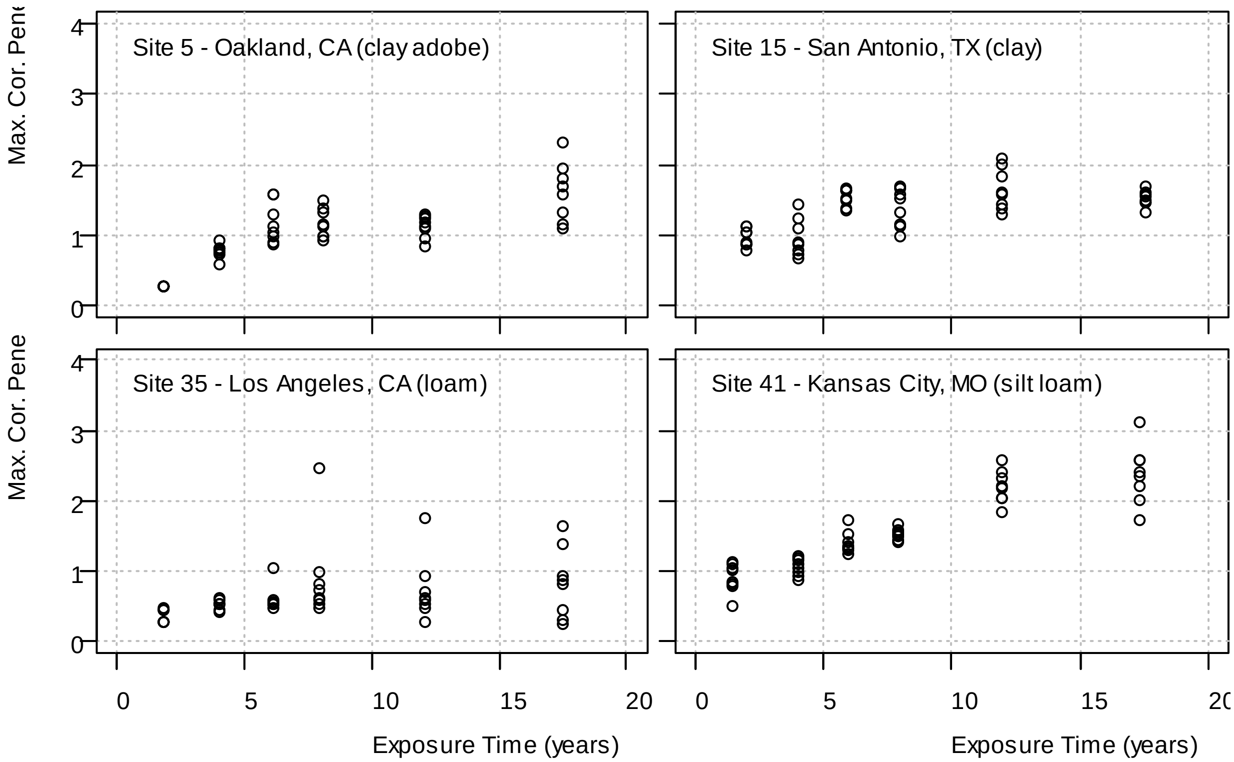

Figure 1 Maximum corrosion penetration measurements vs. exposure time for selected four sites (refer to [15] for detailed site information).

3. Model Development

The external or outer-diameter (OD) corrosion of buried piping is typically modelled using the following empirical power-law relationship [1, 8, 13, 15, 18]

$$y = at^n \tag{1}$$

where y is the corrosion depth, t is the exposure time, and a and n are site specific constants, and n is typically less than 1. Based on extensive statistical analysis of the data, we found the soil resistivity, pH, and moisture equivalent to be the most statistically important and influential parameters with the following general relationship

$$y_i = \beta_0 + [\beta_1 \ln(\rho_i) + \beta_2 pH_i + \beta_3 \theta_{ME_i}] t_i^n + \varepsilon_i \tag{2}$$

where y is the observed maximum corrosion penetration (mm), ρ is the resistivity (ohm·m), pH is the pH value, θ_{ME} is the moisture equivalent (%), t is the exposure time (years), β_k are the constant regression coefficients, ε is the error term associated with the i^{th} observation, and n is a constant to be determined. As shown by Equation (2), the proposed multiple regression model is consistent with the power-law model of Equation (1), with the coefficient a described explicitly by the site specific environmental conditions.

From a physical point of view, soil resistivity, along with pH, are known to be key factors in determining the corrosiveness of soils. Resistivity, which tends to follow the log-normal distribution, is a measure of the total ion content of the soils, and hence represents the combined concentration of all soluble ions. Aggressive pH and high moisture levels naturally result in higher corrosion rates.

3.1 Model Fitting

The proposed model was fitted to the observed maximum corrosion penetration data using a weighted least squares (WLS) approach with the following variance function

$$\sigma_i^2 = \sigma_0^2 \ln(\rho_i) t_i^n \tag{3}$$

where σ_0 is the standard error of regression. The WLS approach was needed to stabilize the model residuals. Because ion chemistry was measured only for a limited number of sites, the model was fitted to data from only 18 different sites. Similar to [15], initial data points (i.e., zero exposure time, zero damage) were also included in the model fitting.

Figure 2 shows a plot of the constant exponent *n* as a function of adjusted R^2 from the regression analysis. As shown in Figure 2, the optimal model fit is achieved when *n* is equal to 0.5. This value is consistent with other studies and indicates that the rate of corrosion penetration is decreasing with time.

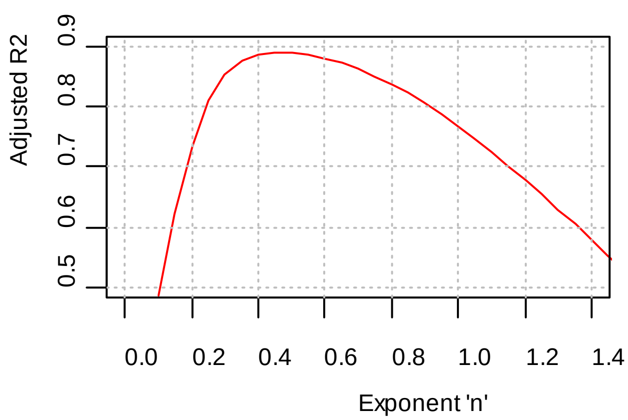

Figure 2 Constant exponent ‘n’ vs. adjusted R^2.

Table 1 shows the fitted model coefficients assuming *n* is equal to 0.5, while the overall model fit is illustrated in Figure 3, which shows the residual plot, the normal plot of the residuals, and a plot of the fitted vs. observed values. As shown in Figure 3c, a relatively large scatter in the observed data still remains despite the high R^2 value shown in Table 1 for the fitted model (the R^2 is generally higher in WLS because the observations are weighted by the variance function).

Table 1 Parameter estimates for the proposed WLS multiple regression model.

n	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$	$\hat{\sigma}_0$	R^2
0.5	-1.06E-04	0.181	-0.065	0.0138	0.156	0.889

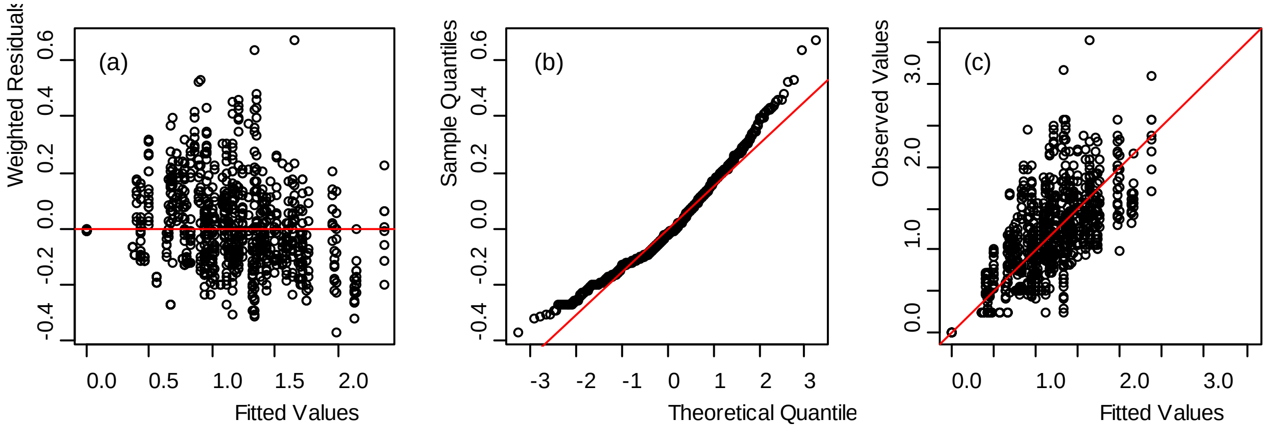

Figure 3 The (a) weighted residual plot, (b) normal probability plot of the weighted residuals, and (c) fitted vs. observed values for the WLS multiple regression model.

As shown in Table 1, the value of the intercept term β_0 is very small. The p-value for β_0 (equal to 0.96) also indicates that the coefficient is not significant, and can therefore be removed from the model. As expected, the coefficient β_3 for moisture equivalent is positive, indicating that the corrosion rate increases with moisture, while the negative β_2 coefficient for pH means that the corrosion rate increases with decreasing pH value (i.e., more aggressive/acidic environment).

In general, corrosion rates tend to increase with decreasing resistivity of a soil. However, higher resistivities (i.e., lower overall corrosion rates) may also make it easier for corrosion to localize to a small spot or region of the surface and initiate pitting [15]. This phenomenon was observed in the original NBS study and was identified as a major source of scatter and uncertainty in the assessment [15]. As shown in Table 1, the positive β_1 coefficient for resistivity indicates that the corrosion process for the modelled sites may be more localized and pit-like, rather than general corrosion.

4. Model Results

Figure 4 shows the model predicted mean maximum corrosion penetration (solid red lines) and the 95 % prediction intervals (dashed lines) over time for the selected four sites discussed in Figure 1. As shown in Figure 4, the model captures the general trend in the external corrosion rates quite well, with the rate of penetration decreasing over time. The large scatter or uncertainty in the data is also well accounted for by the prediction interval, which increases with time and resistivity according to the variance function in Equation (3).

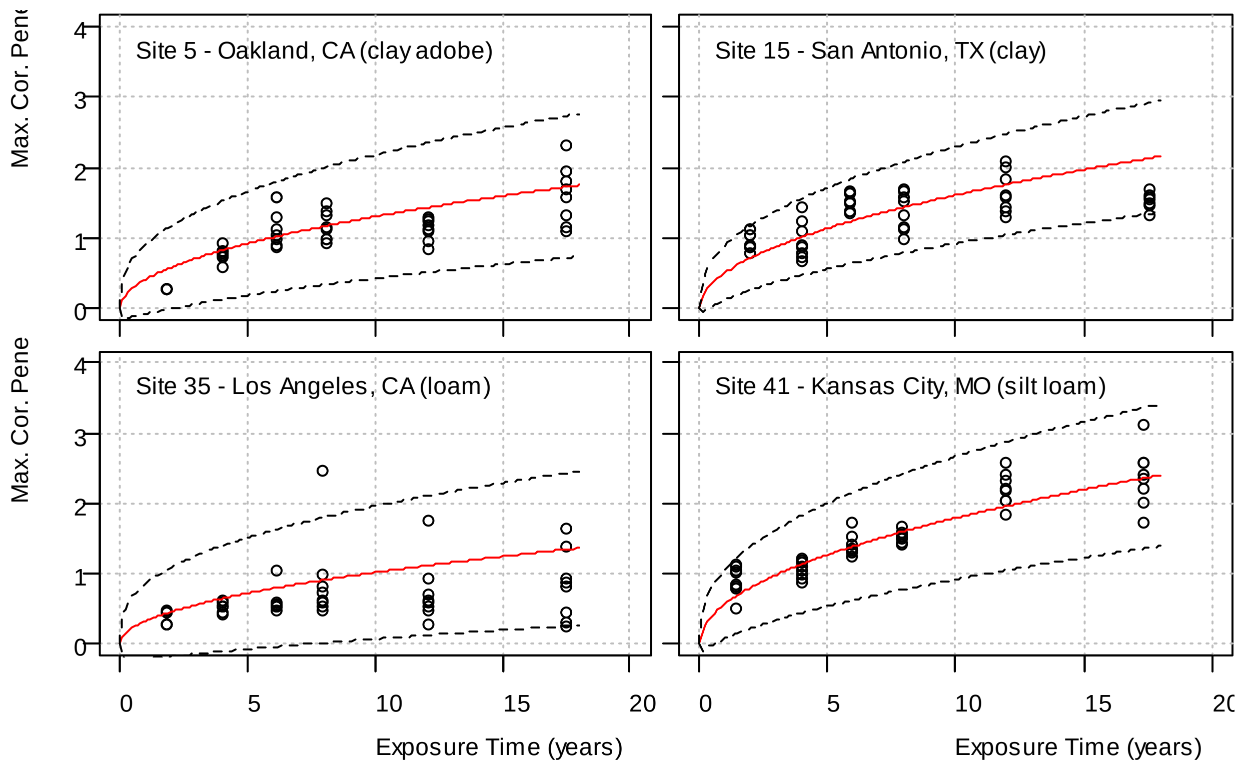

Figure 4 Model predicted mean (solid red lines) and 95 % prediction intervals (dashed lines) for the selected four sites.

As shown in Figure 4, the fitted model allows the prediction of external corrosion rates for buried piping at any time. Given the initial pipe wall thickness, the model can also be used to predict the probability of leak (i.e., maximum corrosion penetration exceeding the pipe wall thickness) at any time. For example, consider a pipe with a nominal 3.5 mm thickness buried under the same conditions as found at Site 41, with a resistivity of 13.2 ohm·m, a pH of 5.5 and moisture equivalent equal to 33.1 %. Using the mean and variance of the fitted model (Equations (2) and (3), respectively) Figure 5 shows the estimated probability of leak over time for this pipe.

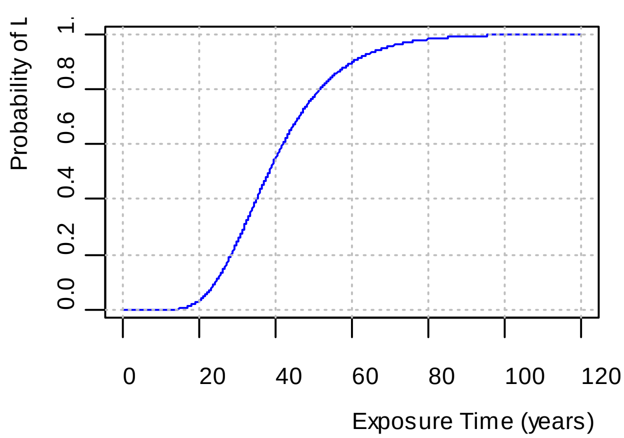

Figure 5 Probability of leak over time for a 3.5 mm thick pipe at Site 41.

As shown in Figure 5, the probability of leak begins to increase rapidly after 20 years and becomes one (i.e., near certainty) after approximately 80 years, while the median lifetime or time to leak is around 40 years. The range of uncertainty present in the prediction is directly related to the degree of scatter found in the observed data.

As shown by the above results, the developed WLS multiple regression model can readily be used to compute the risk of leakage of various pipe segments under different site specific soil conditions. However, because of the limitations of the original field data with respect to soil parameters, pipe sizes and alloy types, care should be taken when applying the model to other sites, and especially when dealing with different pipe sizes and materials. As suggested by Appendix B in [10], data from other assessments, such as visual inspections, pressure testing, etc., should also be taken into consideration in the overall risk assessment. Long term changes in soil conditions may also have to be factored in for plants operating beyond refurbishment and licence extension.

The data used in this study was based on the corrosion of bare metal specimens under various environmental conditions. Therefore, the proposed model does not directly apply to protected piping (i.e., using coatings or other methods), although it can be used to estimate corrosion rates following the breakdown of protection. Naturally, predicting the occurrence and timing of failure of any protective barriers is a challenging task.

Notwithstanding the above limitations, the model provides a valuable tool for risk-informed decision making and management of buried piping at nuclear power plants by facilitating the probabilistic or risk-based ranking and comparison of various pipe segments across the overall population.

5. Summary and Conclusions

The reliability of buried piping is a serious concern for nuclear power plants, particularly in the context of licence extension and refurbishment. External corrosion is a major threat, however, it is very difficult to quantify due to accessibility issues.

In this study, we developed a weighted least squares (WLS) multiple regression model for predicting the external corrosion rate of buried piping as a function of site specific environmental conditions. The data for the study was based on field observations by the U.S. National Institute of Standards and Technology (NIST) as summarized in [15]. The key parameters for the external corrosion rate were found to be the soil resistivity, pH, moisture equivalent, and exposure time, with the maximum corrosion penetration increasing as a square-root of the exposure time, and the variance function in the WLS approach formulated in terms of resistivity and exposure time.

The results showed that both the mean behaviour and scatter in the observed data were captured well by the fitted model. The model can readily be used to predict not only the corrosion rate, but also the probability of leak over time for a given pipe segment and site specific conditions. These results, along with consequence analysis (e.g., safety impact), directly support the risk-informed decision making and management of buried piping at nuclear power plants.

6. Acknowledgements

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