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Resilience Assessment of Gas Pipeline Network System Based on Complex Network Theory

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Abstract

To enhance the response and recovery capabilities of gas pipeline networks in the face of sudden disturbances, complex network theory is introduced to explore the performance changes of gas pipeline networks under disturbances. A network performance function that comprehensively considers the structural and functional dimensions of gas pipeline networks is proposed. Combined with the resilience stage, a performance response function method is adopted to establish an evaluation method for quantifying system resilience. This evaluation process covers the entire process from the system's resistance and adaptation to disturbances to the restoration of specific functions. An example of a certain gas pipeline network system is used for practical application.

Keywords

Gas pipeline network system; Resilience assessment; Network resilience; Complex network; Performance response function

1. Introduction

Gas pipeline accidents has been increasing. Among them, there were 64 pipeline accidents. With the development of resilience, it has been widely applied in the field of disaster assessment. Combining resilience assessment with the gas pipeline network system is of great significance for the safe construction of the pipeline network and the protection of people's lives and property.

The internal characteristics of the gas pipeline network system are highly complex in relation to the external environment[1]. Many scholars have introduced the theory of complex networks to conduct research on the gas pipeline system. At the level of the physical topology structure of the pipeline network, Chen[2]used graph theory to construct the topological structure diagram of the natural gas pipeline network. By calculating some specific indicators of this topological network, he identified the important nodes and pipelines within the pipeline network. He also conducted an in-depth analysis of the impact of network structure characteristics on the operational efficiency and social welfare of the natural gas pipeline network. Ma [3]was used in the robustness evaluation of the urban gas pipeline network to accurately identify the key nodes of the gas pipeline network. Based on the theory of complex networks, the node betweenness centrality was calculated using MATLAB software, and the gas pipeline network node structure importance evaluation model was constructed by using the node degree centrality and betweenness centrality. At the level of considering the functional characteristics of the flow, Wang[4] proposed a method for analyzing the vulnerability of gas pipeline network transportation capacity based on network traffic. They established the network topology structure in the form of a graph and used the maximum flow algorithm to identify the key pipelines that affect the gas pipeline network's transportation capacity. Su[5] based on the shortest path algorithm and network flow algorithm, a model for calculating the gas supply capacity of the pipeline network and analyzing accident consequences was constructed. An evaluation index was proposed from three aspects: probability, the sufficiency of gas supply capacity, and the duration of gas shortage events, and the gas supply reliability of the pipeline network was quantified. Regarding the resilience issue of the gas pipeline network system, Li[6]based on the topological structure characteristics, a resilience analysis of the gas pipeline system is conducted. By analyzing the complexity of the topological structure of the natural gas pipeline network and its evolution mechanism, a gas supply resilience evaluation method applicable to the natural gas pipeline network is proposed. Marino Antonio[7] proposed a novel resilience analysis framework for the complex natural gas pipeline transmission network to quantify the resilience value. In the paper, the maximum flow algorithm was used to calculate the supply capacity of the natural gas network. When a fault occurs, the pressure at the network nodes and the gas supply capacity will change, resulting in the unmet demands of users.

The above research on the resilience of the gas pipeline network system only considers the topological structure characteristics or flow supply and current research on the resilience of the gas pipeline network system rarely conducts in-depth dynamic whole-process studies on the changes in system performance by combining resilience stages. In view of this, this paper intends to apply the complex network theory to consider the comprehensive performance of the network structure and function dimensions, combine the resilience stages with performance response functions to analyze the changes in the comprehensive performance of the gas pipeline network system after disturbance, and construct a resilience assessment method applicable to the gas pipeline network system.

2. Method for Assessing the Resilience of Gas Pipeline Network Systems

2.1. The concept of resilience of the gas pipeline network system

Due to the differences in the specific research subjects and problems, currently in the academic community, there is no widely accepted concept of resilience. However, there has been a gradually unified understanding of the essence of resilience, which is manifested as the resistance, adaptability and recovery ability of the system's resilience[8] . This article, based on the characteristics of gas pipeline networks and the concept of resilience, defines the resilience of the gas pipeline network system as: After the gas pipeline network system is subjected to disturbances, it has the ability to resist and cope with the disturbances to maintain its structural stability and gas supply function, and to recover to a specific operating state as quickly as possible.

2.2. Introduction to Resilience Assessment Methods

In order to investigate the dynamic changes of the gas pipeline network after being disturbed, we refer to the evolution process of the system performance (function) curve proposed by scholars[9]，This paper constructs a PRF curve that takes into account the comprehensive performance of the gas pipeline network system to quantify the resilience of the gas pipeline network system (see Figure 1).

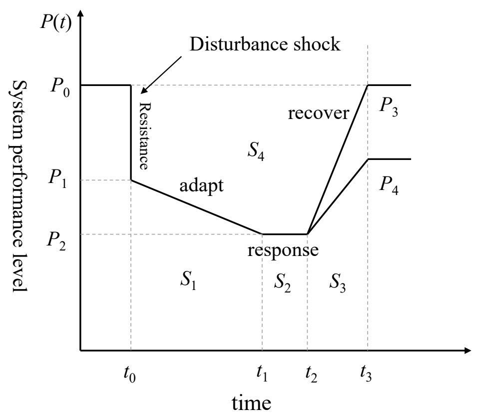


Figure 1. Perturbed PRF Curve of Gas Pipeline Network System

According to the PRF curve, the size of the system's resilience is quantified by the area enclosed by the performance function curve within the specified time period (t0-t3) and the time axis[10]. Therefore, the resilience R of the gas pipeline network system can be expressed by the following formula:

$$R = \frac{\int_{t_0}^{t_3} P(t)dt}{P_0(t_3 - t_0)} = \frac{S_1 + S_2 + S_3}{S_1 + S_2 + S_3 + S_4} \quad (1)$$

Among them, P(t) represents the performance function of the urban gas pipeline system, and P0 represents the performance level of the system during normal operation. The larger the area enclosed by the performance response function and the coordinate axes, the stronger the resilience of the system.

2.3. Comprehensive performance calculation of gas pipeline network

Applying complex network theory to explore the characteristics of transmission networks is an emerging research hotspot at present[11] . The gas pipeline network is a complex system. By applying the theory of complex networks to study the topological structure and network flow status of the gas pipeline network system, the structural and supply performance of the gas pipeline network can be reasonably quantified. This paper constructs a network system performance function that comprehensively considers the structural and functional dimensions of the gas pipeline network. The calculation formula is as follows.

$$P(t) = \alpha R_s + \beta R_f \tag{2}$$

In the formula: P(t) represents the overall performance of the system; Rs indicates the structural performance level of the system, Rf represents the functional performance level of the system, and α and β are weight coefficients.

2.3.1. Gas network structure performance calculation

The connectivity degree of a network structure is usually measured by its network efficiency, which can reflect the transmission efficiency of the network structure.The calculation formula is as follows:

$$E = \frac{1}{N(N-1)} \sum_{i \neq j} \frac{1}{d_{ij}} \tag{3}$$

In the formula: E represents the network efficiency. N is the total number of nodes in the entire network; dij represents the number of shortest path edges between node i and node j.

To reflect the fact that the network performance level of the gas pipeline system decreases after it is damaged, the structural performance changes of the gas pipeline system after being disturbed are measured by using the normalized network efficiency and the proportion of nodes.

$$R_s = \frac{E'}{E_0} G(P) \tag{4}$$

In the formula: represents the current network efficiency, represents the initial network efficiency, and G(P) represents the proportion of nodes existing.

2.3.2. Gas supply performance calculation of the gas network

When solving the functional status of the gas pipeline network, that is, the problem of network transportation capacity, the hydraulic calculation has high requirements for computer configuration, takes a long time and is very difficult to solve. Utilizing the maximum flow algorithm of complex network theory to calculate the transportation capacity of the gas pipeline network system has obvious advantages.

The Ford-Fulkerson algorithm is applied to solve the maximum flow of the network, denoted as Cfmax. In this paper, the normalized maximum flow is selected to measure the gas supply performance level of the gas pipeline network system.

$$R_f = \frac{C'_{f\max}}{C^0_{f\max}} \tag{5}$$

3. Establish a resilience assessment process for the gas pipeline network system

3.1. Simulation of disturbance process

The types of current urban infrastructure disturbance events can be classified as natural disturbances, human-induced disturbances and technical disturbances[12]. This paper studies the resilience of the gas pipeline network system at the network level. To simplify the research, the disturbance is abstracted as the failure of network nodes, and the types of disturbance are simulated as random attacks and intentional attacks[13]. Usually, nodes with high degree centrality and betweenness centrality are selected as the targets for deliberate attacks.

3.2. Simulation of the resistance process

When the gas pipeline network system is disturbed, if the occurrence time of the disturbance is sufficiently rapid, the external structure will first be subjected to the impact of the disturbance, and the structural performance will immediately deteriorate, while the gas supply capacity will remain temporarily unchanged. At this point, the performance of the gas pipeline network system can be expressed as:

$$P(t_0) = \alpha \frac{E(t_0)}{E_0} G(P) + \beta \tag{6}$$

In the formula: represents the weight of structural performance and gas supply performance.

3.3. Adaptation process simulation

After the gas pipeline network system is disturbed and the network structure is damaged, the transmission path of this link is blocked and the gas supply is interrupted. However, due to the pipeline's certain gas storage capacity and redundancy, the gas is transported to the demand nodes through other links, and the gas supply capacity gradually decreases and eventually can maintain a certain level of supply capacity. At this time, the performance of the gas pipeline network system can be expressed as:

$$P(t_1) = \alpha \frac{E(t_1)}{E_0} G(P) + \beta \frac{C^{(t_1)}_{f\max}}{C^0_{f\max}} \tag{7}$$

The duration of the adaptation process is set as the time it takes for the gas stored in the associated pipeline to be fully delivered to the demand node through the shortest path after the disturbance occurs, as shown in Equation (8):

$$t_a = \sum_{i}^{n} \frac{V_r}{f_{ij}} \tag{8}$$

The time taken for the adaptation process in the formula is expressed as the ratio and sum of the volume of gas stored in the pipelines that can be delivered to the demand nodes and the flow rates of the relevant pipelines along the transmission route.

3.4. Recovery process simulation

The response and recovery phases of gas pipeline network accidents are closely linked. Before the recovery phase begins, it is required that emergency response personnel and necessary resources immediately arrive at the scene. According to the principle of the most unfavorable situation, the response time tx can be assumed to be the latest time requirement for emergency forces to reach the scene. For pipeline accidents, in remote areas, the time requirement may be appropriately relaxed, but generally, it is required to arrive at the scene within 1 hour.

The impact of the recovery process on the system's resilience is reflected in the recovery degree and recovery time. When a disturbance causes the failure of a single node in the gas pipeline system, there is no need to consider the issue of repair sequence. The recovery of the gas pipeline system to a normal operating state only depends on the recovery time. When a large-scale disaster disturbance leads to the failure of multiple nodes, a reasonable recovery strategy can enable the gas pipeline system to recover to a normal state as soon as possible. According to the method of recovering one node at a time, the default structure performance recovery will be followed by the recovery of the supply performance. This paper considers two recovery strategies:

1）Priority restoration. That is, prioritize the restoration of nodes with higher importance based on the degree centrality or betweenness centrality, from high to low. Note: When nodes with the same degree centrality or betweenness centrality need to be restored, the node with a higher other centrality should be restored first.

2）Local restoration. Repair the failed nodes in sequence from the lowest to the highest distance from the emergency forces and the failed nodes.

$$t_r = C + \frac{L}{v} \tag{9}$$

In the formula: tr represents the recovery time of a failed node; C represents a time step, which adopts the normal distribution average value recommended by FEMA for the repair time after pipeline leakage simulation, and is set as C = 6 hours; L is the distance between the emergency force and the failed node; v represents the maximum driving speed, which is set as v=60km/h[14].

4. Case study

4.1. The background situation of a gas pipeline network

Selecting a certain gas pipeline network system as the research object, the above evaluation method is applied in an example. The gas source information is shown in Table 4.1, the demand node information is shown in Table 4.2, the gas pipeline network topology structure is shown in Figure 3, The direction of the pipeline network and the hydraulic direction are simulated by TGNET. The gas pipeline network information in this paper is obtained by referring to the literature [15].

Figure 2. Flowchart for Assessing the Resilience of Gas Pipeline Network System

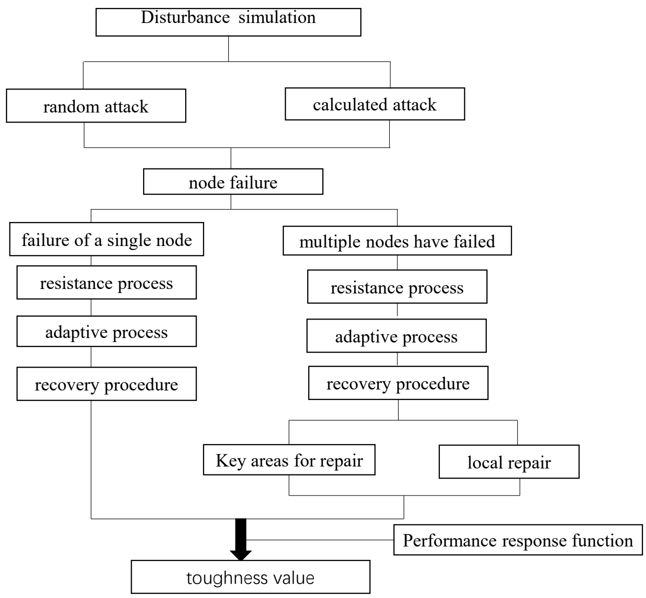


Table 4.1. Gas Source Information

Gas source location	Gas source type	Upper limit of gas supply capacity (megameters cubed per day)
1	Inflow source	31
2	Liquefied Natural Gas Terminal	4
3	Inflow source	7
4	gas storage	25

Figure 3. Topological Structure Diagram of Gas Pipeline Network System

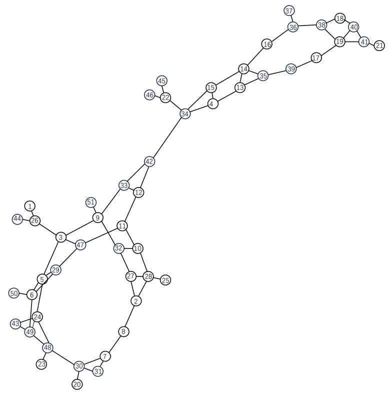


Table 4.2. Information of Demand Nodes

Demand node	User demand (m3/d)	Demand node	User demand (m3/d)
29	3.43	41	0.4
30	0.57	42	1
31	0.66	43	1.74
32	1.03	44	1
33	0.46	45	0.4
34	8.4	46	0.5
35	0.54	47	1.06
36	0.6	48	2.82
37	0.8	49	0.68
38	3.5	50	1.17
39	6	51	0.98
40	0.4		

4.2. Network parameter analysis

Subsequently, the network was simulated by attacking the network nodes one by one, and the results of network efficiency and maximum flow after node failure were shown in Figures 4 and 5 respectively. As shown in Figure 4: when nodes 34 and 42 were damaged, the network efficiency decreased significantly compared to the initial value. This phenomenon can be explained as that nodes 34 and 42 are at the core position in the entire gas pipeline network system connection. Since there is no redundant path between the two nodes, when either node fails, the network will be split into two isolated parts, and the network connectivity is severely damaged. As shown in Figure 5: when node 4 was damaged, the maximum flow of the network decreased significantly compared to the initial value. This phenomenon can be explained as that node 4 provides a large flow supply to the gas source node.By comparing Figures 4 and 5, it can be seen that the impact of node damage on the structural and functional dimensions is different. Node 34 and 42 have a greater impact on the network structure dimension, and node 4 has a greater impact on the network functional dimension. It is necessary to comprehensively consider the structural and functional characteristics of the nodes.

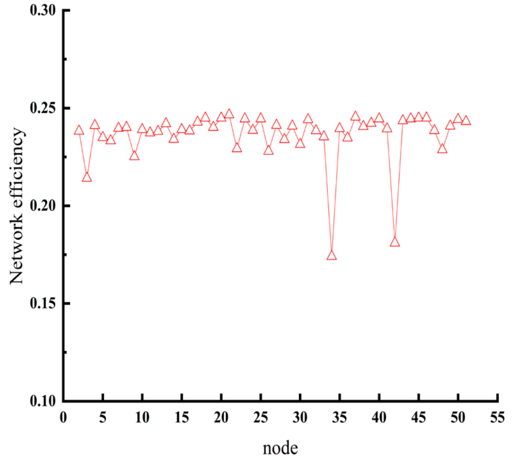


Figure 4. Network efficiency

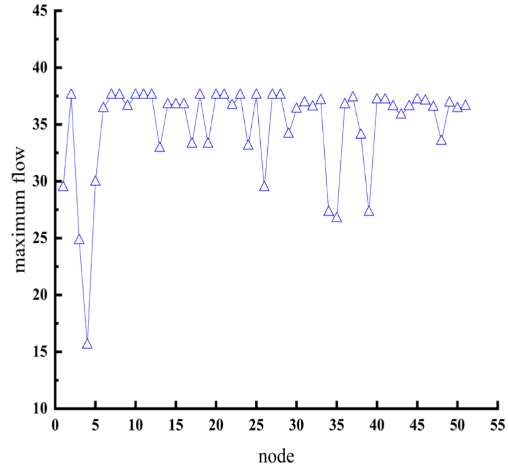


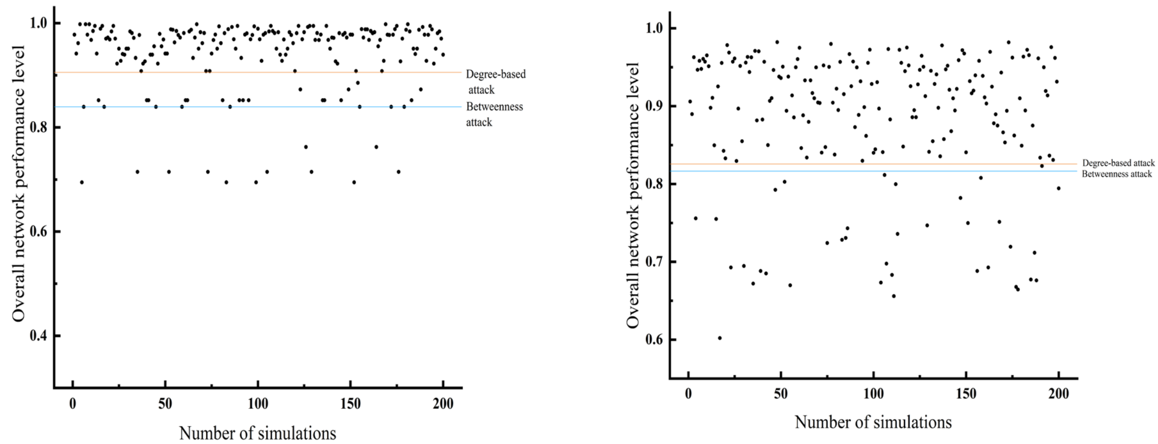
Figure 5. Maximum flow results

4.3. Resilience assessment and result analysis of the gas pipeline network system

According to the process in Section 3, the lowest comprehensive performance level during network failure in scenarios of single-node failure and multiple-node failure when the gas pipeline system is subjected to random attacks or deliberate attacks is analyzed. Assuming that the structure and function of the pipeline system have equal importance with a weight value of 0.5 for each, to ensure the generality of the results, the number of random attacks is simulated 200 times. The results are shown in Figure 6.

Figure 6 (a) shows that the network still maintains a relatively high overall performance level even in the case of a single node failure. Under the degree attack scenario, the overall performance level of the network is 0.9056, which is lower than the 81.5% of the random attack simulation's overall performance level; under the betweenness attack scenario, the overall performance level only higher than the 6% of the random attack simulation. In the single-node failure scenario, it is highly likely that the damage caused by deliberate attacks to the overall performance level of the network is more severe than that caused by random attacks. Figure 6(b) shows that the overall performance level of the network under random attacks ranges from (0.6062, 0.9822), and 81.5% and 82% of the random simulation times are higher than the performance levels under degree attack and betweenness attack scenarios. This indicates that in the two-node failure scenarios, deliberate attacks are more likely to cause more severe damage to the gas pipeline network than random attacks. As the number of failed nodes increases, the overall performance level of the network under random attack simulations gradually decreases, and the values under deliberate attacks gradually decrease, indicating that the performance level of the pipeline system tends to decline as the number of failed nodes increases.

Based on the above results, the disturbance scenarios were set up. The betweenness attack strategies that had a significant impact on the overall network performance in the case of single-node failure and two-node failure, as well as the random attack strategies that had the greatest impact on the overall network performance in the case of four-node and six-node failures, were selected for resilience assessment. It was assumed that the system was subjected to an impact at t = 1h, and the emergency rescue station was located at node 34 in the central area. The resilience of the gas pipeline network system within the specified time t = 36h was investigated.



(a) Single-node failure (b) Two nodes are out of service.

Figure 6. Network Comprehensive Performance Levels under Different Attack Strategies

1. Evaluation of resilience for a single node and two nodes

The specific parameters of the nodes and the failure results of the nodes are shown in Table 4.3 and Figure 7.

Table 4.3. Node Parameters and Resilience Results

node	structural performance	Gas supply performance	Minimum overall performance level	Repair method	toughness value
35	0.9675	0.7115	0.8395	—	0.9816
35、49	0.9394	0.6934	0.8164	betweenness centrality	0.9699
				Degree centrality	0.9150

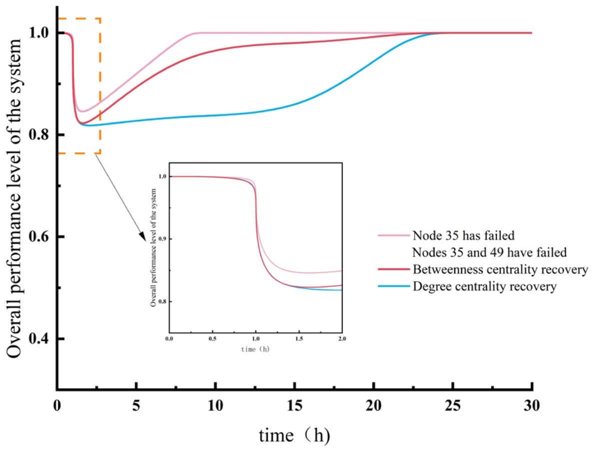


Figure 7. nodes affected and restored

As shown in Figure 7, all three scenarios were able to return to the initial performance level within the specified time. The single-node failure scenario (where node 35 failed) recovered to the initial operating state earlier than the scenarios where nodes 35 and 49 failed, and the resilience level was also the highest. In the scenarios where nodes 35 and 49 failed, the resilience values of the two recovery methods were as follows: degree centrality recovery < betweenness centrality recovery.

2. Evaluation of resilience of four-node failures

The disturbance scenario where four nodes fail is set as the node failure situation that causes the greatest damage to the overall performance level of the gas pipeline system under random simulation, namely, node 1, node 3, node 30, and node 34 fail. The process of node disturbance recovery is shown in Table 4.4 and Figure 8.

Table 4.4. Results of Resilience for Failure of Four Nodes

Repair method	Node recovery sequence	Minimum overall performance level	toughness value
Degree centrality recovery	34,3,30,1	0.4264	0.7938
Betweenness centrality recovery	34,3,1,30		0.8115
local recovery	34,3,1,30		0.8115

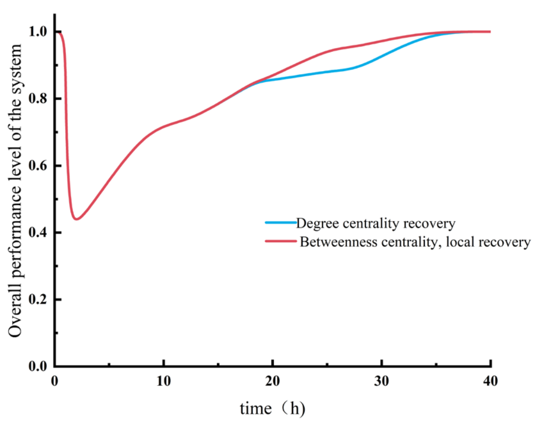


Figure 8. Curve of comprehensive performance changes of the system with four nodes subjected to disturbances and restored

As shown in Figure 8 in the failure scenarios of nodes 1, 3, 30, and 34, the resilience values are as follows: degree centrality recovery < betweenness centrality recovery = local recovery. Within the specified time, the overall performance level of the system is close to the normal operating level.

5. Conclusion

This paper constructs a comprehensive performance function for the network system, and combines the resilience stage and performance response function method to conduct resilience quantitative assessment for the situations where the comprehensive performance level of the system is low in different failure scenarios with different numbers of nodes. The main conclusions are as follows:

1. After the nodes are damaged, their impacts on the structural and functional dimensions vary. Node 34 and Node 42 have a significant influence on the structural dimension of the pipeline network, while Node 4 has a considerable impact on the functional dimension of the pipeline network. Therefore, the structural and functional characteristics of the nodes need to be comprehensively considered.
2. Even in the cases of single-node and two-node failures, the network can still maintain a relatively high overall performance level. Moreover, in these two failure scenarios, the damage caused by deliberate attacks to the overall performance level of the network is likely to be more severe than that caused by random attacks. However, in the cases of four node failures, the damage caused by deliberate attacks to the overall performance level of the network is at a medium level compared to that caused by random attacks. As the number of failed nodes increases, the performance level of the network tends to decline.
3. When multiple nodes fail, it is advisable to prioritize the repair of the nodes that are closer to each other, so as to enable the system to quickly return to its normal performance level and thereby enhance the system's resilience.

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