Pipeline volumetric defect assessment method based on multi risk factors and in-line inspection data

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Abstract. Volumetric defects in pipeline are one of the main factors causing pipeline leakage accidents. Once an accident occurs, it will cause huge economic and environmental loss. At present, the assessment of pipeline volumetric defects in existing standards is only calculating the residual strength of pipeline by defect size (length, width, depth), without considering the influence of other external risk factors. Therefore, defect-related risk factors were introduced when calculating the residual strength of defects using in-line inspection data. Due to the massive data resources produced during the construction and the operation period, a risk factor correlation analysis model for extracting the risk factors related to pipeline safety was established. The weight of each factor is obtained by using analytic hierarchy process algorithm, and a new defect risk index was put forward. Therefore, the volumetric defect assessment method based on multiple risk factors of defects and in-line inspection data is proposed. The result of on-site examples shows that the defect assessment method proposed in this paper can reflect the true safety status of the defects, it can also provide support for scientific and reasonable pipeline maintenance decision.

1. Introduction

The rapid growth of energy demand accelerates the development of pipeline constructions, therefore, the pipeline safety problems is becoming increasingly significant. Monitoring pipeline status through evaluation and putting forward maintenance measures to ensure the safety of pipelines can effectively avoid oil and gas pipeline accidents [1]. At present, researchers at home and abroad have done a lot of research on residual strength evaluation of pipelines with defects. K. H. Choi et al. [2] have studied X65 pipeline with single corrosion defect. Aiming at the corrosion of inner and outer walls of pipeline, the influence of depth, width and length on failure pressure of pipeline is analyzed by using finite element software. It is found that the depth of defect is the most important parameter affecting the safety of pipeline. Zhao X W et al. [3] established the degradation law of elastic modulus and yield strength of X70 pipeline with hole damage by simulating the tensile test of porous materials. Shuai J et al. [4] fitted the failure pressure prediction formula of corroded pipeline on the basis of finite element calculation results. Xiao G Q and Su C [5,6] have fitted the failure pressure prediction formula of high-grade steel pipelines based on the finite element calculation results.
Volumetric defect is a kind of common defect in pipeline, while corrosion is the main damage form which always leads to thinner pipeline wall thickness. With further aggravation of corrosion, local rupture and leakage of pipeline will occur. Due to the long pipeline laying distance, most of the pipelines are buried in soil, the corrosion of pipelines is closely related to soil type, current density, microorganisms and other factors. In recent years, the pipeline system realized electronic records and network management, management processes, inspection records and daily operation records can be connected through a huge data network to form pipeline big data [7], from which many data related to pipelines can be obtained easily. In this paper, defects will be evaluated based on the size and risk factors, which can achieve a more accurate assessment of defects.

2. Volumetric defects assessment

At present, the volumetric defects assessment of pipeline is mainly to evaluate the residual strength, that is, to calculate the failure pressure of different types of defects [8]. Since the 1960s, the United States, Canada, the United Kingdom, and other Western countries have been conducting pipeline defect assessment research. So far, ASME B31.G standard, DNV RP-F101 standard, PCORRC and other pipeline integrity assessment standards and methods have been established. These methods have their own application and limitations [9]. In addition to the semi-theoretical and semi-empirical formula method, another evaluation method is based on the finite element numerical calculation. Because of the need for better modelling, this method consumes more time and energy, and is usually used in the evaluation of important defects. The relevant standards regard the finite element numerical method as the last level evaluation method.

2.1. ASME B31.G

ASME B31.G [10] is based on semi-empirical formula and NG-18 formula of fracture mechanics. This method needs fewer parameters to evaluate residual strength of pipeline. The process is simple and can quickly calculate the failure pressure of pipeline with defects. The calculation is as follows:

\[
S_r = S_{\text{flow}} \left( \frac{1-A/A_0}{1-(A/A_0)/M_1} \right) \]

\[A = 0.85dL\]

Where \(S_r\) is the predicted circumferential failure stress, \(S_{\text{flow}}\) is the rheological stress of the material, \(A_0\) is the area of the pipeline wall at the defect, \(A\) is the projection area of the defect section, \(M_1\) is the expansion coefficient, \(L\) is the axial length of the corrosion defect, and \(d\) is the depth of the corrosion defect. The calculation of defect failure pressure is as follows:

\[
P = \frac{S_r \times 2t}{D} = \frac{1-A/A_0}{1-(A/A_0)/M_1} \times \frac{2tS_{\text{flow}}}{D} \]

Among them:

\[R_S = \left[ \frac{1-A/A_0}{1-(A/A_0)/M_1} \right] \]

\[P_0 = \frac{2tS_{\text{flow}}}{D} \]

It can be obtained by formula:
Where $P$ is the failure pressure, $R_S$ is the residual strength coefficient, and $P_0$ is the predicted failure pressure of normal pipelines, $D$ is the outside diameter of the pipeline, $t$ is the wall thickness of the pipeline.

The defect can be evaluated by comparing the values of the failure pressure $P$ and the maximum operating pressure (MAOP), when $P$ is greater than or equal to MAOP, the defect is considered safe to operate.

### 2.2. DNV RP-F101

The DNV RP-F101 [11] was jointly completed by British Gas Company (BG) and Det Norske Veritas (DNV), and more than 70 blasting experiments of full-scale defective pipelines were carried out. Among them, the allowable stress method is a safety criterion based on the allowable stress design (ASD). It does not need to consider many uncertain factors. The calculation process of this method is simple and convenient. The failure pressure specified in this standard is expressed as:

$$ P = P_0 R_S $$

(6)

### 2.3. PCORRC

The PCORRC method [12] was developed by Battle Laboratory in the United States. The failure of pipelines with corrosion defects was determined by the tensile strength of the pipe, not the yield strength. The safety criterion based on the burst strength of the pipe was adopted. The formula for calculating failure pressure is fitted by the results of finite element calculation. It is used to evaluate the residual strength of medium and high strength pipelines with blunt corrosion defects caused by plastic instability. The failure pressure is expressed as:

$$ P = \frac{2t}{(D-t)} \sigma b \left[ 1 - \frac{d}{t} \left[ 1 - \exp \left( -0.157 \frac{L}{\sqrt{R(t-d)}} \right) \right] \right] $$

(8)

Where $\sigma_b$ is the tensile strength of the pipe and $R$ is the radius of the pipe.

### 3. Safety factor

#### 3.1. Definition of safety factor

The state of defective pipeline is judged by comparing the failure pressure and maximum operating pressure of defective pipeline. So the ratio of failure pressure and maximum operating pressure is proposed as the safety factor of pipeline defect. On the basis of original evaluation method [13], which only considering the factors such as pipeline internal pressure, defect size. This paper proposes a modified safety factor in combination with the relevant risk factors, so as to make a more reflective evaluation of the real state of defects. The safety factor is taken as a parameter to characterize the defect safety state, and its expression is as follows.

$$ SF = \frac{P}{MAOP} $$

(9)
\[ SF_m = SF \times f(x_1, x_2, x_3, \ldots, x_n) \]  

(10)

Where \( SF \) is safety factor, \( SF_m \) is the modified safety factor, \( P \) is failure pressure, \( x_n \) is the risk factor, \( n \) is the number of risk factor.

According to the modified safety factor, the pipeline can be maintained and repaired in a planned way, so that the limited resources can be allocated reasonably.

3.2. Defect-related risk factors

In order to evaluate the defects accurately, it is necessary to identify the risk factors related to the defects [14,15]. After consulting the relevant literature and analysing the causes of domestic and foreign pipeline accidents, risk factors related to defects are divided into three categories: attribute risk, environmental risk, and corrosion risk. Pipeline geographic data, inspection and monitoring data, corrosion data and operation data related to pipeline are collected for correlation analysis. Finally, nine risk factors are extracted as shown in Table 1.

| Attribute risk               | Environmental risk               | Corrosion risk                  |
|------------------------------|----------------------------------|---------------------------------|
| Buried depth of pipeline     | Regional environment             | Soil corrosiveness              |
| Defect location              | External temperature difference  | Atmospheric corrosion           |
| Regional level               | Geologic hazard                  | Current density                 |

3.3. Weight of risk factors

The analytic hierarchy process (AHP) [16] combines qualitative and quantitative analysis which also integrates their respective advantages. It is a mathematical process of experts’ thinking on complex system evaluation. The steps are as follows: Firstly, the decision maker initially determines the ranking of the importance of each factor based on experience, and then uses the algorithm program to calculate the weight of each factor. Finally, the specific weight can accurately express the importance relationship between each factors and between factors and overall goals. The detailed analysis flow chart is shown in Figure 1.

![Figure 1. Flow chart of AHP.](image-url)
In order to quantitatively analyze the nine risk factors mentioned above, the weights of them are calculated by AHP. According to the relevant criteria of analytic hierarchy process, the importance of each element is expressed by corresponding numerical value, and the judgment matrix is constructed. Using the scale method from value 1 to value 9 to assign the corresponding values to the importance of each element in the judgment matrix, this paper gets the relationship of the importance of risk factors by the expert's scoring of each risk factor as shown in Table 2.

**Table 2. Importance of risk factors.**

| Risk matrix      | Buried depth | Location | Regional level | Regional environment | Temperature difference | Geologic hazard | Soil corrosion | Atmospheric corrosion | Current density |
|------------------|--------------|----------|----------------|----------------------|------------------------|-----------------|----------------|-----------------------|-----------------|
| Buried depth     | 1            | 6/5      | 6/9            | 1                    | 6/5                    | 6/8             | 6/4            | 6/5                   | 6/7             |
| Defect Location  | 5/6          | 1        | 5/9            | 5/6                  | 1                      | 5/8             | 5/4            | 1                     | 5/7             |
| Regional level   | 9/6          | 9/5      | 1              | 9/6                  | 9/5                    | 9/8             | 9/4            | 9/5                   | 9/7             |
| Regional environment | 1               | 6/5      | 6/9            | 1                    | 6/5                    | 6/8             | 6/4            | 6/5                   | 6/7             |
| Temperature difference | 5/6          | 1        | 5/9            | 5/6                  | 1                      | 5/8             | 5/4            | 1                     | 5/7             |
| Geologic hazard  | 8/6          | 8/5      | 8/9            | 8/6                  | 8/5                    | 1               | 8/4            | 8/5                   | 8/7             |
| Soil corrosion   | 4/6          | 4/5      | 4/9            | 4/6                  | 4/5                    | 4/8             | 1              | 4/5                   | 4/8             |
| Atmospheric corrosion | 5/6        | 1        | 5/9            | 5/6                  | 1                      | 5/8             | 5/4            | 1                     | 5/7             |
| Current density  | 7/6          | 7/5      | 7/9            | 7/6                  | 7/5                    | 7/8             | 8/4            | 7/5                   | 1               |

The calculation results of the weights between related factors are shown in Table 3, and the maximum eigenvalue is $\lambda_{\text{max}} = 8.9830$. The consistency index CI = -0.0021, the consistency ratio CR = -0.0015 and the CR value is less than 0.10 indicates that the consistency of the judgment matrix is acceptable. Therefore, the consistency of the matrix is acceptable, which means that the weight scale assignment in the judgment matrix is reasonable and not contradictory with each other.

**Table 3. Weights of risk factors.**

| Risk factors | Buried depth | Defect location | Regional level | Regional environment | Temperature difference | Geologic hazard | Soil corrosion | Atmospheric corrosion | Current density |
|--------------|--------------|----------------|----------------|----------------------|------------------------|-----------------|----------------|-----------------------|-----------------|
| Weight       | 0.11         | 0.09           | 0.16           | 0.11                 | 0.09                   | 0.15            | 0.07           | 0.09                  | 0.13            |

It can be concluded from the table that the regional level occupies the largest weight, this is because once the defect leads to an accident, the level of the area where it is located will directly affect the severity of the accident loss, so this factor should be taken into account in the defect evaluation. According to the weight of each risk factor, the pipeline defect risk score is determined as follows:

**Table 4. Attribute risk score.**

| Risk factors | Description | Score |
|--------------|-------------|-------|
| Buried depth | cross-over or exposed segment | 0 |
|              | buried segment | $d/145$ and not more than 11 ($d$ is the buried depth) |
| Defect location | mountains and rivers | 0 |
|              | urban | 4.5 |
|              | farmland | 9 |
|              | the forth level | 0 |
| Regional level | the third level | 6 |
|              | the second level | 10 |
|              | the first level | 16 |
Table 5. Environmental risk score.

| Risk factors            | Description                   | Score |
|-------------------------|-------------------------------|-------|
| Regional environment    | seasonal river                | 4     |
|                         | permafrost, ponds             | 7     |
|                         | non-seasonal river            | 9     |
|                         | non-seasonal and stable river | 11    |
| Temperature difference  | >20°C                         | 3     |
|                         | 15~20°C                       | 5     |
|                         | 0~15°C                        | 9     |
| Geologic hazard         | frequent natural disasters    | 6     |
|                         | occasional natural disasters  | 12    |
|                         | almost no natural disasters   | 15    |

Table 6. Corrosion risk score.

| Risk factors          | Description                          | Score |
|-----------------------|--------------------------------------|-------|
| Soil resistivity      | <200 Ωm                              | 0     |
|                       | 20~500 Ωm                            | 4     |
|                       | >500 Ωm                              | 7     |
| Atmospheric corrosion | cross-over or exposed segment        |       |
|                       | marine climate                       | 3     |
|                       | industrial atmosphere/ general       | 5     |
|                       | atmosphere                           |       |
|                       | buried pipeline                      | 9     |
| Current density       | >20μA                                | 0     |
|                       | 10~20μA                              | 2     |
|                       | 2~10μA                               | 6     |
|                       | 0.5~1μA                              | 9     |
|                       | <0.5μA                               | 13    |

3.4. Modified safety factor

The original safety factor is only determined by the pipeline internal pressure and defect size, the modified safety factor is revised according to the risk score calculated by table 4 – table 6 to solve the problem of comparison between various risk factors. Firstly, score each risk factor according to the actual situation of the pipeline. Secondly, all risk scores are normalized. Finally, the original safety factor is multiplied by the normalized safety factor to obtain the final modified safety factor.

4. Case study

To validate the accuracy and practicability of this method, a pipeline with a diameter of 1016 mm and a design working pressure of 10 MPa is presented for demonstration. The data collected include 12 attributes such as the depth, width and length of defects, buried depth, regional level, temperature difference of external environment, soil corrosion, and current density. Due to the limited space, only 10 defects information are listed in the table 7.

Table 7. Pipeline original data.

| Number | Buried depth(mm) | Defect location | Regional level | Regional environment | Temperature difference | Geologic hazard | Soil corrosiveness | Atmospheric corrosion | Current density (μA) |
|--------|------------------|-----------------|----------------|----------------------|------------------------|----------------|---------------------|-----------------------|---------------------|
| 1      | 800              | farmland        | second level   | stable               | 18                     | almost no       | 42                  | buried                | 7.86                |
| 2      | 1300             | farmland        | second level   | stable               | 16                     | almost no       | 37                  | buried                | 8.75                |
3 1200 farmland second level stable 10 almost no 39 buried 6.92
4 900 urban second level stable 19 occasional 48 buried 15.24
5 1020 farmland second level stable 18 almost no 74 buried 9.65
6 1350 farmland second level stable 16 almost no 36 general 8.82
7 1250 urban third level stable 17 occasional 41 buried 6.78
8 1600 farmland second level stable 12 almost no 38 buried 7.65
9 830 farmland second level stable 16 almost no 62 buried 8.93
10 900 farmland second level stable 14 occasional 41 buried 7.62

4.1. Tradition method
According to the defect size obtained from in-line inspection, the failure pressure of the defects and the safety factors are calculated based on the ASME B31G criterion, as shown in the table 8.

Table 8. SF of defects.

| Number | Length | Width | Depth | Failure pressure | SF |
|--------|--------|-------|-------|------------------|----|
| 1      | 101    | 67    | 1.92  | 15.544           | 1.554 |
| 2      | 67     | 15    | 1.82  | 15.710           | 1.571 |
| 3      | 63     | 21    | 1.39  | 15.761           | 1.576 |
| 4      | 48     | 19    | 1.47  | 15.798           | 1.580 |
| 5      | 48     | 83    | 0.64  | 15.837           | 1.584 |
| 6      | 72     | 17    | 1.33  | 15.740           | 1.574 |
| 7      | 97     | 77    | 1.23  | 15.679           | 1.568 |
| 8      | 38     | 19    | 1.55  | 15.819           | 1.582 |
| 9      | 173    | 142   | 0.82  | 15.604           | 1.560 |
| 10     | 82     | 24    | 1.13  | 15.735           | 1.573 |

4.2. Defect-related risk factor
The risk status of different defects can be determined according to the risk value mentioned above. Table 9 lists the risk scores of the 10 defects in Table 7.

Table 9. Defect risk score.

| Number | Buried depth | Defect location | Regional level | Regional environment | Temperature difference | Geologic hazard | Soil corrosiveness | Atmospheric corrosion | Current density | Total score |
|--------|--------------|-----------------|----------------|----------------------|------------------------|----------------|-------------------|----------------------|----------------|-------------|
| 1      | 5.52         | 9               | 10             | 11                   | 5                      | 15             | 4                 | 9                    | 6              | 74.52       |
| 2      | 8.97         | 9               | 10             | 11                   | 5                      | 15             | 4                 | 9                    | 6              | 77.97       |
| 3      | 8.28         | 9               | 10             | 11                   | 9                      | 15             | 4                 | 9                    | 6              | 81.28       |
| 4      | 6.21         | 4.5             | 10             | 9                    | 5                      | 12             | 4                 | 9                    | 2              | 61.71       |
| 5      | 7.03         | 9               | 10             | 11                   | 5                      | 15             | 7                 | 9                    | 6              | 79.03       |
| 6      | 9.31         | 9               | 10             | 7                    | 5                      | 15             | 4                 | 5                    | 6              | 70.31       |
4.3. Modified safety factor

In order to combine risk factors with safety factor effectively, the risk score corresponding to defects is normalized to correct safety factor. The safety factor before and after the correction is shown in Table 10.

**Table 10. Comparison of safety factor.**

| Number | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Risk score | 74.52 | 77.97 | 81.28 | 61.71 | 79.03 | 70.31 | 66.12 | 84.03 | 75.72 | 74.21 |
| Normalization constant | 0.88  | 0.92  | 0.96  | 0.73  | 0.94  | 0.83  | 0.78  | 1     | 0.9   | 0.88  |
| Safety factor | 1.554 | 1.571 | 1.576 | 1.580 | 1.584 | 1.574 | 1.568 | 1.582 | 1.560 | 1.573 |
| Modified safety factor | 1.368 | 1.445 | 1.513 | 1.153 | 1.489 | 1.306 | 1.223 | 1.582 | 1.404 | 1.385 |

The safety factor before and after the correction is compared as shown in Fig. 2. Before the correction, the safety factor is about 1.50. It can be found that the modified safety factor fluctuates more, because the revised safety factor synthesizes the risk of different defects to reflect its safety status. If the defect is in a high-risk state, the safety factor value is smaller; conversely, if the defect is in a low-risk state, the safety factor value is larger. The revised safety factor reflects the real state of defects reasonably. In addition, it avoids the problem of incomparability and non-quantification among various factors.

![Figure 2. Comparison of Safety factor before and after Correction.](image)
5. Conclusion
The size of the defect and the nine risk factors related to the pipeline including burial depth, location, regional level, regional environment, temperature difference of external environment, geological hazard, soil corrosion, atmospheric corrosion and current density are taken into consideration in the pipeline defect evaluation. The relationship between factors has been analysed, and the pipeline defect risk scores are calculated to modify the defect safety factor, the modified safety factor can improve the accuracy of pipeline defect evaluation. It was evident from the analysis that the modified safety factor is appropriately increased in areas where the public or the environment is more easily at risk, and correspondingly reduced in areas where the consequences of an accident may be remote or ineffective. Comparing the safety factor before and after the correction, the modified safety factor can specifically indicate the actual risk status of the pipe section. Defects that do not meet the requirements of safe operation can be found through the comparison of modified safety factor, which can provide a more reliable basis for the priority of defect maintenance.

Acknowledgments
This work was funded by the Science and Technology Innovation foundation of CNPC (2018D-5007-0601), the Science and Technology program for strategic cooperation of CNPC-China University of Petroleum (ZLZX2020-05).

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