Risk Analysis of High Pressure Gas Pipeline Leakage Based on Bow-tie Model and IAHP

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Abstract. Natural gas is a kind of inflammable and explosive high-risk gas, and its transportation mainly depends on high-pressure pipelines. Serious pipeline leaks can cause fires and explosions. These accidents will cause loss of life and property to residents along the line. Therefore, it is very important to conduct risk analysis on high-pressure gas pipelines. In this paper, the Bow-tie model is used to conduct a strict logical reasoning on the causes and consequences of pipeline leakage, and a complete and clear risk evaluation index system for high-pressure gas pipelines is proposed. Secondly, the improved analytic hierarchy process (IAHP) is used to calculate the weight of each indicator and sort the weights. The calculation shows that the equipment plays a major role in the first-level indicators. Among the secondary indicators, the safety equipment, alarm system, natural disasters, operational misoperations, safety inspection errors, and design misoperations account for a significant weight ratio. The evaluation results of various factors are basically consistent with the actual situation. The research results can provide a reliable basis for the daily safety management of gas pipelines.

1. Introduction

Natural gas is a kind of clean energy, which has higher calorific value, less pollution and safer use than traditional energy such as coal and oil. As a result, dependence on natural gas has increased year by year in China and around the world. However, natural gas is a flammable, explosive, toxic and highly corrosive gas, and the means of transportation relies on high-pressure pipelines. Therefore, natural gas pressure pipeline engineering has become a high-risk industry. Once the gas pipeline leaks, it will cause different degrees and different types of disasters such as explosion, fire, poisoning and so on. According to the analysis report of China’s natural gas explosion accident in 2017, a total of 702 gas explosion accidents occurred throughout the year, causing more than 1,100 people to be injured and 126 deaths. The accident has caused many people to lose their young lives and homes, seriously affecting the harmonious and stable development of society. Based on the above reasons, it is very necessary to analyze the leakage risk of high pressure gas pipeline.

Under the unremitting exploration of researchers, the current research on the risk analysis of high-pressure natural gas pipeline leakage has achieved rich results. Li [1] used a Bayesian network and a bow-tie model for quantitative risk analysis of subsea oil and gas pipelines. Guo [2] used Bayesian network to analyze the failure of oil and gas pipelines caused by third-party damage. Ahamed et al. [3] studied the corrosion failure of pipelines by applying the equivalent effect method and analyzed the reliability of the pipeline. Xie et al. Shin [4] introduced a new underground pipeline safety management method based on the principle of pipeline management, which also reflects the corrosion effect of pipeline corrosion effect. Shahriar [5] explored the interactions between...
various factors leading to the failure of oil and gas pipelines, and introduced fuzzy utility value (FUV) and three bottom line (TBL) sustainability criteria for risk assessment of natural gas pipelines. Yang [6] used the Analytic Hierarchy Process (AHP) and entropy method to establish a comprehensive evaluation index for the gas pipeline leakage disaster system. Liu [7] studied the leakage and diffusion laws of natural gas pipelines under different building layouts through experiments and CFD numerical simulations. Rui [8] developed a mathematical model that can be used to detect multiple leaks in the same natural gas pipeline. Trowsdale et al. [9] studied the probability of a leakage accident during the operation of a buried pipeline through laboratory experiments. Kim et al. Lu [10] used numerical simulation to study the leakage and diffusion laws and ventilation schemes of natural gas pipelines in Myanmar.

In summary, although theoretical analysis and experimental research in the field of high-pressure gas pipeline leakage risk research have achieved some results. However, most scholars' research on cause analysis only makes a deeper analysis of some aspects of pipeline leakage, such as pipeline corrosion, third-party damage, and so on. In the analysis of leakage consequences, most researchers used CFD numerical simulation to study the law of natural gas leakage and diffusion. However, there are some errors in computer simulation, and it is difficult to provide more clear ideas for managers in pipeline management. Therefore, in view of the above deficiencies, this paper will firstly use the bow-tie model to conduct strict logical reasoning on the causes and consequences of pipeline leakage, aiming to propose a relatively complete and clear risk evaluation index system for high-pressure gas pipeline leakage risk assessment. Secondly, the improved analytic hierarchy process (IAHP) is used to calculate the weight of each indicator and sort the weights. The research results can provide a reliable basis for the daily safety management of gas pipelines.

2. Methodology

2.1 Bow-tie model

David Gill of the University of Queensland in Australia presented the bow-tie model for the first time in 1979. Because the bow-tie model is easy to grasp in control logic and operating standards, it is widely used as a qualitative and semi-quantitative risk management technology. The bow-tie model is based on the combination of accident tree analysis (FTA) and event tree analysis (ETA). Using FTA to determine the initial event and identify all potential risk factors triggering the accident and their relationship. The ETA takes the top event of the FTA as the initial event and obtains the impact and potential consequences of the accident through the evolution of a series of possible processes.

2.2 Improved Analytic Hierarchy Process (IAHP)

Both Analytic Hierarchy Process (AHP) and Improved Analytic Hierarchy Process (IAHP) analyze the factors that influence decision-making, divide them into different target and criterion layers, and use these levels to qualitatively and quantitatively analyze the system. The difference between them is that the traditional analytic hierarchy process uses the 9-scale method to establish a judgment matrix. 9 scale method is more detailed and accurate, but it is easy to be interfered by personal subjective reasons in the judgment process, resulting in error and logic confusion. The improved analytic hierarchy process simplifies the 9-scale method to the 3-scale method. Because this method is easier to make accurate judgments, it is often used in the analysis of engineering projects. The basic steps of IAHP are detailed in the references[11].

3. Risk analysis of high pressure gas pipeline leakage

3.1 The establishment of the bow-tie model

After analyzing a large number of natural gas pipeline accidents, it can be found that the cause of fires and explosions in high-pressure pipelines is almost caused by the ignition source after the pipeline leaks. Therefore, this paper selects “pipe leakage” as the top event. According to the survey, pipeline
penetration and rupture are the most fundamental causes of pipeline leakage failure. Pipeline penetration and pipe rupture are then analyzed as sub-top events, and combined with hazard source identification results, the events are analyzed one by one until the most basic bottom events are found.

Figure 1 shows the bow-tie model for high-pressure gas pipeline leakage. Table 1 shows the event list. The model considers 28 basic events and 8 consequence paths.

| Event code | Event name                              | Event code | Event name                                      |
|------------|-----------------------------------------|------------|-----------------------------------------------|
| T          | Pipeline leakage                        | X5         | Corrosion detection failure                   |
| M1         | Penetration                             | X6         | Pipes have poor corrosion resistance          |
| M2         | Rupture                                 | X7         | Alarm system failure                          |
| M3         | Third party destruction                 | X8         | Low pipeline inspection frequency             |
| M4         | Corrosion                               | X9         | Pipeline inspection is not serious            |
| M5         | Violent construction above the pipeline | X10        | Acidic medium corrosion                       |
| M6         | Destruction of others                   | X11        | Anticorrosion measures failure                |
| M7         | Corrosion cracking                       | X12        | Current interference                          |
| M8         | Misoperation                            | X13        | Cathodic protection failure                   |
| M9         | Pipeline safety inspection              | X14        | Large tensile stress                          |
| M10        | Quality deterioration of anticorrosive insulating layer | X15        | Equipment aging                              |
| M11        | Internal corrosion of pipe              | X16        | Construction supervision failed               |
| M12        | External corrosion of pipeline          | X17        | Pipe welding failed                           |
| M13        | Defect                                  | X18        | Corrosion insulation layer is damaged         |
| M14        | Severe pressure along the line          | X19        | Pipe installation failed                      |
| M15        | Stress corrosion                         | X20        | Excessive external facilities                 |
| M16        | Operational misoperation                 | X21        | Unreasonable design of pipeline               |
| M17        | Maintenance misoperation                 | X22        | Operator error                                |
| M18        | Construction misoperation                | X23        | Communication system failure                  |
| M19        | Construction defect                      | X24        | Safety equipment failure                      |
| M20        | Stole natural gas by punching            | X25        | Poor maintenance equipment                    |
| X1         | Natural disaster                         | X26        | Maintenance personnel mistakes                |
| X2         | Malicious destruction                    | X27        | Unreasonable construction of pipe ditch       |
| X3         | Farming activities                       | X28        | Lack of public education                      |
| X4         | Initial defect                           |            |                                               |

3.2 Pipeline Leakage Risk Assessment Index System

According to the bow-tie model established in Figure 1, the basic events are classified, and the pipeline failure analytic model and the accident consequence analytic model can be constructed, as shown in Tables 2 and 3.

| Target layer               | Standard layer     | Index layer                          |
|----------------------------|--------------------|--------------------------------------|
| High-pressure gas pipeline failure index system | Third party factor | Public education                     |
|                            | Corrosion          | Construction supervision              |
|                            |                    | Safety check frequency               |
|                            |                    | Acid medium content                  |
|                            |                    | Corrosion detection                 |
|                            |                    | Natural disaster                     |
|                            |                    | Malicious destruction                |
|                            |                    | External facilities activities       |
|                            |                    | Current interference                |
|                            |                    | Cathodic protection                  |
|                            |                    | Tensile stress                       |
Pipe corrosion resistance  
Anti-corrosion layer  
Maintenance misoperation  
Pipeline construction misoperation  
Design misoperation  
Operation misoperation  
Installation misoperation  
Welding misoperation  
Maintenance equipment  
Alarm system  
Equipment construction  
Communication system  
Safety inspection error  
safety equipment  
Initial defect

| Misoperation | Equipment condition | Safety inspection error |
|--------------|---------------------|-------------------------|
| Pipe corrosion resistance | Maintenance misoperation | Anti-corrosion layer |
| Design misoperation | Installation misoperation | Pipeline construction misoperation |
| Operation misoperation | Maintenance equipment | Operation misoperation |
| Welding misoperation | Equipment aging | Communication system |

Table 3. Analytical model of accident consequences

| Target layer | Standard layer | Index layer | Minor injuries |
|--------------|----------------|-------------|----------------|
| High-pressure gas pipeline leakage consequence | Security consequences | Death | Serious injury | Suspension loss |
| Economic losses | Poisoning | Building destruction | Equipment destruction | Air pollution | Water pollution |
| Environmental pollution | Repair cost | Plant destruction | Lost medium | Soil pollution |
3.3 Calculating weights

Refer to 2.2 above to improve the calculation steps of the analytic hierarchy process, and then combine the expert scoring to establish the judgment matrix. Next, the weights of each indicator need to be calculated and sorted. Due to space limitations, the indicators involved are numerous and complex. Therefore, the calculation result is directly given, as shown in Table 4. The calculation shows that the equipment plays a major role in the first-level indicators. Among the secondary indicators, the safety
Equipment, alarm system, natural disasters, operational misoperations, safety inspection errors, and design misoperations account for a significant weight ratio. The evaluation results of various factors are basically consistent with the actual situation, indicating that the method has certain practical value. At the same time, relevant departments can formulate risk mitigation measures according to Table 4.

### Table 4: Pipeline leakage influence factor weights

| Factors affecting pipeline leakage | Weights   | Weight sorting |
|-----------------------------------|-----------|----------------|
| Third party factor               |           |                |
| (0.310029418)                     |           |                |
| Public education                  | 0.022634886 | 13            |
| Malicious destruction             | 0.065816573 | 7             |
| External facilities activities   | 0.039243838 | 9             |
| Construction supervision          | 0.039243838 | 9             |
| Farming activities               | 0.017611736 | 16            |
| Natural disaster                 | 0.091846568 | 3             |
| Safety check frequency           | 0.033632894 | 11            |
| Corrosion                        |           |                |
| (0.049947235)                     |           |                |
| Acid medium content              | 0.003697985 | 27            |
| Current interference             | 0.003697985 | 27            |
| Anti-corrosion layer             | 0.009402426 | 20            |
| Corrosion prevention             | 0.010217808 | 19            |
| Tensile stress                   | 0.003943369 | 25            |
| Pipe corrosion resistance        | 0.007334094 | 24            |
| Corrosion detection              | 0.007955582 | 22            |
| Cathodic protection              | 0.003697985 | 26            |
| Misoperation                     |           |                |
| (0.315845019)                     |           |                |
| Welding misoperation             | 0.020777154 | 15            |
| Pipeline construction misoperation | 0.024641659 | 12           |
| Safety inspection error          | 0.079825395 | 5             |
| Design misoperation              | 0.074259176 | 6             |
| Operation misoperation           | 0.085717309 | 4             |
| Installation misoperation        | 0.02265744  | 13            |
| Maintenance misoperation         | 0.007955582 | 22            |
| Equipment condition              |           |                |
| (0.324178328)                     |           |                |
| Initial defect                   | 0.016241245 | 17            |
| Alarm system                     | 0.117154888 | 2             |
| Safety equipment                 | 0.123999706 | 1             |
| Equipment aging                  | 0.011568189 | 18            |
| Communication system             | 0.046691893 | 8             |
| Maintenance equipment            | 0.008522407 | 21            |

### 4. Conclusion

This paper combines the bow-tie model with the improved analytic hierarchy process (IAHP). According to the bow-tie model, the indicators of the IAHP are determined to make the relationship between the indicators more clear, and the evaluation results are more in line with the objective reality. Then, based on the hazard source identification results, a bow-tie model for high pressure gas pipeline leakage was established. The model considers 28 basic events and 8 consequences paths. Secondly, based on the analysis results of the bow-tie model, a high-pressure gas pipeline leakage risk assessment system and an accident consequence evaluation system are established. Finally, the improved analytic hierarchy process is used to calculate the weight of each indicator and sort them. The calculation shows that the equipment plays a major role in the first-level indicators. Among the secondary indicators, the safety equipment, alarm system, natural disasters, operational misoperations, safety inspection errors, and design misoperations account for a significant weight ratio. The evaluation results of various factors are basically consistent with the actual situation, indicating that the method has certain practical value.
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