Failure Probability Model of Buried Pipeline

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ABSTRACT: *This paper presents the effect of external corrosion, material properties, operation condition and design thickness in pipeline on failure prediction using a failure probability model. The effects of environmental, operational, and design random variables such as a defect depth, a pipe diameter, a defect length, fluid pressure, a corrosion rate, a material yield stress and a pipe thickness on the failure probability are systematically studied using a failure probability model for the corrosion pipeline.*

INTRODUCTION

The skill of maintenance and management of the industrial equipments has been emerged as a very important technique to be properly dealt with since the industrial apparatus becomes more complicate and diversified throughout all kinds of industries with the development of various mechanical techniques. It has been often reported as an industrial example in that a catastrophic disaster has been caused by the defect like corrosion arisen by aging and/or environmental effect in pipeline transporting gas and oil[1,2].

The effects of various environmental conditions, such as internal fluid pressure, external soil, traffic loads, temperature change and corrosion on the buried pipelines have been studied by many investigators[3].

This paper identifies varying pipeline stresses corresponding to various boundary conditions and pipeline corrosion. A probability model is used to investigate the effects of environmental, operational, and design random variables such as a defect depth, a pipe diameter, a defect length, fluid pressure, a corrosion rate, a material yield stress and a pipe thickness on the failure probability are systematically studied using a failure probability model for the corrosion pipeline.

PIPELINE STRESSES

Longitudinal stresses

Change in temperature

The change in temperature of pipeline restrained in axial direction generally induces axial stresses by the restrained thermal strains of $\varepsilon_{lt} = \alpha\, \Delta\delta$. Applying Hooke's law to determine σ_{lt}, the following is obtained.[7]

$$\sigma_{lt} = E\alpha\, \Delta\delta \tag{1}$$

where σ_{lt} is the axial thermal stresses in the buried pipeline restrained in axial direction induced by the change in temperature, E is the elastic modulus of pipeline material, α is the thermal expansion coefficient and $\Delta\delta$ is the change in temperature.

Effect of internal pressure

The axial stresses, σ_{lf}, induced in the buried pipeline restrained in axial direction with inner pressure, p, can be estimated by superposition of the stresses by the Poisson's effect induced by the volume expansion[5].

$$\sigma_{lf} = \frac{\nu p\, r}{t} \tag{2}$$

where σ_{lf} is the axial tensile stresses by the inner pressure in buried pipeline restrained in axial direction, ν is the Poisson's rate, p is the inner pressure, r is the inner radius of buried pipeline and t is the thickness of buried pipeline.

Stresses by bending of pipeline

The bending deformation produced by the effect of boundary conditions such as the movement of soil and/or nonuniform fabrication of pipeline on the straight buried pipeline would generate the maximum axial stresses, σ_{lb}.

$$\sigma_{lb} = \frac{Er}{R} \tag{3}$$

where σ_{lb} is the maximum axial stresses, E is the elastic modulus, R is the bending radius of curvature in buried pipeline and r is the outer radius of cross section in buried pipeline.

If the buried pipeline was initially curved to have radius of curvature of R', then the maximum axial stresses, σ_{lb}, is modified as

$$\sigma_{lb} = Er(\frac{R' - R}{RR'}) \tag{5}$$

where is R is the bending radius of curvature in buried pipeline.

The maximum longitudinal stress due to bending (σ_{lb}) can be estimated by[5]

$$\sigma_{lb} = Er\aleph \tag{6}$$

where $\aleph$ is the longitudinal curvature of the pipe.

Effect of soil-friction

The Poisson's effect and the effect of change in temperature may be neglected unless the length of pipeline is very long for the gasket joint buried pipelines.

However, for the very long buried pipelines, it should be noted that the temperature change and Poisson's effect may induce comparable axial stresses.

The axial stresses, $\sigma_{l\mu}$, induced by the friction arisen between long buried pipeline and soil can be represented as

$$\sigma_{l\mu} = \frac{LH\gamma\mu}{2t} \tag{7}$$

where $\sigma_{l\mu}$ is the axial stresses induced in buried pipeline due to the friction between pipeline and soil, L is the length of buried pipelines, H is the height of soil cover above buried pipeline, γ is the unit weight of soil cover, μ is the friction coefficient between buried pipeline and soil and t is the thickness of buried pipeline.

Effect of earthquake

Under the assumption that the buried pipe moves together with the surrounding soil, the maximum axial strain ε_a in a section of a long horizontal pipe are conservatively determined by the following equations[9],

$$\varepsilon_a = \pm \frac{v}{V_a} \tag{8}$$

where v is the particle velocity and V_a is the apparent wave velocity.

The maximum axial stress of straight pipe σ_{ls} is simply calculated from

$$\sigma_{ls} = E\varepsilon_a \tag{9}$$

The maximum longitudinal stress(σ_l) in the pipe wall is then obtained as:

$$\sigma_l = \sigma_{lf} + \sigma_{lt} + \sigma_{lb} + \sigma_{l\mu} + \sigma_{ls} \tag{10}$$

Circumferential stress

Effect of internal pressure

The circumferential stress due to internal fluid pressure(σ_{cf}) can then be estimated by[5,8]

$$\sigma_{cf} = \frac{pr}{t} \tag{11}$$

where p is the inner pressure, r is the inner radius of buried pipeline and t is the thickness of buried pipeline.

Loading of soil

The bending stress in the circumferential direction (σ_{cs}) produced in the pipe wall due to the loading of the overlying soil can be estimated from the following expression[5]

$$\sigma_{cs} = \frac{6k_m C_d \gamma B_d^2 Etr}{Et^3 + 24k_d pr^3} \tag{12}$$

where C_d is the coefficient for earth pressure, γ is the unit weight of soil backfill, B_d is the width of ditch at the level of the top of the pipe, E is the modulus of elasticity of the pipe material, k_m is the bending moment coefficient and k_d is the deflection coefficient.

Traffic loads

A rather similar expression can be used for the estimation of circumferential bending stress(σ_{ct}) produced in the pipe wall by the external traffic loads. The relevant expression is[5]

$$\sigma_{ct} = \frac{6k_m I_c C_t FEtr}{L_e(Et^3 + 24k_d pr^3)} \tag{13}$$

where I_c is the impact factor, C_t is the surface load coefficient, F is the wheel load of traffic and L_e is pipe effective length.

Effect of width of narrow trench

The width of trench, thus, is dependent on the duality of sidefill soil. However, it is well known that the width of trench is limited 2 times the diameter of buried pipelines if the cross-section of buried pipelines are close to the circle configuration. The compressive stresses induced on the wall of buried pipelines under the boundary condition mentioned the above is

$$\sigma_{cr} = \frac{\mathrm{Pr}}{t} \tag{14}$$

where σ_{cr} is the compressive stresses in buried pipelines wall, P is the normal compression of buried pipelines ($= P_l + P_d$), P_l is the surface live load, P_d is the dead load pressure for flexible pipeline ($\cong \gamma H$), γ is the unit weight of soil, H is the height of soil cover, t is the thickness of buried pipeline and r is the radius of buried pipeline.

The maximum circumferential stress(σ_c) in the pipe wall is then obtained from:

$$\sigma_c = \sigma_{cf} + \sigma_{ct} + \sigma_{cs} + \sigma_{cr} \tag{15}$$

EFFECT OF PIPELINE CORROSION

Corrosion in underground pipelines results in the loss of effective pipe wall thickness. The loss of wall thickness may be modeled empirically by a power law first postulated for atmospheric corrosion.

$$Q = kT^n \tag{16}$$

where Q is the loss of wall thickness, k is the multiplying constant, T is the time of exposure and n is the exponential constant.

FAILURE PROBABILITY OF PIPELINE

In this paper, a well-known failure criteria Von-Mises has been used to assess the failure of buried pipelines according to these theories the failure may be represented by the following inequality[4].

$$\sigma_c^2 - \sigma_c \sigma_l + \sigma_l^2 >> \sigma_y^2 \tag{17}$$

where σ_c is the circumferential stress, σ_l is the longitudinal stress and σ_y is the material yield stress.

Using a factional z in the following form

$$z = \sigma_y^2 - (\sigma_c^2 - \sigma_c \sigma_l + \sigma_l^2) \tag{18}$$

It is generally accepted to represent the average failure probability as

$$P_f = P(z < 0) = \Phi(-\beta) \tag{19}$$

Where $\Phi(\cdots)$ is the distribution function of variables. β is the reliability index and can be expressed in terms of the average of z (u_z) and the average variation (σ_z) as

$$\beta = \frac{u_z}{\sigma_z} \tag{20}$$

where

$$u_z = z(L_e^*, B_d^*, C_d^*, \cdots, \Delta\theta^*) + (\overline{L_e} - L_e^*)\frac{\partial z}{\partial L_e} +, \cdots, +(\overline{\Delta\theta} - \Delta\theta^*)\frac{\partial z}{\partial \Delta\theta} \tag{21}$$

$$\sigma_z^2 = (\sigma_{L_e}\frac{\partial z}{\partial L_e})^2 + (\sigma_{B_d}\frac{\partial z}{\partial B_d})^2 + (\sigma_{C_d}\frac{\partial z}{\partial C_d})^2 +, \cdots, +(\sigma_{\Delta\theta}\frac{\partial z}{\partial \Delta\theta})^2 \tag{22}$$

$\overline{L_e}, \overline{B_d}, \overline{C_d}, \cdots, \overline{\Delta\theta}$ are the average values and $L_e^*, B_d^*, C_d^*, \cdots, \Delta\theta^*$ are the values at an inspection time. $\sigma_{L_e}, \sigma_{B_d}, \sigma_{C_d}, \cdots, \sigma_{\Delta\theta}$ are the average variations for each variable. The average variance for each variable is the multiplication of the average of each variable to the coefficient of variation.

The failure probability at the N^{th} check point can be represented as

$$P_f = 1 - (1 - P_{f_1})(1 - P_{f_3}) \cdots (1 - P_{f_n}) \tag{23}$$

EXAMPLE PROBLEM

The variables, means and coefficient of variation listed in TABLE 1 have been utilized to investigate the effect of each variable on the failure probability of corrosion pipeline[6].

TABLE 1: Random variables and their parameters used in the example

Variable Symbol	Mean	Coefficient of variation	Variable Symbol	Mean	Coefficient of variation
E	201Mpa	0.033	V_a	762m/s	0.1
α	11.7×10^{-6}°C	0.1	k_m	0.235	0.15
ΔT	10°C	0.15	C_d	1.32	0.2
p	5Mpa	0.1	B_d	760mm	0.1
r	225mm	0.04	k_d	0.108	0.15
t	7mm	0.06	I_c	1.25	0.2
χ	-1.0×10^{-6}rad/mm	0.1	C_t	0.12	0.15

L	10000mm	0.1	F	150kN	0.1
H_s	700mm	0.1	L_e	1000mm	0.1
γ	18.9×10^{-6}N/mm	0.1	k	0.02	0.56
μ	0.3	0.1	n	0.53	0.26
v	3.425m/s	0.1	σ_y	400MPa	0.05

RESULTS AND DISCUSSIONS

Figure 1 shows the relationship between the failure probability of the corrosion pipeline and the exposed period in years by utilizing practical data listed in TABLE 1. It is noted from Figure 1 that the failure probability increases slowly during a period between 0 and 30 years and the rate of increase is found to be very fast after 30 years of exposure period.

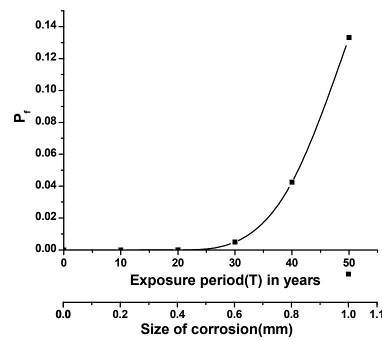

Figure 1: A relationship between failure probability(P_f) and exposure period(T).

Figures 2-7 show the aspect of change in the failure probability corresponding to the each variable appeared in TABLE 1. Figure 2 and Figure 3 show the increase of failure probability as the increase of operation service inner gas pressure and the corrosion rate.

Figure 4 show the variation of the failure probability corresponding to the yield stresses of the pipeline. The corrosion rate is known to be highly affected by the environment in which the pipeline is set. However, the change of the corrosion rate is found to be dependent on the exposed period even under the same environmental condition. Figure 5 shows the variation of the failure probability corresponding to the ratio variation of the corrosion rate for varying exposure periods. The larger the variation ratio, the increase of failure probability becomes more pronounced.

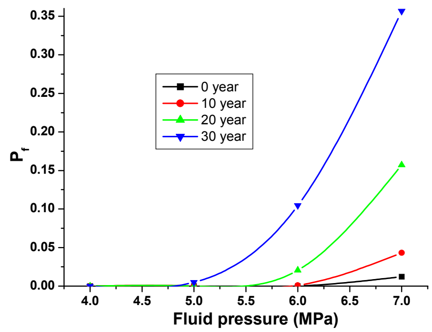

Figure 2: Relationships between failure probability(P_f) and fluid pressure(p_a) for varying exposure periods(T)

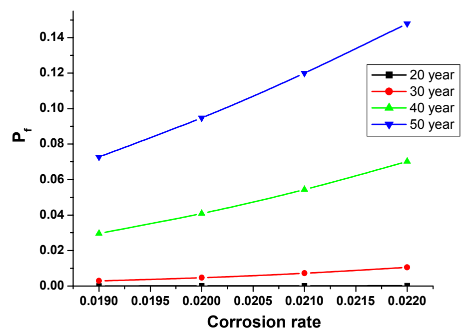

Figure 3: Relationships between failure probability(P_f) and corrosion rate(R_d) for varying exposure periods(T)

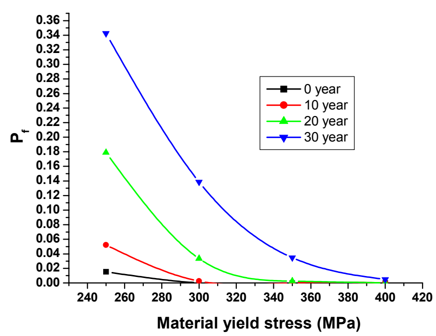

Figure 4: Relationships between failure probability(P_f) and material yield stress(σ_y) for varying exposure period(T)

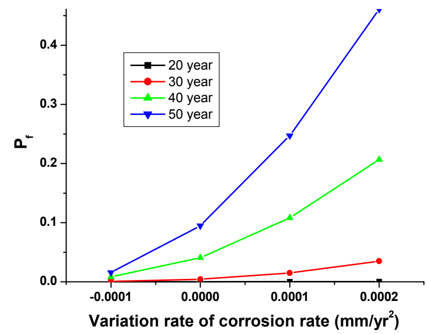

Figure 5: Relationships between failure probability(P_f) and variation rate of corrosion rate for varying exposure periods(T)

CONCLUSIONS

In this study, the effect of varying boundary condition on the stresses and the deformation behavior in the pipelines are studied systematically.
1) The model can accommodate both circumferential and longitudinal stresses, as well as the degradation of pipelines by environmental factor such as corrosion.
2) For old pipelines, corrosion parameters appear to be the most significant among all the random variables.

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