A New Risk-based Excavation Inspection Decision-making for Long-distance Pipelines

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Abstract. With the number of long-distance pipelines increasing in China, the excavation inspection and maintenance is the most important means to avoid the leakage of pipeline. However, the current excavation and maintenance decision-making models are absent to make satisfying results based on the comprehensive data of pipeline. To address this problem, a new quantitative risk-based model is proposed to guide decision-making on excavation inspection and maintenance. Based on previous failure cases, the model includes data about the surrounding soils as well as about the pipeline’s protective layer, cathodic protection and thickness readings. Case of the proposed model on previous failure cases shows that the new model can correctly predict a rational excavation inspection and maintenance span for a long-distance pipeline during its whole service life.

1. Introduction

As a cheap and efficient way of energy transportation, pipelines are widely used all around the world, and the proportion of developed countries make up about 60-70% of the total energy transportation capacity. China started late in using pipelines for energy transportation but has developed rapidly. By the end of 2015, the total length of long-distance pipeline trunks in China had exceeded 10 x 104 km [1, 2], most of which are buried pipelines. Affected by soil corrosion, stray current, transportation medium corrosion and other factors, the pipeline body has suffered from corrosion damage, and its service life has been significantly reduced [3-7]. Approximately 30–40 % of long-distance pipeline accidents are caused by corrosion [8, 9]. This figure compares with more than 18% of long-distance pipeline accidents in the United States (of which 45% are external corrosion accidents), more than 33% (42.7% external corrosion) in Russia, and 24% in Europe. Furthermore, leakage problems are more severe in China, with corrosion accidents accounting for about 70% of all accidents in some enterprises and 47.4% of accidents being caused by the external corosions [10, 11]. The long-distance pipeline accident types in China are shown in Fig. 1. NACE proposed a corrosion evaluation method allows for potential external corrosion problems due to damage of the protective layer [12]. However, the method is only to guide the selection of excavation inspection locations. So quantitative model is proposed to predict the optimal excavation and maintenance span based on a semi-quantitative assessment model that comprehensively evaluates the influence of various detection data on the external corrosion risk of long-distance pipelines.
2. Excavation inspection decision-making model based on risk

2.1. Risk-based decision-making threshold on excavation inspection

Based on the risk matrix shown in Fig. 2 and Table 1, and the total failure risk score, $R$, can be expressed as Eqs (1),(2) and (3) according to Ref [12].

$$R = S \cdot C$$ (1)

$$S = 100 - (a_1 S_1 + a_2 S_2 + a_3 S_3 + a_4 S_4)$$ (2)

$$C = \sum_i C_i$$ (3)

where: $S$ is the total damage score of the pipeline body; $a_1$ is the correction coefficient of the third-party damage score in the failure probability score correction model during the in-service stage; $a_2$ is the correction coefficient of the corrosion damage score in the failure possibility score correction model during the in-use stage; $a_3$ is the correction coefficient of the equipment (device) and personnel operation score in the failure possibility score correction model during the in-service stage; $a_4$ is the correction coefficient of the body...
safety score in the failure possibility score correction model during the in-service stage; $S_t$ is the third-party damage score in the failure probability score correction model during the in-service stage; $S_r$ is the corrosion damage score in the failure probability score correction model during the in-service stage; $S_b$ is the equipment (device) and improper operation damage score in the failure probability score correction model during the in-service stage; and $C$ is the body safety score in the failure probability score correction model during the in-service stage; $C$ is the total score of leakage consequence; and $C_i$ is the score of each item leakage consequence.

In Eq. (2), the best choice of correction coefficients $a_1$, $a_2$, $a_3$, and $a_4$ is based on the statistical results of previous failure cases in the pipeline, but in most cases, the statistical results might not be very reliable or even available. In this situation, it can be assumed that the probabilities of the four kinds of pipeline problems are equal; that is, each correction coefficient is 0.25. Then, according to the later statistical results, Bayesian analysis is used to iterate the correction coefficients, as shown in Eq. (4), so as to keep close to the real state of the pipeline body and make full use of the relevant data that can be retrieved from some references.

\[
p^{(i+1)} = \frac{p^{(i)} \cdot q_i}{\sum_{j=1}^{N} p^{(i)} \cdot q_j}
\]

(4)

where: $p^{(i)}$ is the probability of the i-th influencing factor after the k-th Bayesian iteration; and $q(k)_i$ is the probability of the i-th influencing factor in the k-th failure statistics.

In the risk model shown in Fig. 2, it can be assumed that when a long-distance pipeline is assessed at being high risk, corrosion perforation may be difficult to control using conventional external corrosion control means according to Ref [13]. Instead, detailed excavation inspection have to be done and its span can be determined for different pipeline. Therefore, the threshold of the prediction model can be obtained according to critical external corrosion thinning rate ($ECT$) according to Ref [12], when the pipeline falls into the high-risk (red) region of the matrix, as shown in Fig. 2. Thus, the threshold of wall thickness reduction, $\Delta T_{th}(t,r_a)$, is expressed in Eq. (5).

\[
\Delta T_{th}(t,r_a) = ECT_{th} \times T_a
\]

(5)

where: $ECT_{th}$ is the threshold of $ECT$ shown in Fig. 3 as the pipeline fall into high risk (red) region shown in Fig. 2.

2.2. Prediction on excavation inspection and maintenance span

At the same time, the reliability of inspection, local sampling excavation and other uncertain factors need to be considered in a pipeline excavation and maintenance span prediction. Considering the influence of various uncertain factors, the thinning thickness, $\Delta T(t,r_a)$, based on the expected reliability, $r_a$, is now shown in Eq. (6).

\[
\Delta T(t,r_a) = v_e \left[ 1 - c_i \left[ 0.7797 \ln(-\ln r_a) + 0.450 \right] \right]
\]

(6)

where: $v_e$ is the equivalent corrosion rate, mm/a, which not only considers the average corrosion rate but also includes the influence of confidence, that is considering the influence of corrosion rate deviation according to the confidence, its calculation is shown in Eq. (7); $c_i$ is the variation coefficient of the corrosion rate, and its calculation is shown in Eq. (8); and $r_a$ is the expected reliability of the protective layer.

\[
v_e = \left( x^* + t_{0.90,N-1} \cdot S/\sqrt{N-1} \right) / t
\]

(7)

\[
c_i = S \cdot \sqrt{t_{0.90,N-1} / x^*}
\]

(8)

where: $x^*$ is the mean value of the maximum corrosion depth, mm, which can be obtained by Eq. (9); $S_i$ is the variance of the maximum corrosion depth, mm, which can be obtained by Eq. (10); $N$ is the amount of corrosion detection pits; $t_{0.90,N-1}$ is the t-distribution coefficient under 90% confidence; and $\chi^2_{0.90,N-1}$ is the chi-square distribution coefficient under 90% confidence.
where: $x_i$ is the measured maximum corrosion pit depth, mm. And the prediction model on optimal excavation inspection and maintenance span, $t_{\text{optimal}}$, can be determined as Eq.(11) according to Eqs.(5)-(10).

$$t_{\text{optimal}} = \frac{\Delta T(t, r_c)}{v_c [0.7797 \ln (-\ln r_c) + 0.450]}$$  \hspace{1cm} (11)

3. Case study

3.1. A long-distance pipeline introduction

A gas transportation pipeline from a natural gas field in the western plateau in China began operating on 31 August 1996. Its route is mainly Yadan landform in the Gobi Desert, where there is less traffic and people flow and cultural activities are underdeveloped. The specifications of the pipeline are presented in Table 2.

### Table 2. Specifications of the case study pipeline

| Items             | Value                     |
|-------------------|---------------------------|
| Distance          | 345,295 m                 |
| Material          | X52                       |
| Dimensions        | $\Phi 323.9 \times 6.0$ and $\Phi 323.9 \times 7.1$ mm |
| Design pressure   | 6.4 MPa                   |
| Operational pressure | 4.5 MPa               |
| Design temperature | atmospheric temperature   |
| Cathodic protection | forced current           |

3.2. Risk assessment on the long-distance pipeline

The pipeline in this case study was divided into 87 areas for risk assessment. And the 87 areas has been inspected for different key external corrosion factors, such as pipeline buried depth (PBD) (as shown in Fig. 3),

![figure 3](image_url)

**Figure 3.** Buried depth inspection along the long-distance pipeline protective layer quality(PLQ) (as shown in Fig. 4),
Figure 4. Current decay inspection along long-distance pipeline protective layer damage (PLD) (applying the same technology with PBD), cathodic protection effectiveness (CPE) (as shown in Fig. 5) and soil corrosivity (as shown in Fig. 6 and Table 3).

Figure 5. CP - CIPS inspection along the long-distance pipeline

Figure 6. Statistical models of the resistivity of the three soil types
Table 3. Soil corrosive media test data

| Samples | PH  | Cl\(^{-}\) (mg/kg) | Total salt (g/kg) | Redox potential (mV) | Water content (%) | SO\(_4^{2-}\) (mg/kg) |
|---------|-----|-------------------|------------------|---------------------|------------------|---------------------|
| 1       | 8.5 | 44.08             | 1.77             | 398                 | 11.6             | 49.6                |
| 2       | 8.0 | 4.2×10\(^4\)     | 186              | 390                 | 7.89             | 1.89×10\(^3\)      |

And the inspection data from PBD to PLD are shown in Table 4 with 50m inspection interval, besides, all the critical values are listed in Table 5 to judge a inspection results. And applied inspection techs and their critical values are shown in Table 4. After those inspections, 23 exposed and underburied pipe areas were identified, 9 areas have obvious quality problems in the protective layer, and 209 damage points are across 33 of the 87 risk assessment areas. The combined length of these 23 areas is 1336 m, accounting for 0.39% of the total length of the pipeline, and the most severely damaged areas on their protection layer are shown in Table 4. The soil resistance statistical models, shown in Fig. 6, indicate that almost all the resistances (>90%, as shown in Table 6) are larger than 50Ω, so their corrosivity are all weak in general.

Table 4. Inspection data of the protective layer

| Area | Total length (m) | Poor PLQ length (m) | CP potential (V) | PLD (Y/N) |
|------|------------------|---------------------|------------------|-----------|
| 17   | 2454             | 10                  | -1.00            | -1.80     | -1.35 | -0.92 | -1.06 | N        |
| 18   | 2740             | 20                  | -1.39            | -1.10     | -1.20 | -1.08 | -1.12 | N        |
| 56   | 4452             | 2                   | -1.20            | -1.40     | -1.20 | -1.50 | -1.10 | Y        |
| 58   | 2170             | 100                 | -1.10            | -1.30     | -1.00 | -1.30 | -0.90 | Y        |
| 70   | 4146             | 48                  | -1.20            | -1.80     | -1.26 | -1.00 | -1.30 | Y        |
| 72   | 5630             | 200                 | -1.30            | -1.60     | -1.12 | -1.09 | -0.96 | Y        |
| 74   | 3000             | 50                  | -0.90            | -1.10     | -1.00 | -1.35 | -1.30 | Y        |
| 81   | 2245             | 60                  | -1.32            | -1.23     | -1.23 | -1.07 | -1.13 | Y        |
| 87   | 5500             | 94                  | -1.23            | -1.19     | -1.07 | -1.17 | -1.03 | Y        |

Table 5. Inspection techs and their critical values

| Items          | Measurement tech                             | Data Units | Critical values |
|----------------|---------------------------------------------|------------|-----------------|
| PBD            | Pipeline current mapper(PCM)                | m          | 1               |
| PLQ            | Multi-stage current attenuation             | dB/m       | 0.129           |
| PLD            | AC voltage gradient method (ACVG)           | dBuV       | 70              |
| CPE            | Close-interval potential inspection system (CIPS) | V          | -0.85 to -1.2   |
| Soil corrosivity | Soil resistance                           | Ω          | 50              |
Table 6. Soil conductivity assessment scores and their probabilities

| Soil types | Conductivity ($\Omega$ m) | Classes | Probability |
|------------|--------------------------|---------|-------------|
| Silt       | < 20                     | Strong  | 0.04        |
|            | $\geq$ 20 – 50           | Moderate| 0.06        |
|            | > 50                     | Weak    | 0.90        |
|            | < 20                     | Strong  | 0.01        |
| Sand       | $\geq$ 20 – 50           | Moderate| 0.02        |
|            | > 50                     | Weak    | 0.97        |
|            | < 20                     | Strong  | 0.01        |
| Gravel     | $\geq$ 20 – 50           | Moderate| 0.03        |
|            | > 50                     | Weak    | 0.96        |

Table 7. Weight results of each item influencing pipe safety

| Weight | Third party | Corrosion | Improper operation and maintenance | Defects of pipeline body |
|--------|-------------|-----------|-------------------------------------|-------------------------|
| $p^{(2)}_i$ | 0.2750     | 0.4360    | 0.0270                              | 0.260                   |
| $q^{(2)}_i$ | 0.1538     | 0.6948    | 0.0017                              | 0.1497                  |
| $p^{(k+1)}_i$ | 0.1101     | 0.7885    | 0.0001                              | 0.1013                  |

When evaluating the external corrosion risk of a long-distance pipeline, not only should the influence of soil corrosivity be considered, but the damage of the protective layer should also be evaluated. A comprehensive risk, $R$, can be evaluated according to Eqs (1), (2) and (3), and the weight factor $a_i$ can be calculated according to Eq. (4). It is assumed that the prior value $p^{(k)}_i$ in Eq. (4) is based on statistical data from the same industry. The posterior value $p^{(k+1)}_i$ and the conditional weight value $q^{(k)}_i$ are shown in Table 7. Using $p^{(k+1)}_i$ to replace $a_i$ in Eq. (2) to calculate $S$. 

![Image](image-url)
Figure 7. Comparing on pipe risk with (a) default mean weight \( a_i = 0.25 \), (b) prior weight \( a_i = p^{(k)}_i \), and (c) posterior weight \( a_i = p^{(k+1)}_i \).

The default mean weight \( a_i = 0.25 \), a prior weight \( a_i = p^{(k)}_i \) and a posterior weight \( a_i = p^{(k+1)}_i \) are separately used to calculate \( S \), and \( S_i \) and \( C_i \) are calculated according to [13]. Finally, \( R \) of all the areas are obtained shown in Fig. 7, where Fig. 7(a) takes the mean weight \( a_i = 0.25 \), Fig. 7(b) takes the prior weight of \( p^{(k)}_i \), and Fig. 7(c) takes the posterior weight \( p^{(k+1)}_i \). Comparing with Figs 7(a), 7(b) and 7(c), the average weight and prior weight do not change the risk level screening results. However, after considering statistical data from similar domestic pipelines in the same industry as the conditional probability and using the posterior value, the risk levels of pipelines changed significantly. Compared with the two earlier calculations using average weight and prior weight, the number of low-risk areas (the yellow regions in Fig. 7) along the pipeline has increased from 7 to 17 when the risk is calculated using posterior weight \( p^{(k+1)}_i \) (see Fig. 7(c)). Thus, because Eq. (4) provides a method to calculate the dynamic evolution of risk that takes into account both historical experience data and current failure statistical data, the model can be used to find any change in current pipeline risk in time.

3.3. Risk-based decision-making model on pipeline excavation inspection span

To research a more effective quantitative excavation decision-making model, some low-risk areas were also excavated and sampled and 185 locations of these 87 areas were selected for excavation. In some locations pipe body are damaged as shown in Fig. 8. And the 39 of the 185 excavated locations revealed areas of the pipeline with a seriously damaged protective layer and the most severely damaged 10 points are shown in Table 8 after ultrasonic thickness reading are done, the rest areas have a less wall thinning than 0.11mm. So except for two areas with 9% and 14%, almost all thinning rate is less than 6%. The maximum thinning rate happens in the location with groove-like damage of the protective layer and the exposed pipe body show in Fig. 8. According to historical statistical data on long-distance pipeline leakage cases, the location with this damage will result in heavy corrosion of the surface of the pipeline. Even if the cathodic protection is perfect, the pipeline will still undergo rapid corrosion perforation.

Figure 8. Damaged pipe body with third-party damage of the protective layer
The location in Fig.8 in this case study with pipeline specification is $\Phi 323.9 \times 6.0$, the operating pressure is 4.5MPa and atmospheric temperature, transports natural gas and the initial operational date is 1 October 1998, the amount of excavation locations in the excavation inspection was 5. Besides, according to Fig.7(c), its critical values of the thinning rate are between 10% and 30% due to the different expected reliability. And then all of these data are substituted into Eqs (5)–(11) to obtain the optimal excavation inspection span, $t_{optimal}$, under different reliability expectations, shown in Fig. 9. When the expected reliability of the pipe is higher because the less information about the corrosion of pipe or higher safety expectation to the pipe, then a shorter excavation span should be expected to ensure safer running of the pipe. Due to the uncertainty of pipeline external corrosion information, the $t_{optimal}$ in this prediction model is closely related to variable $N$, the amount of excavated locations during precious inspections. As shown in Fig. 9, when $N$ increases from 5 to 25, the $t_{optimal}$ under different reliability will increase significantly. Therefore, the model provided in this paper can be applied to rationally extend the excavation maintenance span by selecting a suitable amount of excavation locations, enabling someone to choose an optimal excavation maintenance span according to the expected excavation maintenance cost and safety risk. For example shown in Fig. 9, when the expected reliability of the pipeline is 0.95 and if $N$ were to increase from 5 to 10, effectively doubling the amount of information obtained, then the pipeline excavation and maintenance span can be extended from 6 years to 10 years.

### Table 8. Top 10 areas with max wall thinning

| Area | Nominal wall thickness (mm) | Wall thinning (mm) |
|------|----------------------------|-------------------|
| 17   | 7.1                        | 0.35, 0.63, 0.31, 0.02, 0.14 |
| 22   | 6                          | 0.39, 0.39, 0.11, 0.09, 0.04 |
| 26   | 6                          | 0.06, 0.11, 0.14, 0.02, 0.06 |
| 34   | 6                          | 0.15, 0.01, 0.09, 0.03, 0.04 |
| 44   | 7.1                        | 0.38, 0.03, 0.01, 0.04, 0.02 |
| 62   | 6                          | 0.1, 0.16, 0.05, 0.02, 0.04 |
| 74   | 7.1                        | 0.07, 0.13, 0.12, 0.16, 0.05 |
| 80   | 6                          | 0.17, 0.19, 0.1, 0.04, 0.82 |
| 81   | 6                          | 0.01, 0.02, 0.16, 0.02, 0.01 |
| 82   | 7.1                        | 0.19, 0.12, 0.12, 0.07, 0.07 |

### Figure 9. Different the excavation maintenance span the amount of excavated locations

**4. Conclusion**

A new quantitative excavation inspection span prediction model is proposed to complete a more rational excavation decision-making for long-distance pipeline based on inspection data, such as the protection layer...
quality, external corrosion thinning and so on. The practical testing results presented in the paper verify that the model can guide the optimal excavation inspection or maintenance span for long-distance pipelines. With the new model, the threshold of the thinning rate of the pipeline can be dynamically determined according to the failure consequence level and the protective layer conditions of the pipeline, and then the optimal excavation and maintenance span of high-risk pipeline can be predicted according to expected reliability and amount of excavation during precious inspections. Besides, The new model can fully consider the impact of uncertainty of pipeline information on pipeline safety and allow 2–5 years time allowance between the early effective medium-high or high-risk identification and the optimal excavation time, it is more enough to draft an optimal pipeline excavation and maintenance plan, consistent with the demands on the inspection and maintenance of long-distance pipelines in China.

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