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Stress Analysis of Buried Pipes

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Abstract: Pipeline plays a vital role in transporting water, gas and oil from one place to another. Over the years, several failures have been reported in pipeline mainly due to aging (i.e., corrosion). The failure occurs when the stresses in a pipe segment due to applied loads exceed the capacity of the pipe. Therefore, it is important to predict the realistic pipe stress at the design and assessment stages to ensure the safety across the entire lifetime. As significant portion of the pipeline is buried in the underground in most of the occasions, the soil-structure interaction analysis is important as part of the stress analysis. Depending on the location of the network, the pipe will be subjected to varying levels of traffic and pressure loads that need to be accurately determined in order to perform reliable pipe stress estimations. Several pipe stress prediction methods have been developed over the years and reported in the literature. However, these methods are either analytical or empirical based models. The former uses the structural mechanics of the pipe by discarding the complex soil-structure interaction effect while the later fully depends on the experimental results. To overcome these problems, the numerical methods can be used to incorporate the soil-structure interaction effect more efficiently in pipe stress analysis together with traffic and internal pressure loads. In this study, the finite element method is used to analyse the pipe-soil system subjected to external traffic and internal pressure loads. Further, the model developed is used to understand the effect of soil properties, pipeline characteristics, and loading on pipe stress through sensitivity analysis. Finally, the response surface method is used to develop a new pipe stress predictive equation using the results of finite element analyses.

Keywords: Buried pipe, soil-structure interaction, finite element, response surface method, corrosion

1. Introduction

Pipelines are a safe and reliable mode of transportation for liquid and gas. Failure of a critical pipeline is extremely serious and has major consequences in terms of economic loss, social impacts and environmental issues. The failure of a pipe occurs when the applied stresses in the pipe exceeds the structural capacity of the pipe (Gould et al., [1]). The structural capacity reduces over time due to material deterioration, the mechanisms of which are dependent on the pipe material described by Rajani et al, [2]. The failures in the pipe barrel and joint result from a combination of causes such as operational condition (i.e., traffic load and pressure load), environmental factors (i.e., soil corrosivity and reactivity) and intrusion (i.e., third party damage) as classified in Rajeev et al., [3]. Figure (1) shows the causes of pipe failures and its contribution to the total number of failures in buried water pipeline. The corrosion has significant influence on the failure of buried pipeline followed by ground movement and pressure transient.

The failure modes of the pipeline differ depending on the level of applied external loads, operational conditions and pipe geometry (i.e., diameter and thickness etc). For example: (a) the longitudinal failure occurs due to increase in internal pressure that increases the tensile stress higher than the capacity; and (b) the circumferential failure occurs due to increase in flexural stress in the pipe exceed the bending capacity of the pipe. Moreover, the pipe corrosion both external and internal causes leakage and reduces the structural capacity. In order to have the appropriate level of functioning of a pipe network, It is important to know the factors that leads the pipe to failure, behaviour of pipeline under internal and external loads and pipe deterioration process. This information helps the pipeline industry to manage the asset and plan the renewal and rehabilitation in a cost effective manner.

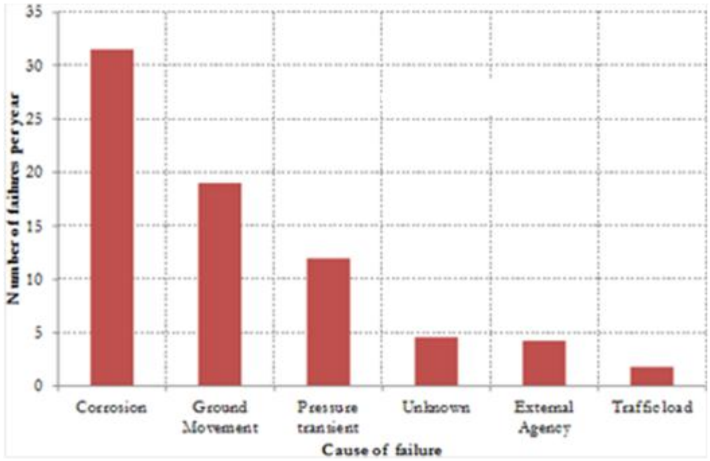

Figure 1: Causes of failures in buried cast iron pipe (Adopted from Rajeev et al., [3])

However, the prediction of possible failures in a pipe network is mainly based on the statistical approach using past pipe failure data. Existing statistical models for the prediction of failures in pipe network consider only one or a few factors in estimating the number of failures. Neglecting to account for the important factors can lead to inaccurate conclusions, which result in sub-optimal failure prediction and renewal strategies (Rajeev et al., [3]). Further, the statistical approach uses the past failure data that should be sufficient enough to perform the statistical inference. In most of the cases, the data is not sufficient to conduct the analysis (e.g., large diameter water, oil and gas pipes). The results of the statistical analysis do not distinct the mode of failure and the location of failure etc, rather provide the total number of failures possibly occur in particular time period (say one year) with the network. This type of approach is viable for distribution network (i.e., small diameter pipes, less than 300 mm diameter), where the replacement of similar cohort at once is economical than assessing the condition of each pipe segments. On the contrary, the renewal or replacement of critical pipe based on the condition of each pipe section is not cost effective in many cases.

Therefore, to understand in-service pipe failures, it is necessary to have knowledge of the stresses to which the pipes are subjected to and any degradation of mechanical performance of the pipe with time that might contribute to failure. Several stress prediction models were developed in the past to estimate the stresses in a pipe segment subjected to external and internal loads with varying levels of accuracy. Most of the existing models are analytical based on the structural analysis of 2-D pipe ring. Some of the models can accommodate the soil effect using predefined soil stress distribution. Thus, the stresses in the pipe at the field may be significantly different from the estimated stress using the analytical models. This provides unreliable information to renewal and rehabilitation decision making process. Therefore, it is necessary to have reliable pipe stress prediction model incorporating the factors that have significant contribution to pipe stress.

In this study, the finite element method is used to analysis the pipe-soil system subjected to external traffic and internal pressure loads. For this purpose, a 3-D finite element model was developed to include the pipe-soil interaction and pipe deformation. The model developed is used to understand the effects of soil type, pipe diameter, pipe burial depth, pipe wall thickness, and traffic and pressure loads on pipe stress and the sensitivity analysis is performed to identify the influence of each parameter in maximum pipe stress. Further, the response surface method is used to develop a new pipe stress predictive equation using the results from finite element analyses.

2. Pipe Stress Prediction Models

Spangler [4] developed the first pipe stress perdition equation for buried pipe subjected to traffic loads. This equation has been widely used by pipeline industries in design and condition assessment stages. The equation computes the circumferential bending stress at the pipe invert due to vertical load as follows:

$$\sigma = \frac{3 \cdot K_b \cdot W_{vertical} \cdot E \cdot t \cdot D}{E \cdot t^3 + 8 \cdot K_z \cdot p \cdot D^3} \qquad (1)$$

where $W_{vertical}$ is the vertical load due to backfill and surface loads including an impact factor, E is the pipe modulus of elasticity, *D* is pipe diameter, *t* is pipe wall thickness, and *p* is the internal pressure. K_b and K_z are bending moment and deflection parameters, respectively, that depend on the bedding angle. The appropriate values of K_b and K_z can be found in Moser and Folkman [5].

However, the equation (1) does not include the effect of soil lateral support on the pipe stress. Lately, Warman et al., [6] proposed a modified Spangler equation by combing the original Spangler formula and the Iowa formula as given in equation (2). Figure (2) shows the assumed stress distribution around the pipe due to soil and traffic load.

$$\sigma = \frac{6 \cdot K_b \cdot W_{vertical} \cdot E \cdot t \cdot r}{E \cdot t^3 + 24 \cdot K_z \cdot p \cdot r^3 + 0.732 \cdot E^{'} \cdot r^3} \tag{2}$$

where $E^{'}$ is the modulus of passive soil resistance and *r* is the radius of the pipe.

Also, the design of pipeline considers the effect of internal pressure on the pipe stress that can be calculated using the equation (3).

$$\sigma_p = \frac{(p_W + p_S) \cdot r}{t} \tag{3}$$

where p_W is the operating/working pressure and p_S is the surge pressure.

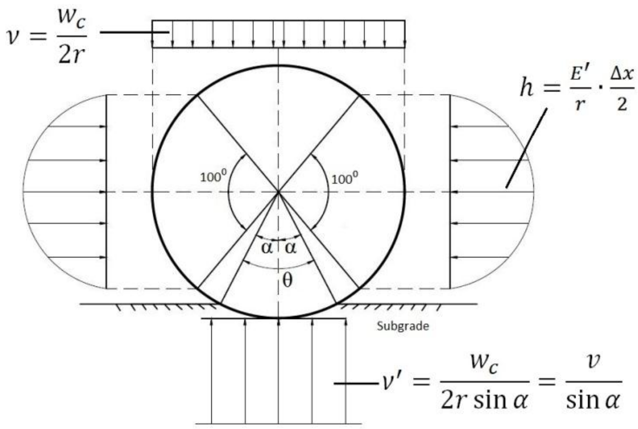

Figure 2: Assumed soil stress distribution around pipe (adapted from Masada [7])

Therefore, the total stress in the pipe can be estimated by adding the equations (2) and (3) to combine the effect of traffic and pressure loads. As stated above, the accuracy in predicting the pipe stress is questionable due to following reasons: (1) the Boussinesq theory is commonly used to estimate the traffic load experienced by the pipe, assuming that the loaded soil mass is homogeneous and neglects the presence of a stiff pipe within the soil; (2) the Spangler stress formula and the Iowa formula consist of somewhat inconsistent treatment of internal pressure stiffening and soil resistance effects (Masada [7]); (3) stress equations are based on assumed and approximate soil stress distribution around the pipe; (4) the variations of soil density that can occur in the various zones during pipe installation is not considered; and (5) the slip between the pipe and the surrounding soil is not considered. A more complete stress analysis using finite element method is able to reduce most of these limitations.

3. Numerical modelling of pipe-soil system

Three dimensional (3D) finite element (FE) analyses were carried out using ABAQUS 6.11/standard to obtain the pipe and soil stress distribution around the pipe. The soil was represented by 8-noded brick reduced integration elements and the pipe was represented by 8-noded shell reduced integration elements. The behaviour of both soil and pipe were assumed as a linear elastic material similar to what is assumed in the derivation of available analytical solutions (i.e., soil is assumed to be over-consolidated and behave elastically during the range of tested traffic loads). The soil side boundaries of the FE model were assumed to be smooth and are located far from the pipe (& traffic loads) to eliminate any boundary effects. Figure (3) shows the mesh discretization and model dimensions. The appropriate dimensions and the mesh density of the model were to reduce the computational time. In line with assumption made in the analytical solutions, the interaction between pipe and soil was assumed to be frictionless, and the traffic loads were simplified to point loads.

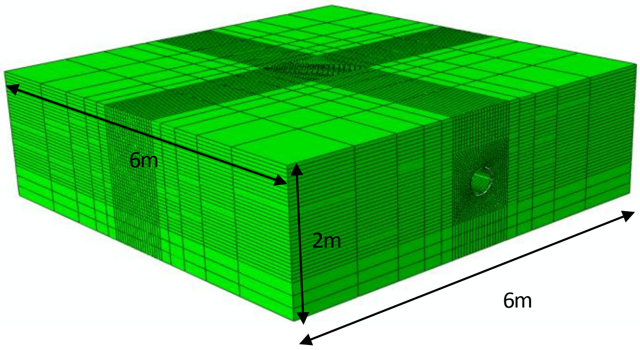

Figure 3: Model dimensions and mesh discretization of the finite element model

4. Development of Stress prediction Equation

The stress in the pipe depends on the magnitude and distribution of the external and internal loads, which the pipe is subjected, as well as the soil condition and pipe material and geometric properties. The contribution of each of these factors needs to be determined and incorporated in to the stress prediction models. In this study, the following variables are considered to develop the pipe stress prediction equation: traffic load (*W*), internal pressure (*P*), soil modulus (E_s), soil density (γ), lateral earth pressure coefficient (*k*), pipe diameter (*D*), pipe wall thickness (*t*), and burial depth (*h*). The finite element analyses were performed with varying levels of the variable and its combinations. Table 1 provides the variables and range considered for the FE simulations. The range for the variables was selected to represent the reality in the field conditions. On the basis of the selected parameters, 576 finite element simulations were performed to develop the stress prediction equation.

The maximum stress in the pipe was determined from the finite element analysis for all the possible combinations of the variable. The response surface method is used to develop the functional relationship between the maximum pipe stress and the variable as:

$$\sigma_{max} = f(D, W, t, k, P, h, E_s) \quad (4)$$

Table 1 . Variables and levels considered in the numerical analysis

Variable	Levels				No. of Levels
D (mm)	300	660	1000	-	3
W (kN)	20	40	60	70	4
t (mm)	8	15	-	-	2
k (-)	0.1	0.25	0.4	-	3
P (kPa)	300	800	-	-	2
h (mm)	800	2000	-	-	2
E_s (MPa)	10	50	-	-	2

4.1. Response Surface Method

Response surface methods (RSM) is a collection of mathematical and statistical techniques for solving problems in which the goal is to optimise the response *y* of a system or process using *n* independent variables, subject to observational errors (Montgomery [8]). Response surfaces are smooth analytical functions and are most often approximated by linear function (first order model) or polynomial of higher degree (such as the second-order model). The second order polynomial response surface has the form:

$$y = \beta_o + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i=1}^{n} \sum_{j=1}^{i} \beta_{ij} x_i x_j \tag{5}$$

The above equation is the regression equation, and β_0, β_i and β_{ij} are the regression coefficients. Estimates of the coefficients β_0, β_i and β_{ij} can be obtained by fitting the regression equation to the response surface values observed at a set of data points. For a second order response surface, (n+1)(n+2)/2 unknown regression parameters are presented and in order to estimate these parameters, an equal number of data points are needed. Different authors have reported generation of response surface method in reliability engineering (Burattia *et al.,* [9]; Möller *et al.,* [10]; Pinto [11]; Rajashekhar and Ellingwood [12], Faravelli [13]).

The various forms of functional relationship were checked to find the better stress prediction model in a systematic way (more details can be found in Merrin and Hung [14]). Some of the trial functions used the variable independently either in linear or quadratic forms. A few of the selected functions used the ratio of the independent variables. It was found that the relationship developed using ratio of the independent variables provides the better correlation to the FE model prediction. The variables listed in Table 1 were rearranged to form four different ratios, which gives the reasonably good prediction model, as: $x_1 = \frac{P \times D}{t}$; $x_2 = \frac{W}{(h \times t \times E_s)}$; $x_3 = \frac{W}{(h \times t \times k)}$; and $x_4 = \frac{W}{(h \times t \times P)}$.

Based on the new variable the maximum stress in the pipe can be written as

$$\sigma_{max} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 \tag{6}$$

The regression coefficients were computed and listed in Table 2. The following units are adopted for the input variable in Eq (6): *P* and E_s are in MPa; *W* is in MN; *t*, *h*, and *D* are in m; and the output stress is in MPa.

Table 2: The regression coefficients

Parameter	Value
β_0	7.7256
β_1	0.422
β_2	22.455
β_3	0.0233
β_4	-0.2512

Figure (4) shows the comparison of the simulated finite element stress values and model predicted values. The comparison has the coefficient of determination of 0.95318, which is acceptable in the real world applications.

The accuracy of the developed model prediction was tested using the 20 randomly generated input variables. The values for the random samples were selected to be with the data space used to develop the model. The coefficient of determination is around 0.98, which is higher than the model prediction. This may be due to the fact that number of samples used in the simulation is small compare to the number of samples used in model development (more than 500). This cannot represent the possible dispersion that can occur in the prediction. However, minimum coefficient of determination of any pipe stress predicted using the developed model is above 0.953.

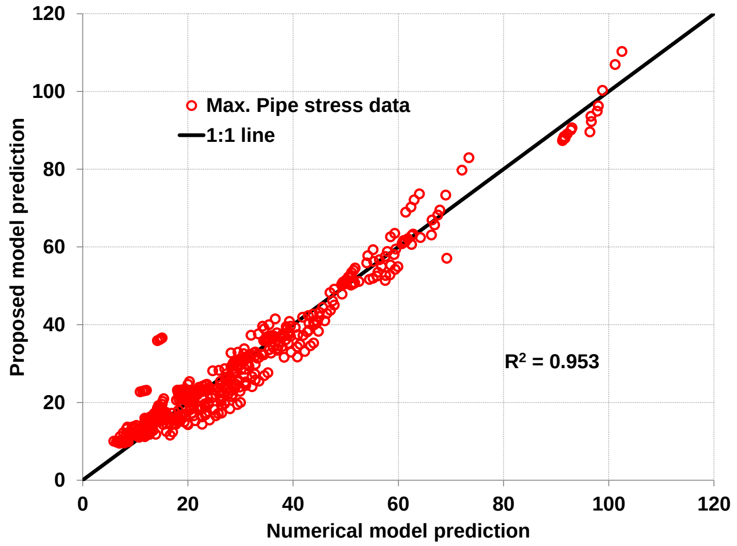

Figure 4: Comparison of proposed equation and numerical model prediction

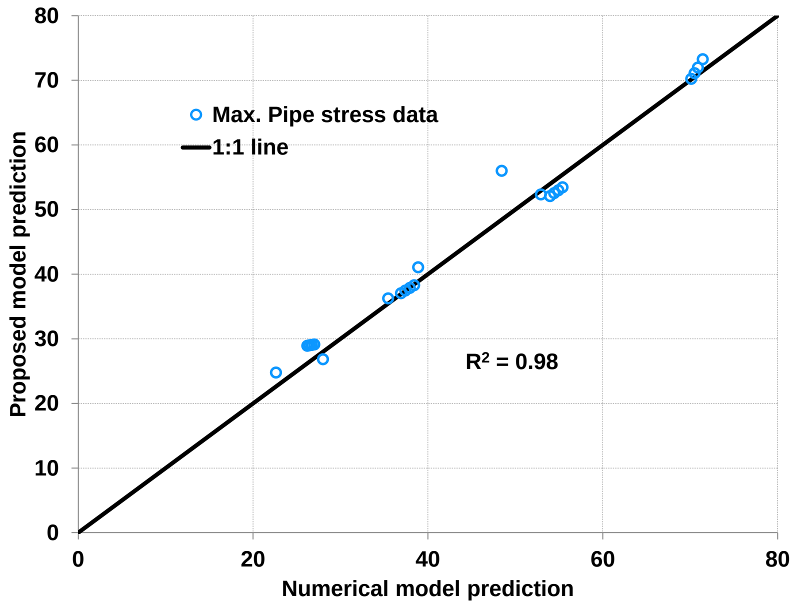

Figure 5: Comparison of proposed equation and numerical model prediction for random simulations

4.2. Sensitivity analysis

Finally, the sensitivity analysis was performed to investigate the relative contribution of each variable in the model prediction. Spearman's rank correlation coefficient (Spearman [15]) was used to perform the sensitivity. The correlation coefficient was computed for each controlling variable with the maximum pipe stress determined from the FE simulations. The correlation coefficient computed was normalised to find the relative sensitivity of each parameters on the pipe stress. Figure (6) shows the result of the sensitivity analysis. The traffic load, pressure and pipe wall thickness have significant contribution to the pipe stress.

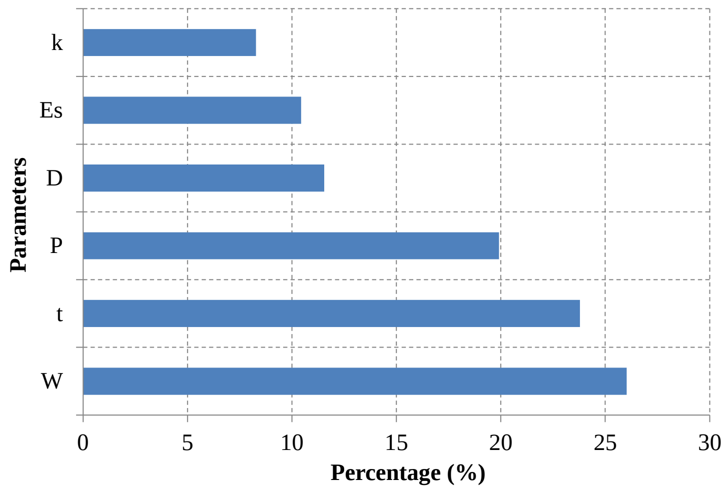

Figure 6: Results of the sensitivity analysis

The effect of each variable on pipe stress prediction was also analysed. Figure (6) shows the effect of diameter and the traffic load have the positive correlation with pipe stress while the lateral earth pressure coefficient and pipe wall thickness have the negative correlation.

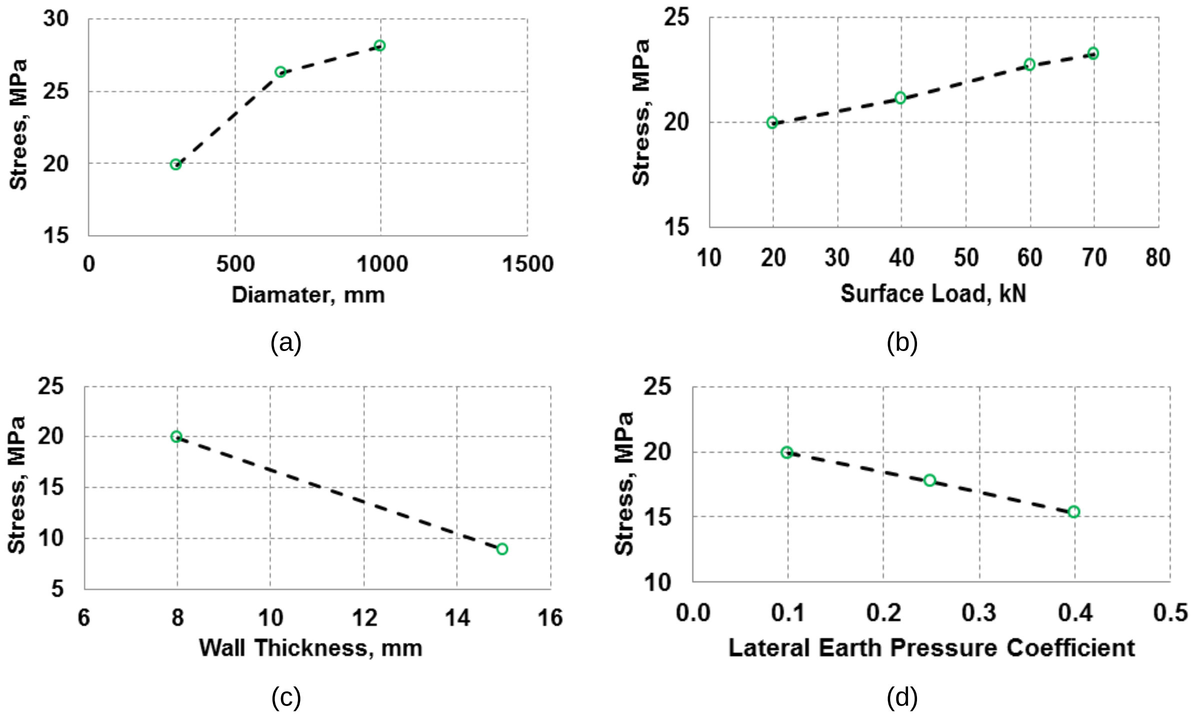

Figure 6: Effect of input variable in pipe stress: (a) pipe diameter (b) traffic load, (c) pipe wall thickness and (d) lateral earth pressure coefficient

7. Summary and Conclusions

This paper developed a new pipe stress prediction equation to estimate the stresses in buried pipe. A 3-D finite element model of the pipe-soil system was developed to obtain the maximum stress in pipes subjected to internal and external loads. The possible variation in the input variables was considered in the analysis to cover the entire practical space of the problem. The sensitivity analysis was also performed to study the relative contribution of each variable in pipe stress. Finally, the response surface method (RMS) was used to develop the functional relationship between the pipe stress and the input variables. The developed model predicts the simulated pipe stress with high accuracy. However, it is not advisable to use the current model to predict the pipe stress outside the range of the input variables considered in this study. Further study in this direction is necessary to improve the model.

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