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Failure Probability of Corrosion Defective Pipelines Considering Failure Correlation between Pipe Sections

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Abstract

In previous studies, the pipeline is usually regarded as an independent system, and there is no connection between the pipe sections, while for the same pipeline, there is often a connection between the pipe sections due to the same internal pressure, the material of each section is not very different, and other similar corrosion environments [1].

The size of the pipe in the axial direction is much larger than the size of the other directions, for the pipe, rope and such one-dimensional length of the engineering structure is very large size effect [2], in the calculation of the pipe reliability, the pipe should be regarded as a continuous system, cannot be regarded as a simple component, if the correlation between the pipe segments is not taken into account will cause a large error [3][4]. In view of this, this paper explores the influence of correlation between pipe segments on the probability of pipeline failure on the basis of previous research by scholars.

Keywords: pipeline , correlation , corrosion

1. Iintroduction

Ignoring the correlation between each pipe section, the estimated failure probability will be too high, resulting in unnecessary pipe replacement and a waste of manpower and financial resources.

As a system with a large length, the pipeline needs to consider the correlation between each pipe section when analyzing the reliability of the pipeline. This article will use the two-stage method to analyze the probability of pipeline failure.

2. Calculation of wide-bound failure probability of series systems

The failure of each pipe segment in the pipeline system will cause the entire pipeline to fail to operate normally, so we can think of the pipeline as being composed of several units connected in series. For series systems, failure of any unit will result in failure of the entire structure[i][ii].

The failure of a pipe segment i is recorded as event A_i, and the failure probability is p_{fi}, then:

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$$p_f \geq \max_{1 \leq i \leq m} p_{fi} \tag{1}$$

When each pipe section is completely correlated, its failure probability is:

$$p_f = \max_{1 \leq i \leq m} p_{fi} \tag{2}$$

When each pipe section is completely independent, its failure probability is:

$$p_f = 1 - \prod_{i=1}^{m} (1 - p_{fi}) \tag{3}$$

In actual engineering, the correlation between each pipe section is between complete correlation and complete independence. Therefore, the failure probability of a wide range is:

$$\max_{1 \leq i \leq m} p_{fi} \leq p_f \leq 1 - \prod_{i=1}^{m} (1 - p_{fi}) \tag{4}$$

3. Narrow bounds on failure probability of series systems

The correlation between different corrosion defects in the same pipeline is not considered in the wide bounds of failure probability, and according to the knowledge of probability theory, the failure probability formula for any event

$$\begin{aligned} P(A) = {} & P(A_1) + P(A_2) - P(A_1 A_2) \\ & + P(A_3) - P(A_1 A_3) - P(A_2 A_3) + P(A_1 A_2 A_3) \\ & + P(A_4) - P(A_1 A_4) - P(A_2 A_4) - P(A_3 A_4) \\ & + P(A_1 A_2 A_4) + P(A_1 A_3 A_4) + P(A_2 A_3 A_4) - P(A_1 A_2 A_3 A_4) \\ & + P(A_5) - \cdots \\ = {} & \sum_{i=1}^{m} P(E_i) - \sum_{1 \leq i < j \leq m} P(A_i A_j) + \sum_{1 \leq i < j < k \leq M} P(A_i A_j A_k) \\ & + \cdots + (-1)^{m-1} P(\bigcap_{i=1}^{m} A_i) \end{aligned} \tag{5}$$

in probability theory. $P(A_i A_j) \geq P(A_i A_j A_k) \geq \cdots \geq P(A_i A_j A_k \cdots A_m)$ If only the above $P(A_i) - P(A_i A_j)$ formula is retained

$$P(A) \geq P(A_1) + \sum_{i=2}^{m} \max\left[P(A_i) - \sum_{j=1}^{i-1} P(A_i A_j), 0 \right] \tag{6}$$

$$P(A_3)-P(A_1A_3)-P(A_2A_3)+P(A_1A_2A_3)=P(A_3)-P\left[(A_1A_3)\cup(A_2A_3)\right] \leq P(A_3)-\max_{j<3}P(A_jA_3) \tag{7}$$

So

$$P(A)\leq\sum_{i=1}^{m}P(A_i)-\sum_{i=2}^{m}\max_{j<i}P(A_iA_j) \tag{8}$$

Therefore, the second-order narrow bound failure probability limit is:

$$P(A_1)+\sum_{i=2}^{m}\max\left[P(A_i)-\sum_{j=1}^{i-1}P(A_iA_j),0\right]\leq P(A)\leq\sum_{i=1}^{m}P(A_i)-\sum_{i=2}^{m}\max_{j<i}P(A_iA_j) \tag{9}$$

4. Calculate pipeline failure probability through multivariate normal distribution function

The pipeline is regarded as a whole and its reliability index is β, then the pipeline failure probability[iii]

$$P_f=\phi(-\beta) \tag{10}$$

The pipeline can be seen as consisting of several pipe segments. If the reliability of each pipe segment $\beta_1,\beta_2,\cdots\beta_n$ and the failure correlation coefficient matrix between each pipe segment is ρ, then the failure probability of the pipeline is:

$$P_f=\phi(-\beta_1,-\beta_2,\cdots\beta_n,\rho) \tag{11}$$

When calculating the failure probability of the whole pipeline, it involves the calculation of the multivariate normal distribution function. The multivariate normal distribution is the extension of the monadic normal distribution to binary or multivariate variables, and it is a probability distribution of vectors composed of related random variables. Each variable follows the monadic normal distribution, assuming that all variables are independent of each other.

Assume that the random vector $X=(X_1,X_2,X_3\cdots X_n)^T$ obeys the normal distribution, assuming that its mean is μ_X, the covariance matrix is C_X, and its normal distribution probability density function and cumulative distribution function are:

$$f_N(x|\mu_X,C_X)=\frac{1}{(2\pi)^{n/2}\sqrt{\det C_X}}\exp\left[-\frac{1}{2}(x-\mu_X)^T C_X^{-1}(x-\mu_X)\right] \tag{12}$$

$$F_N(x|\mu_X)=\int_{-\infty}^{x}f_N(x|\mu_X,C_X)dx \tag{13}$$

It can be seen from the above formula that the calculation of multivariate normal distribution function is a process of calculating multiple integrals, and its calculation is relatively complicated

Assume that the random vector $Y = (Y_1, Y_2, Y_3 \cdots Y_n)^T$ obeys the standard normal distribution, and its mean value $\mu_Y = 0$, variance $\sigma_Y = 1$, and the correlation coefficient matrix are ρ_Y , and the covariance matrix is $C_Y = \rho_Y$, then the probability density function and cumulative distribution function of the standard normal distribution are respectively:

$$\varphi_n(y|\rho_Y) = \frac{1}{(2\pi)^{n/2}\sqrt{\det \rho_Y}} \exp(-\frac{1}{2} y^T \rho_Y^{-1} y) \tag{14}$$

$$\varphi_n(y|\rho_Y) = \int_{-\infty}^{y} \phi_n(y|\rho_Y) dy \tag{15}$$

The probability density function and cumulative distribution function of the binary standard normal distribution can be obtained

$$\varphi_2(y_1, y_2|\rho_{12}) = \frac{1}{2\pi\sqrt{1-\rho_{12}^2}} \exp\left[-\frac{y_1^2 - 2\rho_{12} y_1 y_2 + y_2^2}{2(1-\rho_{12}^2)}\right] \tag{16}$$

$$\Phi_2(y_1, y_2|\rho_{12}) = \int_{-\infty}^{y1}\int_{-}^{y2} \varphi_2(y_1, y_2|\rho_{12}) d_{y1} d_{y2} \tag{17}$$

Among them, ρ_{12} is the correlation coefficient.

Regarding the binary standard normal distribution, the document [iv] Ditlevsen proposed the following approximate calculation method

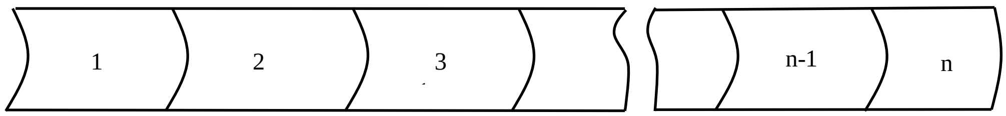
$$\begin{cases} \max(P_1, P_2) \le \Phi_2(y_1, y_2|\rho_{12}) \le P_1 + P_2 & \rho_{12} \ge 0 \\ 0 \le \Phi_2(y_1, y_2|\rho_{12}) \le \min(P_1, P_2) & \rho_{12} < 0 \end{cases} \tag{18}$$

$$\begin{cases} P_1 = \Phi(y_1)\Phi\left(\dfrac{y_2 - \rho_{12} y_1}{\sqrt{1-\rho_{12}^2}}\right) \\ P_2 = \Phi(y_2)\Phi\left(\dfrac{y_1 - \rho_{12} y_2}{\sqrt{1-\rho_{12}^2}}\right) \end{cases} \tag{19}$$

5. Pipeline failure probability calculation

Considering that the pipeline is composed of multiple different pipe sections, since different pipe sections are affected by similar corrosion factors, there must be some correlation between different pipe sections. This section explores the impact of the failure correlation coefficient between different pipe sections on the failure probability of the entire pipeline.

Analyze the range of changes in the failure correlation coefficient between each pipe section and the impact on the failure probability of the entire pipeline. Analyze the impact of the failure correlation coefficient between pipe sections on the failure probability of the entire pipeline under the different reliability indicators of each pipe section. This section uses a multivariate normal function. Calculation method, combined with wide and narrow limits for comparative analysis.



Picture 1 Pipeline segmentation diagram

The pipeline system is considered to be composed of multiple different pipe sections. It is assumed that the pipeline is composed of different units. Let the ultimate reliability state equation of the pipeline section be:

$$Z_i = P_i - P_{\mathrm{op}} \tag{20}$$

Then the probability of safe operation of the pipeline is:

$$P = P(Z_1 \geq 0 \bigcap Z_2 \geq 0 \bigcap \cdots Z_n \geq 0) \tag{21}$$

Calculation method of failure correlation coefficient between different pipe sections:

$$\rho_{Z_i,Z_j} = \frac{Cov(Z_i, Z_j)}{\sigma_{Z_i}\sigma_{Z_j}} = \frac{\sigma_{P_i}{}^2 + \sigma_{P_j}{}^2}{\sigma_{Z_i}\sigma_{Z_j}} \tag{22}$$

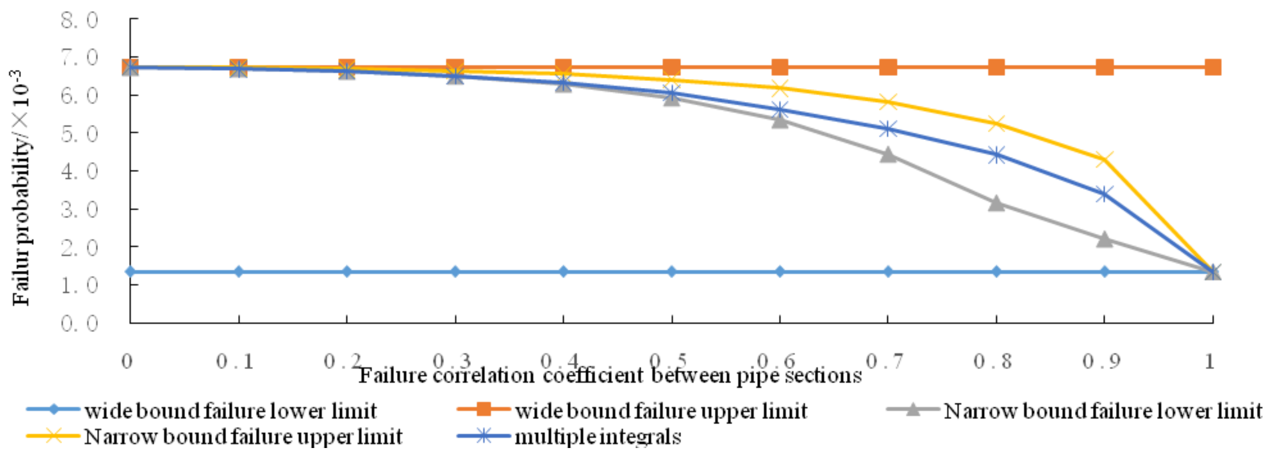


Figure 2 The number of pipe sections is 5, the reliability index of each pipe section is 3, and the pipeline failure probability

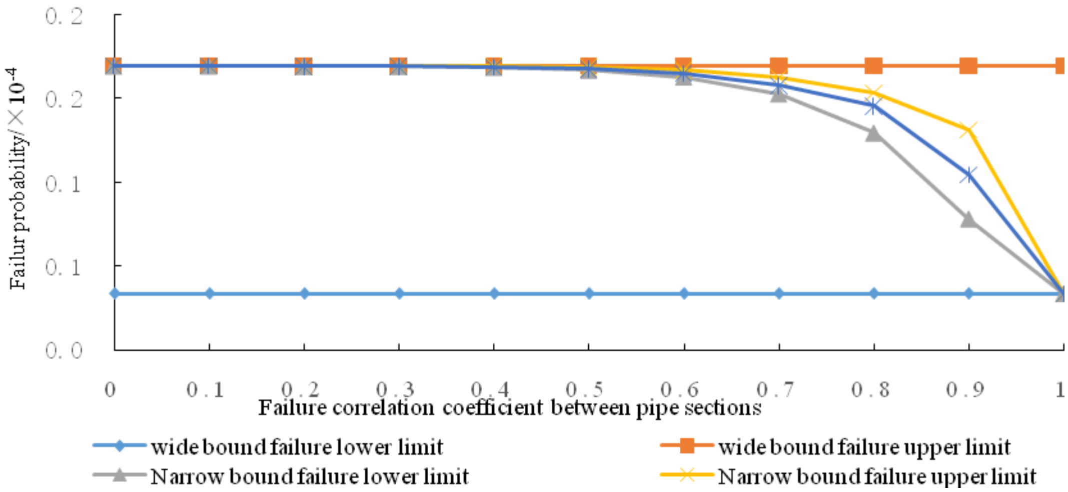


Figure 3 The number of pipe sections is 5, the reliability index of each pipe section is 4.5, and the pipeline failure probability

As the correlation coefficient of failure between pipe sections increases, the upper and lower limits of wide-bounded failure do not change. The upper and lower limits of narrow-bounded failure gradually decrease as the correlation coefficient increases. The failure probability calculated using the multiple integration method also increases with the failure rate between pipe sections. The correlation coefficient increases and shows a gradually decreasing trend. It can be seen that if the correlation between different pipe sections is ignored, the pipeline failure probability will be overestimated.

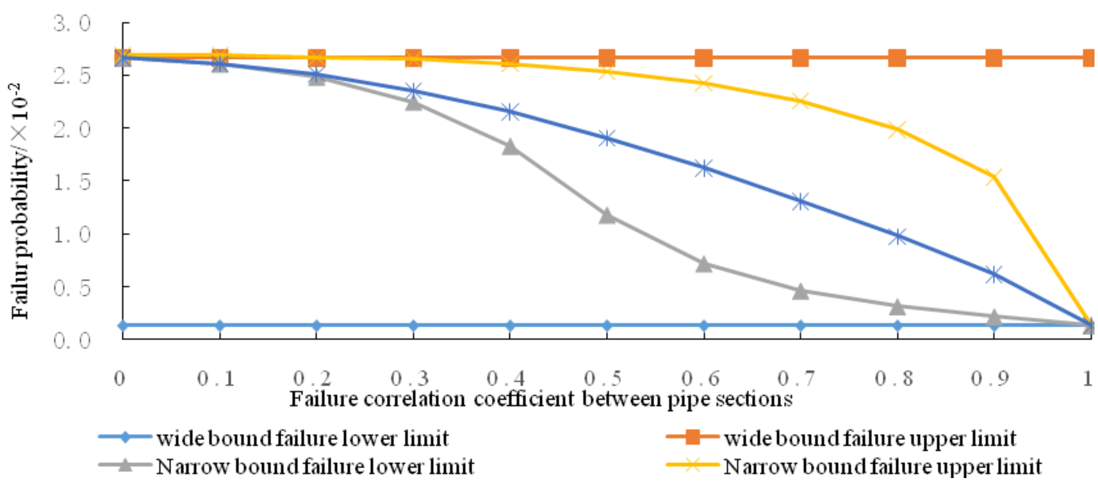


Figure 4 The number of pipe sections is 10, the reliability index of each pipe section is 3, and the pipeline failure probability

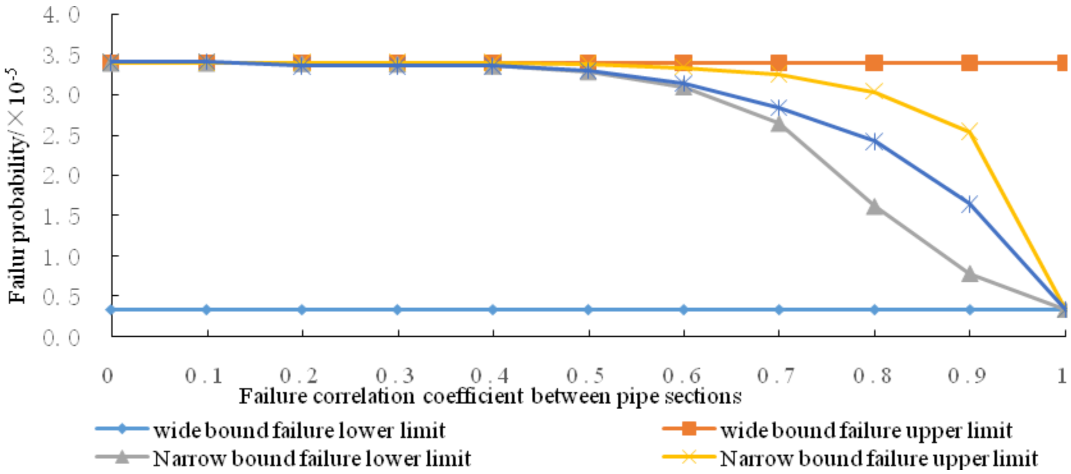


Figure 5 The number of pipe sections is 10, the reliability index of each pipe section is 4.5, and the pipeline failure probability

When the failure correlation coefficient between pipe sections is less than 0.5, whether to consider the failure correlation coefficient between pipe sections has little impact on the calculation of pipeline failure probability. When the failure correlation coefficient between each pipe section is greater than 0.5, ignoring the correlation between pipe sections will lead to a large deviation in the results.

At the same time, as the number of pipe sections increases, the probability of pipeline failure shows an upward trend, and if the correlation between pipe sections is not considered to be too high, the probability of pipeline failure also increases.

It can be seen that when the pipeline length is too large, ignoring the correlation between each pipe section will lead to an overestimation of the pipeline failure probability, and the evaluation results will be conservative, resulting in unnecessary repairs and replacements.

6. Results

(1) This paper introduces the calculation method of wide failure boundary that ignores the failure correlation between pipe sections and the narrow failure boundary that considers the correlation between pipe sections.

(2) Using the multivariate normal function, the failure probability of the entire pipeline is calculated when the reliability indicators of each pipe section are different and the failure correlation coefficients between pipe sections are different.

(3) The results show that if the correlation between pipe sections is ignored, the pipeline failure probability will be overestimated, and the degree of overestimation increases with the increase in

the failure correlation coefficient between pipe sections and the number of pipe sections, causing unnecessary Repair and pipe replacement work.

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