Risk Assessment of Pipeline Failure Based on Fuzzy Analytic Hierarchy Process

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Abstract. Pipeline failure is a serious economic, environmental and safety issue. Risk assessment is an effective method to determine the risk of pipeline failure. This paper proposes an evaluation system. In the evaluation process, the fuzzy concept and method are used to transform the qualitative effect into quantitative fuzzy numbers based on linguistic variables. The weights are calculated by MATLAB software. Calculate the weight result and classify each indicator risk, and finally determine the pipeline failure risk level. Taking a section of the third-line pipeline of the West-East Gas Pipeline as an example, the fuzzy analytic hierarchy process is used for analysis. The two indicators of external corrosion and management system are medium risk grades, and the overall pipeline failure risk level is II (lower). The evaluation results show that the proposed evaluation system and method are effective and objective for evaluating pipeline failure risk. The pipeline failure assessment based on fuzzy analytic hierarchy process can not only objectively assess the risk status of pipelines, but also have a positive effect on improving pipeline risk management.

1. Introduction

Oil and gas pipeline transportation plays an indispensable role in energy allocation for global economic development. Due to aging of pipelines, environmental factors, and improper protection and maintenance, pipelines around the world have been damaged to varying degrees[1].

At present, pipeline safety assessment is receiving more and more attention from science, engineering and society. Gradually the transition from qualitative evaluation to quantitative evaluation[2,3],such as Yu Shurong[4] combined Bayesian network and fault tree analysis method, proposed a modified Bayesian network model, which can improve the quantitative analysis of pipeline failure. Cao Tao[5] constructed a hierarchical analysis structure model for third-party damage of oil and gas pipelines, and applied fuzzy analytic hierarchy process to single-sort and total-sort the influencing factors, and obtained the calculation method of pipeline damage value by third party; Shuai Jian[6] determined the basic failure probability and correction factor index system of oil and gas pipelines by analyzing the pipeline classification failure data of PHMSA database in the United States, and realized the quantification of pipeline failure probability.

Compared with previous studies, this paper uses a modified fuzzy analytic hierarchy process to evaluate the pipeline failure risk comprehensively and systematically. The influence of evaluation factors on pipeline failure is complex. The influence of some factors on pipeline failure may be single. For example, the stronger the soil corrosivity is, the higher the probability of pipeline failure is[7];some
factors may have a dual impact on pipeline failure (negative impact and positive Impact), for example, when a natural disaster occurs, on the one hand, the pipeline will be crushed by external force and cause the pipeline to fail. This is a negative impact of natural disasters on pipeline failure, and on the other hand, it may not cause damage to the pipeline, such as external forces. It may play a role in supporting the pipeline and prolong its service life, which is the positive impact of natural disasters on pipeline failure. In view of these uncertain effects, in the past only qualitative evaluation, this paper uses fuzzy concepts and methods to explain, transform qualitative effects into quantitative fuzzy numbers based on linguistic variables, improve inherent uncertainty and inaccuracy, for each indicator Factor risk is graded to determine the pipeline failure risk level.

2. Pipeline failure risk assessment system

Establishing an objective and appropriate pipeline failure evaluation system is of great significance for evaluation. Therefore, most impotent factors should be included in the hierarchical index system on the basis of comprehensive consideration, and the main influencing factors of pipeline failure should be constructed with pipeline failure as the overall target layer. The hierarchical model of the relationship. There are many factors affecting pipeline failure.

Drawing on the "human-machine-environment-management" system engineering theory [8], it can be summarized into four basic factors: third-party damage (B1), pipelines and facilities (B2), and natural factors (B3). And management level (B4). Each of the basic factors involves a set of interrelated sub-factors, a total of 14. The hierarchical evaluation index system is shown in Figure 1. The evaluation steps of the evaluation system are shown in Figure 2.

3. Fuzzy analytic hierarchy process

Through the investigation of the pipeline failure case and the research and analysis of the system, the fuzzy analytic hierarchy process is described in the case of the secondary combined pipeline failure case.

(1) Triangular fuzzy number conversion

The linguistic variables are used to describe the relative importance of index factors and sub-factors. In order to facilitate mathematical operations, the linguistic variables are converted to fuzzy scales, that is, the fuzzy numbers are used to represent the severity of the events[5,9], as shown in Figure 3[5]. EI is equally important, WMI is slightly more important, SMI is more important, VSMI is quite important, and AMI is absolutely important.

![Figure 1. The fuzzy index system of pipeline failure and the fuzzy influence of each sub-factor on pipeline failure](image)
(2) Constructing a fuzzy matrix
In the fuzzy analytic hierarchy process, the pairwise comparison matrix established by the comparison of the elements in the group is the basis of the weight calculation. A pairwise comparison matrix can be expressed as:

\[ \bar{X} = (\bar{x}_{ij}) \quad (i,j = 1, 2, \ldots, n) \]  

\[ \bar{x}_{ij} = (a_{ij}, m_{ij}, d_{ij}) \]  

\[ \bar{x}_{ji} = (\bar{x}_{ij})^{-1} = (d_{ji}^{-1}, m_{ji}^{-1}, a_{ji}^{-1}) \]  

Construction to obtain judgment matrix \( \bar{X} = (x_{ij})_{n \times n} \).
\( X \) is a pairwise comparison matrix; \( x_{ij} \) is Matrix element, it represents the importance value of \( i \) evaluation criteria relative to the \( j \) evaluation criterion; \( n \) is the number of sub-factors.
(3) Consistency test
The weight of the calculation is guaranteed to be acceptable by checking the consistency of the comparison matrix. First calculate the maximum eigenvalue ($\lambda_{\text{max}}$) of the fuzzy matrix, test according to the consistency test formula:

$$CI = (\lambda_{\text{max}} - n)/(n - 1)$$  \hspace{1cm} (4)

$$CR = \frac{CI}{RI}$$  \hspace{1cm} (5)

CI is Consistency index; $n$ is Matrix order; RI is Random index; Value from table 1 [10]; CR is the random consistency ratio.

| The matrix order | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| RI               | 0.00| 0.58| 0.90| 1.12| 1.24| 1.32| 1.41| 1.45| 1.49|

Matrix consistency is acceptable only when CR<0.10. Otherwise, the judgment matrix needs to be adjusted until it has good consistency.

(4) Determine index weight
Different factors have different effects on pipeline failure. Therefore, they should be weighted to assess their priority for pipeline failure. Comprehensive fuzzy value $D$ of element I in layer K (initial weight).

$$D^k_i = \sum_{j=1}^n x_{ij}^k + \left( \sum_{i=1}^n \sum_{j=1}^n x_{ij}^k \right) \quad (i = 1, 2, \cdots, n)$$  \hspace{1cm} (6)

Suppose that $M_1(l_1, M_1, u_1)$ and $M_2(l_2, M_2, u_2)$ are triangular fuzzy functions

$$V(M_1 \geq M_2) = \text{sup}_{x \in [l_1, u_1]} \{\min(u_{M_1}(x), u_{M_2}(y))\}$$  \hspace{1cm} (7)

$$V(M_1 \geq M_2) = \mu(d) \quad m_1 \geq m_2$$

$$= \begin{cases} 
1 & l_2 - u_1 \\
\frac{m_1 - u_1}{(m_1 - u_1) - (m_2 - l_2)} & m_1 \leq m_2, \quad u_1 \geq l_2 \\
0 & \text{otherwise}
\end{cases}$$  \hspace{1cm} (8)

The probability that one fuzzy number is greater than other K fuzzy Numbers is:

$$V(M \geq M_1, M_2, \cdots, M_k) = \min V(M \geq M_i) \quad (i = 1, 2, \cdots, k)$$  \hspace{1cm} (9)

The above weight values are normalized to get the final weight $W_{Bi}$ of each indicator. Similarly, the weight $W_{Cj}$ of the next level indicator is calculated, so the final weight of indicator $C_{mi}$ is

$$TW_{mi} = W_{Bi} \times W_{Cj} \quad (m = 1, 2, 3, 4; \quad i = 1, 2, \cdots 14)$$  \hspace{1cm} (10)
(5) Grade factor risk
In order to get the pipeline failure risk based on the calculated fuzzy number, the risk is divided into five levels according to the weight: very dangerous (VD) dangerous (D) medium (M) safe (S) and very safe (VS). The classified risk rating of each level is marked in Table 2 and figure 4.

| level of risk       | The weight range  |
|---------------------|-------------------|
| very dangerous (VD) | (0.35, 0.425, 0.5) |
| danger (D)          | (0.25, 0.325, 0.4) |
| moderate risk (M)   | (0.15, 0.225, 0.3) |
| safety (S)          | (0.05, 0.125, 0.2) |
| very safe (VS)      | (0, 0.075, 0.15)   |

(6) Determine the risk level of pipeline failure
In order to obtain the pipeline failure risk grade, the pipeline failure risk is divided into five grades: \( P = \{\text{I, II, III, IV, V}\} = \{\text{very low, low, medium, high, very high}\} \) fuzzy evaluation results can be calculated by the following formula

\[
P = W_{mi} \ast R
\] (11)

\( R \) is the judgment matrix. Experts in this field are invited to evaluate the risk of sub-factors. The judgment matrix is based on the principle of maximum membership, and the evaluation level corresponding to the element with the maximum membership is the final evaluation result [11].

4. Case analysis
In order to avoid the subjective preference and knowledge limitations of the decision-making group in evaluating the influencing factors, the influence of the factor itself on the pipeline failure is used to determine the fuzzy number. Based on the existing research results, constructing 4 basic factors and 15 sub-factors pairwise contrast fuzzy judgment matrix. The fuzzy judgment matrix is shown in Table 3-7.

![Figure 4. Risk level of each indicator and risk level of pipeline failure](image-url)
Table 3. Pairwise comparison of various factors (B1-B4)

|   | B1       | B2       | B3       | B4       |
|---|----------|----------|----------|----------|
| B1| (1, 1, 1)| (3/5, 4/5, 1)| (3/5, 5/6, 1)| (2/3, 4/5, 5/4) |
| B2| (1, 5/4, 5/3)| (1, 1, 1)| (4/5, 4/3, 3/2)| (3/4, 4/5, 1) |
| B3| (1, 6/5, 5/3)| (2/3, 3/4, 5/4)| (1, 1, 1)| (5/4, 5/3, 2) |
| B4| (4/5, 5/4, 3/2)| (1, 5/4, 4/3)| (1/2, 3/5, 4/5)| (1, 1, 1) |

Table 4. Pairwise comparison of various factors (C11-C14)

|   | C11       | C12       | C13       | C14       |
|---|----------|----------|----------|----------|
| C11| (1, 1, 1)| (4/3, 3/2, 2)| (5/4, 4/3, 3/2)| (1, 4/3, 3/2) |
| C12| (1/2, 2/3, 3/4)| (1, 1, 1)| (1/2, 3/4, 4/5)| (1, 5/4, 4/3) |
| C13| (2/3, 3/4, 4/5)| (5/4, 4/3, 2)| (1, 1, 1)| (5/4, 4/3, 3/2) |
| C14| (2/3, 3/4, 1)| (3/4, 4/5, 1)| (2/3, 3/4, 4/5)| (1, 1, 1) |

Table 5. Pairwise comparison of various factors (B1-B4)

|   | C21       | C22       | C23       |
|---|----------|----------|----------|
| C21| (1, 1, 1)| (1, 4/3, 3/2)| (4/3, 3/2, 2) |
| C22| (2/3, 3/4, 1)| (1, 1, 1)| (5/4, 4/3, 3/2) |
| C23| (1/2, 2/3, 3/4)| (2/3, 3/4, 4/5)| (1, 1, 1) |

Table 6. Pairwise comparison of various factors (B1-B4)

|   | C31       | C32       | C33       | C34       |
|---|----------|----------|----------|----------|
| C31| (1, 1, 1)| (1/2, 2/3, 1)| (4/3, 3/2, 5/3)| (4/3, 3/2, 2) |
| C32| (1, 3/2, 2)| (1, 1, 1)| (4/3, 5/3, 2)| (4/3, 3/2, 5/3) |
| C33| (3/5, 2/3, 3/4)| (1/2, 3/5, 3/4)| (1, 1, 1)| (1, 4/3, 3/2) |
| C34| (1/2, 2/3, 3/4)| (3/5, 2/3, 3/4)| (3/2, 3/4, 1)| (1, 1, 1) |

Table 7. Pairwise comparison of various factors (B1-B4)

|   | C41       | C42       | C43       |
|---|----------|----------|----------|
| C41| (1, 1, 1)| (4/3, 3/2, 2)| (4/3, 3/2, 5/3) |
| C42| (1/2, 2/3, 3/4)| (1, 1, 1)| (1/2, 2/3, 3/4) |
| C43| (3/5, 2/3, 3/4)| (4/3, 3/2, 2)| (1, 1, 1) |

The above weight values are normalized to obtain the final weight of each indicator. After calculation, the weight calculation and consistency test results of each basic factor and sub-factor are shown in Table 7. It can be seen that the consistency ratio is less than 0.1, which meets the requirements.
Table 8. Weight calculation and consistency test of each basic factor and sub-factor

| Fuzzy weight vector | Global weight | Factors risk rating | Maximum eigenvalue | Consistency ratio |
|---------------------|---------------|---------------------|--------------------|------------------|
| B1                  | (0.1132, 0.1587, 0.2789) | 0.1802 | S、 VS |                |
| B2                  | (0.1792, 0.2962, 0.4404) | 0.3124 | M 、 S |                |
| B3                  | (0.1887, 0.2885, 0.4587) | 0.2740 | S 、 VS | 4.1230          | 0.045          |
| B4                  | (0.1651, 0.2510, 0.3768) | 0.2334 | S 、 VS |                |
| C11                 | (0.2414, 0.3122, 0.4045) | 0.1019 | S 、 VS |                |
| C12                 | (0.1580, 0.2216, 0.2618) | 0.0141 | VS     | 3.0881          | 0.032          |
| C13                 | (0.2195, 0.2669, 0.3573) | 0.0553 | S 、 VS |                |
| C14                 | (0.1624, 0.1994, 0.2562) | 0.0089 | S       |                |
| C21                 | (0.3160, 0.4107, 0.5347) | 0.1782 | M 、 S |                |
| C22                 | (0.2765, 0.3304, 0.4158) | 0.1227 | S 、 VS | 3.0129          | 0.011          |
| C23                 | (0.2054, 0.2589, 0.3030) | 0.0115 | S 、 VS |                |
| C31                 | (0.2101, 0.2742, 0.3648) | 0.1473 | S 、 VS |                |
| C32                 | (0.2353, 0.3330, 0.4292) | 0.0785 | S 、 VS | 4.0894          | 0.033          |
| C33                 | (0.1563, 0.2116, 0.2575) | 0.0331 | S       |                |
| C34                 | (0.1815, 0.1812, 0.2253) | 0.0151 | S       |                |
| C41                 | (0.3359, 0.4211, 0.5426) | 0.1557 | M 、 S |                |
| C42                 | (0.1832, 0.2456, 0.2907) | 0.0212 | VS      | 3.0299          | 0.025          |
| C43                 | (0.2687, 0.3333, 0.4360) | 0.0564 | S 、 VS |                |

The final weight obtained is as Wij=[0.1019, 0.0141, 0.0553, 0.0089, 0.1782, 0.0212, 0.0212, 0.0031, 0.0151, 0.1557, 0.0212, 0.0564].

Inviting experts in this field to judge each sub-factor risk according to five levels, constructing a fuzzy judgment matrix R:
$$R = \begin{bmatrix}
0.25 & 0.45 & 0.15 & 0.15 & 0 \\
0.20 & 0.70 & 0.10 & 0 & 0 \\
0.05 & 0.55 & 0.40 & 0 & 0 \\
0.15 & 0.65 & 0.20 & 0 & 0 \\
0 & 0.25 & 0.55 & 0.10 & 0.10 \\
0 & 0.65 & 0.35 & 0 & 0 \\
0 & 0.80 & 0.10 & 0.10 & 0 \\
0.05 & 0.45 & 0.35 & 0.10 & 0.05 \\
0 & 0.25 & 0.55 & 0.10 & 0.10 \\
0.15 & 0.65 & 0.15 & 0 & 0 \\
0.20 & 0.65 & 0.15 & 0 & 0 \\
0.70 & 0.20 & 0.10 & 0 & 0 \\
0 & 0.65 & 0.25 & 0.10 & 0 \\
0.60 & 0.35 & 0.05 & 0 & 0 
\end{bmatrix}$$

After calculation, get $P = W_{mi} \times R = [0.190575, 0.40733, 0.30835, 0.058955, 0.033035]$, according to maximum membership degree law maximum membership degree. It can be determined that the pipeline failure risk level is II (lower).

5. Conclusion
Aiming at the failure of oil and gas pipelines, this paper proposes an evaluation system. In the evaluation process, the fuzzy concepts and methods are used to transform the qualitative effects into quantitative fuzzy numbers based on linguistic variables. The weights are calculated according to the calculation results. The risk is graded and the pipeline failure risk level is finalized. Through the analysis and evaluation of a section of the West-East Gas Pipeline, the risk level is II (lower) and meets the safety production requirements.

(2) Through the risk assessment of 14 sub-factors for oil and gas pipeline failure, the C21 external corrosion and C41 management system are classified as medium-risk risk levels. Therefore, the anti-corrosion measures for pipelines should be strengthened to improve the personnel equipment management system.

(3) The safety assessment of oil and gas pipelines based on fuzzy analytic hierarchy process needs to be optimized in the following two aspects: (1) There are limitations in the selection of evaluation indicators, and more comprehensive evaluation indicators should be selected on the basis of accident data statistics; (2) Industry experts assess the risk of indicators and get more authoritative evaluation indicators.

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