Study on topology-based identification of sources of vulnerability for natural gas pipeline networks

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Abstract. Natural gas pipeline networks are the primary means of transporting natural gas, and safety is the priority in production operation. Investigating the vulnerability of natural gas pipeline networks can effectively identify weak links in the pipeline networks and is critical to the safe operation of pipeline networks. In this paper, based on network evaluation theory, a pipeline network topology-based natural gas pipeline network method to identify sources of vulnerability was developed. In this process, based on characteristics of actual flow in natural gas pipeline networks, network evaluation indices were improved to increase the accuracy of the identification of sources of vulnerability for natural gas pipeline networks. Based on the improved index, a topology-based identification process for sources of vulnerability for natural gas pipeline networks was created. Finally, the effectiveness of the proposed method was verified via pipeline network hydraulic simulation. The result shows that the proposed method is simple and can accurately identify sources of vulnerability in the nodes or links in natural gas pipeline networks.

Keywords: Natural gas pipeline network, Topology, Pipeline network safety, Vulnerability, Fragile source.

1 Introduction

In actual operation, a natural gas pipeline network system is not immune to uncertain internal factors or external hazards such as valve aging or third-party damage [1]. Once a natural gas pipeline network is damaged somewhere and natural gas leaks, the consequences are severe. Therefore, analyzing the weak links or sources of vulnerability in a natural gas pipeline network system and taking relevant control measures is critical to the operational safety of the pipeline network.

The identification of sources of vulnerability belongs to system vulnerability research. Vulnerability is a popular concept in recent years that measures system characteristics such as system disturbance sensitivity, system vulnerability, consequence endurance capability and disaster resiliency. The identification of sources of fragility has been widely adopted in areas such as finance and banking, the electric power grid, network communications, the water supply and drainage systems [2]. In recent years,

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some researchers have attempted to apply the identification of sources of vulnerability to safety assurance for natural gas pipeline network systems and have made some achievements. Zhao et al. [3] analyzed damage factors of urban natural gas pipes, proposed a set of indices to describe urban natural gas pipe vulnerability, created a mathematical model to assess the system vulnerability of natural gas pipeline networks and achieved a determination of the vulnerability grade and measured the system vulnerability. Huang et al. [4] analyzed the impact of subjective factors on weight selection, proposed a weight that combined "ANP-based subjective weight" and "entropy-based objective weight" and provided a more objective evaluation of natural gas pipeline network vulnerability. Zhao et al. [5] created the 3D2R oil and gas pipe risk assessment model based on an accident development mechanism, defined the weight for each index based on specifications in the American Petroleum Institute (API) standards and provided a quantitative representation of pipe risk. You et al. [6] analyzed the third-party damage to natural gas pipeline network systems, provided a quantitative calculation of the threat level to the pipeline network system based on a Markov potential effect model and determined the functional deficiency level of pipeline network systems via pipeline network hydraulic calculations. Based on complex network theory, Zhu et al. [7] performed a significant grading and vulnerability analysis for destructive elements in a Mexico oil transport pipeline network, applied this method to a vulnerability analysis for an urban gas pipeline network in Guangdong, China, and proposed an improvement plan to enhance the disaster resistance capability of pipeline networks.

The aforementioned studies show that a pipeline network topology-based pipeline network vulnerability quantitative evaluation method is a method that provides an objective evaluation of node or pipe vulnerability in a pipeline network. Based on this method, weak links in a pipeline network are identified and then protected or enhanced to improve pipeline network safety. However, studies on pipeline network topology-based pipeline network vulnerability analysis are scarce. In addition, the current literature does not provide a detailed process for the identification of sources of vulnerability. Therefore, in this paper, a topology-based natural method for the identification of sources of vulnerability for gas pipeline network is developed.

In this paper, complex network evaluation theory is applied to the identification of sources of fragility for natural gas pipeline networks. Based on a detailed analysis of characteristics of actual flow in a natural gas pipeline network, network performance evaluation indices are improved to increase the accuracy of the identification of sources of fragility of pipeline networks. Then, based on improved evaluation indices, the process of identification of sources of fragility is designed, and a topology-based natural method for the identification of sources of fragility for gas pipeline network is developed.

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2 Topology-based evaluation index of natural gas pipeline network vulnerability

Similar to other networks, natural gas pipeline networks can be abstracted as a set of nodes and links, i.e., a topological graph **G** (**V**, **E**). Elements in set **V** are nodes in topological graph **G**; elements in set **E** are edges or links in topological graph **G**. Network theory provides various indices to evaluate network topology. In the following section, four commonly used indices are introduced. These indices are the foundation for topology-based identification of natural gas pipeline network vulnerability.

(1) Node degree

Node degree is an essential attribute of nodes in a network. It refers to the total number of links connected to this node, represented as *k*. Nodes with higher degrees have more connections.

(2) Length of the shortest path

In a topological graph, there are numerous paths with various lengths from node *i* to node *j*, and there must be a shortest path. This "shortcut" is called length of the shortest path d_{ij}.

(3) Network efficiency and element vulnerability

Network efficiency means network connectivity and information transmission efficiency, which reflects the efficiency of information transmission in a network at the macroscopic level. Greater value means superior network connectivity.

$$E = \frac{1}{N(N-1)} \sum_{i,j \in \mathbf{V}(i \neq j)} \frac{1}{d_{ij}} \tag{1}$$

where, *N* is the number of nodes in set **V**, *E* is the pipeline network efficiency.

In network analysis and measurement, the effect of a network element on network connectivity usually needs to be determined. In general, the element is removed from the network to simulate failure of this element, and then, the change in network efficiency is measured. To facilitate research on element importance to the network, the relative change rate of network efficiency after the removal of element *i* is defined as element vulnerability $\alpha(i)$. A greater value means this element is more important.

$$\alpha(i) = \left| \frac{E(i) - E}{E} \right| \tag{2}$$

where, $\alpha(i)$ is the vulnerability of element *i* in pipeline network, $E(i)$ is the pipeline network efficiency after element *i* is removed.

(4) Betweenness centrality

Betweenness centrality represents the significance of a node in network as transmission "media". Higher betweenness centrality means this node or link has a higher impact on network. Betweenness centrality is the ratio of the number of shortest paths via a specific node or link versus the total number of shortest paths for all node pairs in the network. There are two types: node betweenness centrality and link betweenness centrality.

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The expression for node betweenness centrality is:

$$C_b(k) = \sum_{i,j \in \mathbf{V}, i \neq j} \frac{n_{ij}(k)}{n_{ij}} \tag{3}$$

where, n_{ij} is the number of the shortest paths from node i to node j, $n_{ij}(k)$ is the number of the shortest paths from node i to node j via node k, $C_b(k)$ is the node betweenness centrality of node k.

The mathematical expression for link betweenness centrality is:

$$C_b(e) = \sum_{i,j \in \mathbf{V}, i \neq j} \frac{n_{ij}(e)}{n_{ij}} \tag{4}$$

where, $n_{ij}(e)$ is the number of the shortest paths from node j to node k via link e, $C_b(e)$ is the link betweenness centrality of link e.

Based on these indices, properties of elements in a natural gas pipeline network and the entire network are evaluated to identify the sources of vulnerability in a natural gas pipeline network and provide guidance for the safe operation of the pipeline network.

3 Improvement of the vulnerability evaluation index for natural gas pipeline networks

In the network evaluation index calculation process in section 2.1, by default, there is such an assumption: in topological graphs, there is a bi-directional logic information transmission path between any pair of nodes. This assumption is valid for social networks and transport networks; however, such an assumption does not completely match the actual operation of a natural gas pipeline network. A natural gas pipeline network has the following characteristics: in the pipeline network, flow is not always bi-directional. Pipe in a natural gas pipeline network is bi-directional; however, gas flow is strictly unidirectional. For example, natural gas can only flow from the gas supply source to the pipeline network and then from the pipeline network to the gas demand source. Due to such constraints, the evaluation of natural gas pipeline network vulnerability should consider the operational characteristics of natural gas pipeline networks, such as unidirectional flow and the functional difference between gas sources and demand sources. If the network evaluation indices in section 2.1 are applied directly to the identification of sources of vulnerability of a natural gas pipeline network, there will be limitations.

Therefore, in this paper, node attributes and flow direction in natural gas pipeline networks are constrained; there is only unidirectional flow from the gas supply source to the gas demand source. When calculating the network efficiency and betweenness centrality, the gas supply source is the starting point of a path and the gas demand source is the end point of a path. A detailed improvement plan for network efficiency and betweenness centrality indices is as follows:

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(1) Network efficiency improvement

Improved network efficiency formula is as follows:

$$E = \frac{1}{N_t \times N_s} \sum_{i \in \mathbf{T}, j \in \mathbf{S}} \frac{1}{d_{ij}} \tag{5}$$

where, N_t is the number of nodes in set **T**, N_s is the number of nodes in set **S**. **T** is the pipeline network gas supply source node set, **S** is the pipeline network gas demand source node set.

(2) Betweenness centrality improvement

The formulas for improved point betweenness centrality and link betweenness centrality are as follows:

$$C_b(k) = \sum_{i \in \mathbf{T}, j \in \mathbf{S}} \frac{n_{ij}(k)}{n_{ij}} \tag{6}$$

$$C_b(e) = \sum_{i \in \mathbf{T}, j \in \mathbf{S}} \frac{n_{ij}(e)}{n_{ij}} \tag{7}$$

These formulas improve the key indices of the evaluation of natural gas pipeline network vulnerability in this paper. The improvement process is based on the actual operational characteristics of natural gas pipeline networks. Therefore, improved vulnerability evaluation indices should increase the efficiency of the identification of sources of vulnerability in natural gas pipeline networks.

4 The process of identification of sources of vulnerability for natural gas pipeline networks

Based on network theory, network evaluation indices are applied to the identification of sources of vulnerability of natural gas pipeline networks. The procedure is as follows:

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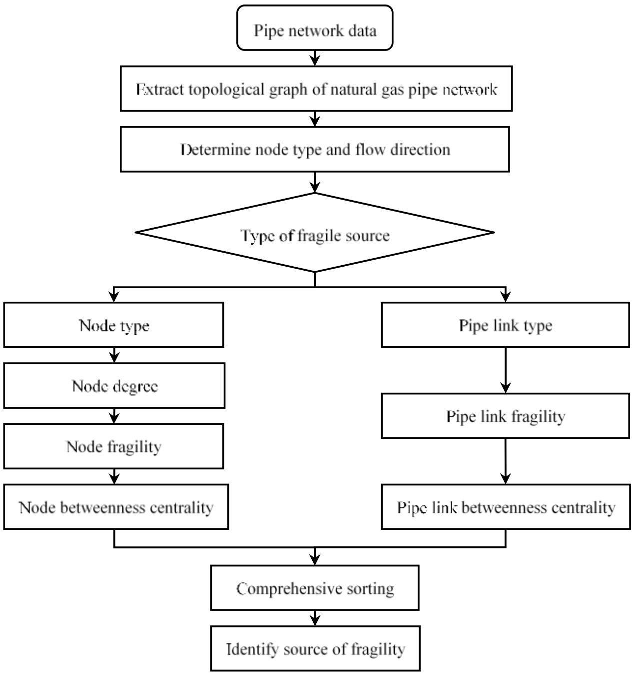

Fig. 1. Natural gas pipeline network topology-based procedure for the identification of sources of vulnerability in a pipeline network

Step 1: Extract the topological graph of a natural gas pipeline network.

Step 2: Classify nodes, i.e., a node is classified into a gas supply source, gas demand source or component connecting point.

Step 3: Determine type of vulnerability. If the source of vulnerability is the node type, then go to step 4. If the source of vulnerability is the pipe type, then go to step 5.

Step 4: Identify source of vulnerability for the node via the following steps:

① Calculate node degrees of all nodes.

② Calculate the network efficiency and network efficiency after a certain node is removed to determine the vulnerability for all nodes.

③ Calculate node betweenness centrality for all nodes.

④ Compare node degree, node vulnerability and betweenness centrality of all nodes. The node with the largest indices is the source of the vulnerability in the pipeline network.

Step 5: Identify source of vulnerability for the pipe via the following steps:

① Calculate the network efficiency and network efficiency after the pipe is removed to determine the link vulnerability for all pipes.

② Calculate the link betweenness centrality for all pipes.

③ Compare the pipe vulnerability and betweenness centrality of all pipes. The pipe with the largest indices is the source of vulnerability in the pipeline network.

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5 Case analysis

5.1 Identification of node fragile source

In this section, a single gas source simple ring natural gas pipeline network is used as an example to illustrate the process of identifying sources of vulnerability in pipeline network nodes. The hydraulic simulation of pipeline networks is performed to verify the accuracy of the improved network efficiency and betweenness centrality proposed in this paper and verify the effectiveness of the topology-based method for the identification of sources of vulnerability for natural gas pipeline networks designed in this paper.

Case overview.
The simple ring pipeline network consists of 11 nodes and 14 pipes. All pipes are horizontal pipes with an exterior diameter of 200 mm, as shown in Fig. 2. Node 1 is connected to the gas supply source; nodes 2-5 are connected to gas demand sources.

Topology-based identification of sources of vulnerability for nodes.
In this paper, node degree, node vulnerability and centrality indices of all nodes except those connected to a gas source (i.e., nodes 6-11) are first calculated. Then, comprehensive sorting is performed to identify the sources of vulnerability for nodes in the pipeline network. Node degree, node vulnerability and centrality indices results for nodes 6-11 are listed in Table 1.

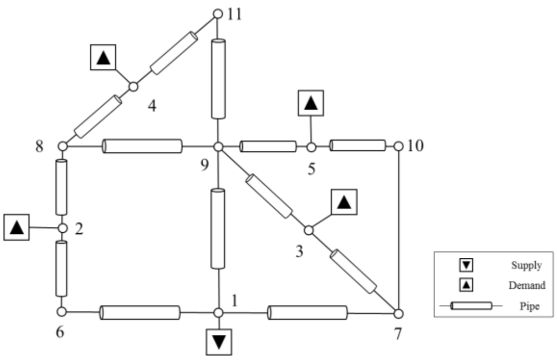

Fig. 2. Topological graph of the ring pipeline network in use case 1

Table 1. Calculation results of vulnerability indices of the natural gas pipeline network

node	node degree	node vulnerability	conventional betweenness centrality	improved betweenness centrality
6	2	0.170	0.056	0.044
7	3	0.220	0.100	0.056
8	3	0.073	0.211	0.033

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9	5	0.280	0.522	0.111
10	2	0.073	0.022	0.022
11	2	0.073	0.067	0.033

Based on each index, the sorting of probability of nodes 6-11 being the source of vulnerability is as follows:

Node degree: node 9>node 7, 8>nodes 6, 10, 11

Node vulnerability: node 9>node 7>node 6>node 8, 10, 11

Conventional betweenness centrality: node 9>node 8>node 7>node 11>node 6>node 10

Improved betweenness centrality: node 9>node 7>node 6>node 8, 11>node 10

Table 1 and sorting for indices show that (1) the node degree, network vulnerability and centrality index can balance node vulnerability and importance. Sorting results for different indices have consistent trends. All indices suggest that node 9 is the most important node; nodes 6, 7 and 8 are important nodes; and nodes 10 and 11 are unimportant nodes. This finding indicates that the network evaluation theory-based network measurement is viable for the identification of sources of vulnerability for pipeline networks. (2) Sorting results for different indices are slightly different. In sorting results for node degree and conventional betweenness centrality, node 8 is before node 6; in sorting results for network fragility and improved betweenness centrality, node 8 is after node 6. This slight difference means that the topology-based identification of sources of vulnerability for pipeline networks should consider multiple indices instead of a single index. (3) The sorting result for conventional betweenness centrality and the sorting result for network vulnerability are significantly different; the sorting result for improved betweenness centrality and the sorting result for network vulnerability are similar. This significant difference is because network fragility is calculated from the effect on the pipeline network after the removal of a node, which in theory is a more accurate reflection of node importance. Therefore, the sorting result for improved betweenness centrality is superior to the sorting result for conventional betweenness centrality.

Based on the above sorting results and improved betweenness centrality proposed in this paper, the final sorting for the vulnerability of pipeline network nodes is as follows: node 9>node 7>node 6>node 8>node 11>node 10.

Verification of fragile source via natural gas pipeline network hydraulic simulation.

Hydraulic simulation was performed for the pipeline network when each node loses function. The purpose was to analyze node vulnerability from the perspective of pipeline network operations and to compare that with topology-based sources of vulnerability. In this paper, the hydraulic simulation was based on the international commercial software Stoner Pipeline Simulator (SPS).

The gas supply source was based on pressure control, and all gas demand sources were based on flow control. The comparison of steady state gas supply pressure after failure at each node is listed in Table 2. The decline in pipeline network service capability is reflected by the relative deviation of gas supply pressure change. To evaluate the effect of node failure on the gas supply capability of the entire pipeline network

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intuitively, the mean deviation of pressure at the gas demand source is listed in Table 3.

Table 2. Mean deviation of pressure at gas demand source

failure node	node 6	node 7	node 8	node 9	node 10	node 11
mean deviation of 4 gas demand sources (%)	15.59	15.62	3.90	19.34	0.90	1.56

Based on Table 2, the sorting result for node vulnerability in descending order is as follows: node 9>node 7>node 6>node 8>node 11>node 10. This sorting result is consistent with the sorting for pipeline network topology-based vulnerability, suggesting that improved vulnerability evaluation indices proposed in this paper generate desirable sorting results for node significance, which also matches the operational simulation result and provides excellent differentiation, helping to identify and providing a reference for sources of fragility for nodes in the pipeline network, as well as a safety evaluation during gas pipeline network design, construction and operation. .

5.2 Identification of pipe fragile source

In this section, a single gas source simple ring natural gas pipeline network is used as an example to illustrate the identification of sources of vulnerability in pipes in a pipeline network. A hydraulic simulation of a pipeline network is performed to verify the effectiveness of the topology-based method of identification of sources of vulnerability in natural gas pipeline networks designed in this paper.

Case overview.
The pipeline network consists of 6 nodes and 8 pipes. All pipes are horizontal pipes whose length and exterior diameters are 30 km and 200 mm respectively, as shown in Fig. 3. Node 1 is connected to the gas supply source; the other 5 nodes are connected to gas demand sources. Detailed topological parameters are listed Table 3.

Topology-based identification of sources of vulnerability of pipe type.
In the identification of sources of vulnerability for pipes, the pipe vulnerability is listed in Table 4.

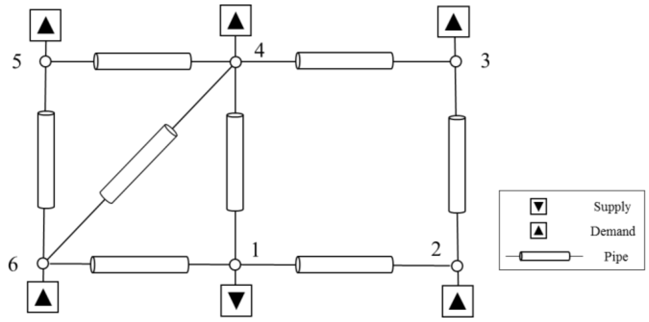

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Fig. 3. Topology of the ring pipeline network in case 2

Table 3. Topological data of the ring pipeline network in case 2

pipe No.	1	2	3	4	5	6	7	8
starting point	1	2	3	4	5	6	6	1
end point	2	3	4	5	6	1	4	4

Table 4. Network efficiency and vulnerability of each pipe

pipe No.	1	2	3	4	5	6	7	8
vulnerability	0.1467	0	0	0	0	0.11	0	0.11

Table 4 shows that after pipe 1 is removed, the network efficiency has the largest decline (0.1467), which is followed by the removal of pipes 6 and 8, with a decline of 0.11; the removal of other pipes has no impact on network efficiency. Next, the fragilities of pipes are differentiated by improved link betweenness centrality. The link betweenness centrality of each pipe in pipeline network is listed in Table 5.

Table 5. Network efficiency and vulnerability of each pipe

pipe No.	1	2	3	4	5	6	7	8
improved link betweenness centrality	0.1	0.033	0.033	0.033	0.033	0.1	0	0.133

Table 5 shows that the link betweenness centrality provides desirable differentiation for pipes 6 and 8. Based on the sorting for network effectiveness, the fragilities of pipes are differentiated further, and the sorting for vulnerability is as follows: pipe 1>pipe 8>pipe 6>pipes 2, 3, 4, 5>pipe 7.

Verification of the source of vulnerability via a hydraulic simulation of a natural gas pipeline network.

Similar to the identification of sources of vulnerability for nodes, this pipeline network underwent a hydraulic calculation via the international commercial software SPS to verify the effectiveness of the identification of sources of vulnerability for pipes.

The gas source is based on pressure control. All gas demand sources are based on flow control. To evaluate the impact of pipe failure on the gas supply capability of the entire pipeline network intuitively, the mean deviation of pressure at gas demand sources is listed in Table 6.

Table 6. Mean deviation of pressure at gas demand sources

failed pipe	pipe 1	pipe 2	pipe 3	pipe 4	pipe 5	pipe 6	pipe 7	pipe 8
mean deviation (%)	9.11	2.49	1.31	0.33	0.65	7.24	0.32	7.3

Table 6 shows that the vulnerability of pipes 1, 6, and 8 has a significant impact on the gas supply capability of the entire pipeline network; vulnerability of the other pipe only has a slight impact on the gas supply capability of the pipeline network. Based

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on the mean relative deviation of the pressure change in the pipe-line network operation, the vulnerability of pipes in descending order is as follows: pipe 1>pipe 8>pipe 6>pipe 2>pipe 3>pipe 5>pipe 4>pipe 7. It can be seen that the pipeline network topology-based ranking of sources of vulnerability matches the simulation result of the operation, which provides reference for the identification of sources of fragility and safety evaluation during gas pipeline network design, construction and operation.

6 Conclusions

In this paper, network evaluation theory is applied to identify sources of fragility in natural gas pipeline networks. Network performance evaluation indices are improved. The process for the identification of sources of fragility for natural gas pipeline networks is designed. A topology-based method identification of the sources of vulnerability for natural gas pipeline networks is developed. The conclusions are as follows:
(1) Node degree, element fragility and betweenness centrality indices rep-resent the fragility and importance of each node. Therefore, network evaluation theory-based network measurement is viable for the identification of sources of vulnerability for pipeline networks.
(2) Improved network efficiency and centrality index increased the identification efficiency for sources of vulnerability for natural gas pipeline networks. The result of the calculation matches the operational simulation result, which proves the effectiveness of the improvement plan proposed in this paper.
(3) The topology-based method for the identification of sources of vulnerability for natural gas pipeline networks can effectively identify the source of vulnerability for nodes or pipes in a pipeline network.

References

1. Kim, D.K., Yoo, H.R., Cho, S.H., et al.: Inspection of unpiggable natural gas pipelines using in-pipe robot. In: International Conference on Advanced Engineering Theory and Applications, pp. 364-373. Springer International Publishing, Cham (2016).
2. Efatmaneshnik, M., Bradley, J., Ryan, M. J.: Complexity and fragility in system of systems. International Journal of System of Systems Engineering 7(4), 294-312 (2016).
3. Zhao, X., Chai, J.: Study on indicators of vulnerability assessment for city buried gas pipeline system. Journal of Safety Science and Technology 7(7), 93-94 (2011).
4. Huang, L., Yao, A., Xian, T., et al.: Research on risk assessment method of oil & gas pipeline with consideration of vulnerability. China Safety Science Journal 24(7), 93-99 (2014).
5. Zhao, D., Chen, S., Zhao, Z., et al.: Study on oil-gas pipeline risk assessment method based on vulnerability and its application. China Safety Science Journal 24(7), 57-62 (2014).
6. You, Q., Zhu, W., Bai, Y., et al.: Vulnerability analysis of external threats for urban gas pipeline network system. Oil & Gas Storage and Transportation 33(9), 950-955 (2014).
7. Zhu, Y.: Topological properties and vulnerability analysis of oil and gas pipeline networks. South China University of Technology. (2013).

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