Analysis and Countermeasures of Safety Accidents in Urban Gas Pipeline Networks

Cong Liu*

Wenzhou Gas Group Co., Ltd., Wenzhou, Zhejiang 325000, China

*Corresponding author: Cong Liu (Email: 9075380@qq.com)

Abstract

Urban gas pipeline network is the lifeline engineering infrastructure of the city responsible for energy transmission. With the accelerated urbanization process, the construction of urban gas pipeline network has begun to expand rapidly. However, in recent years, due to the aging of some pipelines, third-party construction damage and other factors, urban gas pipeline network safety accidents have occurred frequently, causing huge casualties and property losses. Therefore, this paper analyzes the gas pipeline safety accidents that occurred this year. From the perspective of safe operation of urban gas pipeline network, with the purpose of improving its disaster bearing capacity and improving the safety resilience level of gas system, this paper comprehensively uses the combined weighting method to study the urban gas pipeline network system. Finally, according to the results of evaluation and analysis, specific improvement countermeasures are proposed from the three dimensions of pressure, state and response, which can better explain the process of resisting, digesting, reorganizing and optimizing the uncertain risks faced by gas pipeline network, and then achieving a dynamic stable state, which provides new ideas for disaster prevention of urban gas system.

Keywords

Urban Resilience; Gas Accident; Risk Assessment.

1. Introduction

The urban gas pipeline system is an important part of modern urban infrastructure, mainly responsible for the transportation and distribution of natural gas. At present, with the accelerated urbanization process, the construction of urban gas pipeline network in my country has begun to usher in rapid development. With the national dual carbon target of "3060", natural gas plays an important role in the process of "carbon peak" and "carbon neutrality" and is the core pillar of the future low-carbon economy.

At present, the scale of urban gas pipeline systems is getting larger and larger, and the pipeline network planning is becoming more and more complex. New and old pipelines are interwoven to form an urban pipeline system. However, gas safety accidents caused by factors such as pipeline corrosion and aging, third-party damage, etc. occur frequently. Gas is flammable and explosive. If it is not handled promptly and accurately in the early stage of the accident, it will cause significant economic losses to the society and the people, environmental pollution, and even cause major casualties. According to the accident analysis report of the China Urban Gas Association, there were 802 gas safety accidents in my country in 2022, 487 people were injured, and 66 people died. The painful lesson has forced us to pay attention to the safety of gas pipelines. Therefore, it is imperative to analyze and study the safety accidents and countermeasures of urban network management. This

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paper analyzes the gas pipeline safety incidents that have occurred in recent years, and from the perspective of the overall gas pipeline system, combined with the pipeline safety resilience theory, the combined weighting method is used to study the urban gas pipeline system. Finally, according to the results of evaluation and analysis, specific improvement countermeasures are proposed from the three dimensions of pressure, state and response, which are of reference significance for improving the response capability of the pipeline system, reducing the occurrence of safety accidents, and restoring the normal operation of the pipeline system as soon as possible.

2. Analysis of Types and Causes of Urban Gas Pipeline Safety Accidents

With the increasing use of urban gas, the complex characteristics of the gas pipeline network and the aging of some gas pipelines in reality, various gas accidents have occurred frequently in recent years, and accidents such as leakage, poisoning and suffocation, fire, and explosion have shown a high incidence and frequency, causing huge losses to the lives and property of the people. In addition, the occurrence of gas pipeline accidents is universal, sudden and unpredictable. For example, in 2013, a gas pipeline leakage accident occurred in Sinopec Storage and Transportation Company in Qingdao, Shandong. The maintenance personnel did not deal with it in time, which eventually caused 62 deaths and 136 injuries, resulting in direct economic losses of 750 million yuan. Such accidents have serious consequences, affect a wide range of areas, and are prone to secondary disasters. Moreover, the less timely and appropriate the handling is, the more serious the consequences will be.

Based on online public data, this article collects relatively typical and representative urban gas safety accident cases in the past seven years, and briefly analyzes the types and causes of the cases [1].

In 2017, a large urban gas pipeline leakage and explosion occurred in Songyuan City on July 4, 2017. The accident caused 5 deaths on the spot, 2 deaths after rescue efforts failed, and 85 injuries, including 13 serious injuries and 72 minor injuries, resulting in direct economic losses of 44.19 million yuan. The main cause of the accident was the construction of rotary jet piles near the gas pipeline, which caused the gas pipeline to leak, and the open flames generated by the construction caused the gas pipeline to explode. What is reflected behind this is that the construction company failed to assume its own safety production responsibility, has not yet established and improved rules and regulations, the implementation of the training mechanism is not ideal, and the implementation effect of gas pipeline protection work is poor; the implementation of the gas facility safety management mechanism is poor; there is a lack of emergency preparedness mechanism; after the leakage occurred, it failed to deal with it in time; and it failed to carry out construction project management in accordance with laws and regulations.

In 2021, a large gas explosion occurred on December 3 in Shunyi District, Beijing. Gas in the production workshop exploded and caused 4 deaths and 10 injuries, resulting in direct economic losses of 14.29563 million yuan. The main reason was the corrosion of the flange gasket of the main gas valve, which caused a large amount of explosive mixed gas to leak due to internal pressure, and the explosion was caused by the ignition source. It reflects that the safety management mechanism and daily maintenance mechanism of gas equipment are not perfect, and the relevant administrative departments have failed to investigate the problem in time.

In 2021, a large gas leakage and explosion occurred on January 25 in Jinpu New District, Dalian, which caused 3 deaths and 6 injuries, resulting in direct economic losses of 9.0538 million yuan. The main cause of the accident was that the welding part of the underground pipeline was broken due to excessive ground load, and a large amount of natural gas leaked, which exploded when it came into contact with open flames. It reflects that the gas company lacked supervision during the construction of the gas pipeline and failed to rectify the hidden dangers of the safety pipeline in time.

In 2021, a major gas explosion occurred in Shiyan City on June 13, killing 26 people, injuring 138 people, seriously injuring 38 patients, and causing direct economic losses of 53.9541 million yuan. During the investigation, it was found that the natural gas medium-pressure steel pipe was severely corroded and cracked, and the gas leaked and accumulated in the closed space in the river below the

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market building, which caused the explosion when it met the kitchen exhaust pipe and produced sparks. It reflects that the quality of some projects did not meet the standards during the acceptance of construction, and the hidden dangers were not rectified in time.

According to the above accident investigation and analysis, as well as the review and summary of the gas pipeline network safety accident report materials, the main factors for the occurrence of gas pipeline network safety accidents are human influence, facility system, environmental impact, and management organization. The safety accident factors caused by human influence mainly include malicious destruction, barbaric construction, illegal occupation, improper design, operation, maintenance and construction, etc. The safety accident factors caused by the facility system are mainly pipeline corrosion, failure of the protective layer, pipe defects, pipeline stress, etc. The safety accident factors affected by the environment include factors such as too small burial depth, unclear markings, geological disasters, and corrosive soil. Safety accident factors caused by management organizations include unreasonable and irregular inspection process, irregular operating procedures, and poor management of daily inspection and maintenance.

3. Concept of Safety Resilience of Gas Pipeline Network

Based on the operation characteristics of gas pipeline network and relevant theories of safety resilience, this paper defines the concept of safety resilience of urban gas pipeline network on the basis of PSR model, that is, the performance of urban gas pipeline network in various safety risks and disturbances (such as leakage, poisoning, suffocation, explosion, fire, etc.) during operation, including early warning capability before safety accident, system response capability and self-regulation capability during safety accident, after safety accident, the system returns to normal operation and takes corresponding measures to enhance its feedback capability through learning. Resilience theory is a concept that is constantly being improved and expanded. It was first introduced into system evaluation by Professor Holling. For a long time, the theory has gone through three stages: engineering resilience stage, ecological resilience stage and evolutionary resilience stage. In the engineering resilience stage, resilience is defined as the ability of an object to restore equilibrium or stable state when subjected to external forces. The scope of engineering resilience is relatively small, involving only a single safety state, and the strength of its system resilience often depends on its initial safety state and its own material properties. Professor Holling then proposed the concept of ecological resilience, which is a revision of the concept of resilience theory. Ecological resilience theory focuses on the disturbance margin that a system can absorb before changing its own structure. In the evolutionary resilience stage, resilience is defined as the risk resistance, risk adaptation and self-change capabilities of a system when encountering risk shocks[2]. From then on, resilience no longer refers only to the ability of a system to recover to its initial state, but is regarded as the resilience of a complex social-ecological system in response to pressures and constraints.

4. Construction of Gas Pipeline Network Safety Resilience Evaluation System

4.1 Overall Idea of Evaluation System Construction

As a complex network system, the continuous interaction and adaptation process between internal and external factors of the gas pipeline system actually constitutes a dynamic cycle of urban gas pipeline network resilience development. This inherent complexity gives the resilience of the gas pipeline system a dynamic characteristic, so it is particularly important to conduct a comprehensive evaluation of it [3]. Through in-depth statistical analysis of gas pipeline safety accidents, we start from the perspective of resilience theory, focus on the system characteristics of safety resilience, and refer to the PSR process model to carefully select the three core indicators of pressure dimension, state dimension, and response dimension as the first-level indicators. At the same time, we further refine a total of 27 second-level indicators such as geological disasters, operation redundancy, pipe corrosion, and fire rescue response time, so as to construct an evaluation model for the safety resilience of urban gas pipeline networks. The construction of this model aims to provide us with a comprehensive and objective perspective to accurately evaluate the resilience of urban gas pipeline networks. The specific process idea is shown in the figure below.

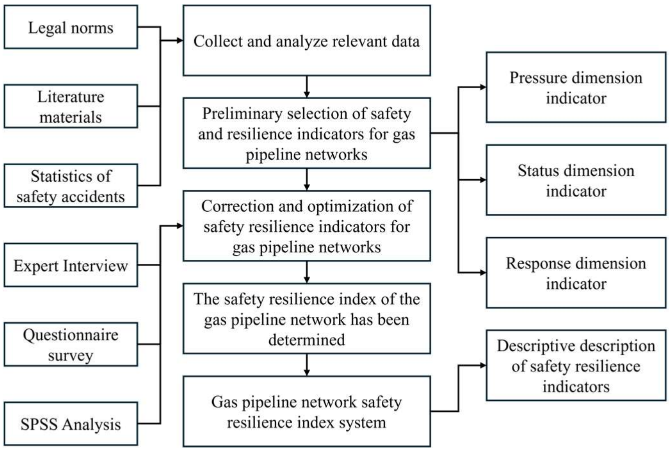

Figure 1. Construction process of gas pipeline network safety resilience evaluation index system

To ensure the accuracy and rationality of the gas pipeline network safety resilience evaluation index system, the construction process should emphasize the practicality, universality, adaptability and scientificity of the system. Following the basic principles, and referring to relevant laws and regulations, documents and domestic and foreign academic achievements, the index system is initially constructed based on the phased process of urban gas pipeline network safety resilience.

4.2 Determination and Optimization of Evaluation Indicators and Weights

In the selection process of evaluation indicators, the construction principles and basis of the gas pipeline network safety resilience index system are followed, relevant literature is searched, and the actual situation of safety accidents in the operation of urban gas pipeline networks is fully considered. According to the three dimensions of pressure, state and response of the PSR model, the gas pipeline network safety accident factors are preliminarily screened and divided into pressure dimension indicators, state dimension indicators and response dimension indicators. The pressure sources of the "pressure" dimension are mainly human activities and natural environment. The influencing factors of human activities mainly include population density, road vehicle flow, disturbance of underground space by construction and development, and technical quality of gas pipeline network participants; the influencing factors of the natural environment are due to the high sensitivity of urban gas pipeline networks to meteorological and geological activities, so natural environment pressure is an inevitable source of risk pressure. The "state" dimension indicator of the gas pipeline network is to measure the ability of the gas pipeline network system to maintain normal operation and recover quickly in the face of various adverse factors, and has the characteristics of robustness, redundancy, adaptability and vulnerability. The "response" dimension indicator of the gas pipeline network system is to measure the measures and actions taken by the urban gas pipeline network in the face of safety accidents, gradually restore the original normal operation state from failure, and improve its ability to face disasters on the basis of learning, with the characteristics of flexibility, comprehensiveness, inclusiveness and reflection. The following table shows the secondary indicators specified according to three different dimensions.

There are many evaluation indicators for the gas pipeline network system, and each indicator has a different degree of influence on the resilience evaluation. Therefore, in order to more accurately evaluate the safety resilience of the pipeline network, it is necessary to weight each indicator. Considering that the environment in which the gas pipeline network system is located is relatively complex, in order to more accurately evaluate the safety resilience of the pipeline network, this paper chooses a combined weighting method that combines the subjective analytic hierarchy process (AHP

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method) and the objective entropy weight method as the weighting method for the safety resilience evaluation indicators of the urban gas pipeline network.

Table 1. Corresponding indicators under different dimensions

Dimension	Secondary indicators
Pressure	Geological disasters, meteorological disasters, trench cover thickness, soil corrosion, population density, number of motor vehicles, improper construction, improper design, improper maintenance, technical quality of management personnel, urban infrastructure development plan
Status	Years of operation, maintenance, pipeline corrosion, pipe deterioration and deformation, emergency support resource allocation rate, monitoring and early warning system completeness, system operation redundancy
Response	Fire rescue response time, medical rescue response time, information communication feedback efficiency, emergency plan completeness, disaster emergency management system optimization, public safety financial expenditure

Based on the qualitative and quantitative decision-making methods of structural hierarchical analysis, the weights of each indicator are determined to achieve the optimization of the decision-making goal. First, a complex problem is hierarchical, and the target layer, criterion layer and indicator layer are respectively regarded as different levels to determine the deep structure. In addition, according to the importance between the two levels, the relationship between the levels is quantitatively evaluated to construct a judgment matrix. Finally, according to the judgment matrix, the weight vectors between the levels are calculated by finding the eigenvector and normalizing. Similarly, the weight value of the secondary indicator of the safety resilience of the gas pipeline network is calculated by the hierarchical analysis method, which is multiplied by the weight value of the primary indicator and normalized to obtain the weight value of each indicator.

The entropy weight method is a weight allocation method based on the information entropy theory. It mainly determines the objective weight of each indicator by calculating the entropy value and the difference coefficient of the indicator data. In order to more accurately evaluate the safety resilience of the pipeline network, on the basis of obtaining the weight value based on the structural hierarchical analysis, the entropy weight method is used to further correct the objective weight of the indicator.

5. Gas Pipeline Network Safety Resilience Enhancement Strategy

The improvement of the safety resilience of the gas pipeline network system mainly starts from the gas pipeline network system itself. From the three dimensions of "pressure", "state" and "response", a universal optimization strategy is proposed to improve the level of risk prevention and response and the ability to restore response. One of the keys to improving the "pressure" dimension is to avoid "pressure risk factors". Strengthening the monitoring and early warning of "risk factors" is an important control measure for the safety resilience of the gas pipeline network. Sorting out the "pressure" dimension to refine the indicators, discover external environmental pressure factors such as geological disasters, meteorological disasters, and population density, and improve the gas leak detection and early warning system. Starting from the "pressure stage" of the occurrence of safety accidents, the safety accidents are suppressed in the embryonic stage, which is the maximum protection of the "state stage" and "response stage" of the gas pipeline system. When facing safety accidents, the robustness of the urban gas pipeline network directly determines the degree of damage it suffers. Therefore, it is necessary to regularly maintain and overhaul the urban gas pipeline network to ensure that the gas pipeline network system is always operating in the optimal state. After the gas pipeline network system is damaged by a safety accident, it begins to restore its functions. By quickly taking emergency measures to fight against the disaster, this process emphasizes the timeliness of

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"response". When the system safety emergency guarantee efficiency is higher, the system's ability to respond to risks is stronger, and the time to recover from the damage is shorter. First of all, it is necessary to strengthen the management of the emergency department of daily operation organization. Regularly organize emergency education training and lectures, strictly implement safety management regulations and systems, and establish an assessment system, rewards and punishments and other measures to comprehensively improve the professional skills of technical personnel in the emergency management department. Secondly, it is necessary to establish sufficient emergency shelters and emergency rescue channels to ensure that the emergency management department is adequately equipped with manpower, materials and rescue facilities. At the same time, it is also necessary to reasonably equip rescue equipment, medical equipment, basic living materials, communication equipment and other materials. Finally, it is necessary to strengthen the emergency management efficiency of the gas pipeline network system and formulate efficient and practical emergency plans. These measures will effectively improve the system's response capabilities, reduce accident losses, and restore the normal operation of the pipeline network system as soon as possible.

6. Conclusion

This paper focuses on the frequent occurrence of safety accidents in urban gas pipeline networks. By analyzing typical cases and the causes of accidents, combined with the resilience theory, a safety resilience evaluation system based on three dimensions of pressure, state and response is constructed. The combined weighting method is adopted to determine the index weights, and improvement strategies covering dimensions such as risk avoidance, system optimization and emergency response are proposed. Combining the resilience theory with the safety management of gas pipeline networks, a dynamic and multi-dimensional resilience evaluation model has been established, providing a systematic theoretical framework and practical guidance for the risk prevention and control and disaster recovery of urban gas pipeline networks. Future research can further integrate technologies such as the Internet of Things and big data to achieve real-time monitoring and intelligent early warning, and expand resilience assessment in multi-disaster coupling scenarios. At the same time, it is necessary to strengthen the research on the compatibility of cross-departmental collaboration mechanisms and policies and regulations to promote the refined and sustainable development of gas pipeline network safety management.

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