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VULNERABILITY ANALYSIS FOR URBAN NATURAL GAS PIPELINE NETWORK SYSTEM

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Abstract: In order to identify the vulnerable links in urban natural gas pipeline network systems, this study established a concept for the vulnerability analysis of the network system, providing a basis for quantitative analysis of vulnerability. The criteria for selecting nodes in the network were determined based on the network composition. Based on the theory of disaster chain, the vulnerability factors were analyzed thoroughly, the hazard factors causing vulnerability were determined and the vulnerable parts of the network system were identified. A model for the calculation of the structural threats from the network itself was established. The first step is to identify the interdicted point of single pipeline sections through the calculation method for friction resistance loss, and the second step is to determine the key nodes with the maximum or minimum vulnerability of the entire network, thereby realizing the point-to-net analysis of the pipeline network. The FIM model was implemented, combining the geological information system ArcGIS, Java programming language, and Lingo optimization software. Using a natural gas pipeline network in Beijing as a case study, the distribution of vulnerable points in the network was plotted and the key nodes with high vulnerability were identified by analyses of vulnerability and importance.

Keywords: natural gas pipeline network, inherent structural threats; vulnerability analysis, importance.

Introduction

Compared with other infrastructure (such as heat, water, and drainage) in cities, natural gas is flammable and explosive. Gas leak may easily lead to severe accidents such as explosion or fire. In urban areas with high-density natural gas pipeline, population and buildings, due to the influences from the external environment and the internal factors, there is a greater chance for a gas leak to develop into accidents (Zhang et al., 2009). Preliminary statistics show that in 2011, the natural gas explosion accidents in the major cities across China killed around 40 people and caused enormous economic loss. All of those accidents occurred in highly developed urban areas with high-density population, where a gas explosion not only causes casualties, building damage, and traffic interruption, but also result in damage of other infrastructure such as water, heat, and electricity (You et al., 2009). Meanwhile, in the information age, the social and political impact of media reports cannot be ignored. Therefore, it is of important practical significance to analyze the vulnerability of the natural gas pipeline network in high-density population areas and adopt appropriate control measures in order to reduce accidents.

Vulnerability of Urban Natural Gas Pipeline Network

Timmerman firstly proposed the concept of vulnerability in the geoscience field (Timmerman, 1981). It is considered that vulnerability, measured in degrees, refers to the degree of adverse impact caused by a disaster.

Vulnerability is inherent in a system, with sensitivity to the influences from natural and human factors. When the system is threatened, vulnerability can reflect the degree of function damages of the system.

Currently, vulnerability is widely used in many infrastructures (Collins, 2005; Murray and Grubesic, 2007; Collins and Bolin, 2007), but rarely in natural gas pipeline network. The urban natural gas pipeline network should meet the users' requirements of gas volume and pressure. To analyze the vulnerability of urban natural gas pipeline network, the influence of the structure of the urban natural gas pipeline network itself must be considered firstly, followed by the influence of external environment and human factors, as well as the location of the pipeline network facilities, so that the functional damage of the system after an accident can be determined. For instance, for two same pipeline networks with the same protective measure at different locations, one at the suburb and the other at the downtown, their vulnerabilities are the same in terms of the pipeline network facilities. However, in terms of the functional loss of the system after accident, the pipeline network at downtown suffers more damage than the one at suburb.

Based on the above analysis, the vulnerability of urban natural gas pipeline network system was defined as an dimensionless inherent parameter of the system reflecting the degree of functional loss after accidents, prone to be influenced by the system structure and the external environment, determined by the threat level and the degree of functional loss, and measuring the degree of functional less by two indicators, gas volume and pressure. This study mainly focused on the vulnerability of natural gas pipeline network itself.

Structural Threats

A natural gas pipeline network system is usually composed by receiving stations (gate stations or master stations), storage and distribution stations, distributing infrastructure (ultrahigh-pressure pipeline networks, high-pressure pipeline networks, pressure regulating stations or devices, medium-pressure pipeline networks, low pressure pipeline networks, and valve wells), operation facilities, power systems, monitoring systems, etc. (Zhang and Zhou, 2013; Ma and Han,2004), as shown in Fig. 1.

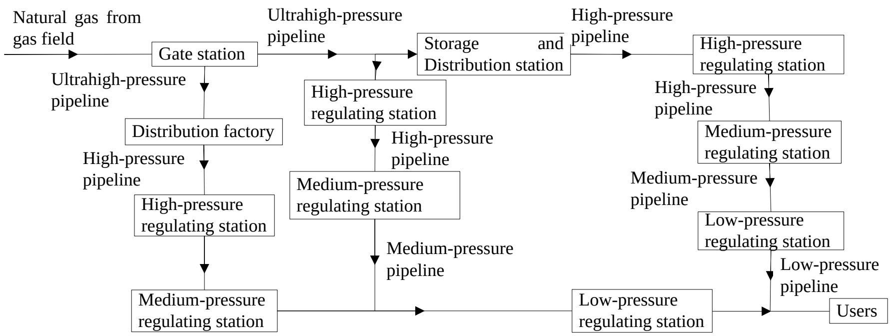


Figure 1: Schematic diagram of urban natural gas pipeline network system.

The parameters of the pipeline networks, including the flow of nodes, the pressure of pipeline sections, the flow of pipeline sections, and the resistance coefficient of the network, are all set at the beginning of the design and construction of the natural gas pipeline networks (Miao and Wang 2013; Wan, 2007). However, due to improper operations or negligence of workers during construction, gravels and other impurities may be left in the pipelines. Those impurities would damage the pipeline network as the system runs for a long time. For example, the H2S, CO2 and other acidic gases and water inside the pipeline will cause corrosion and fouling of the wall, which will change the roughness of the pipeline and further result in changes in flow. When the pipe leaks, pipe flow will drastically change. Therefore, the broken segments or vulnerable points can be identified based on flow changes in the pipelines. Table 1 presents the structural threats from the pipeline network itself.

Vulnerability Analysis Model

Node Selection and Judgment

The criteria adopted for node selecting include (1) the components that have great impact on the connectivity of the entire natural gas pipeline network and (2) important facilities in the natural gas pipeline network. According to those two criteria, the following facilities/components were selected as nodes: ① gate stations or master stations; ② storage and distribution stations; ③ pressure regulating stations or devic-

Table 1: Structural threats and potential consequences.

Type	Type of threat	Location of threat	Potential influences	Consequences
Design and const-ruction	Design and construction not meeting the requirement, insufficient the design margin.	Gate or master station	Structure damage of facilities	1.Explosion, fire, and gas supply cut
		High-pressure pipeline	Breaking pipeline	2.Gas leak and explosion
		Storage and distribution factory	Structure damage of facilities	3.Explosion, fire, and gas supply cut
		Pressure regulating stations or devices	Device damage	4.Gas leak and gas supply cut
		hypo-high-, medium- and low-pressure pipelines	Breaking pipeline or damage of facilities	5.Gas leak and gas pressure drop
		Valve well	Device damage	6.Gas leak and explosion
	Insufficient minimum buried depth of pipelines, or soil disturbance	High-pressure pipeline	Breaking pipeline	1.Gas leak and explosion
		hypo-high-, medium- and low-pressure pipelines	Breaking pipeline or Device damage	2.Gas leak and gas pressure drop
	Insufficient surface protecting facilities, redundant facilities, and spare devices; unclear land use marks; trespassing protection	Gate or master station	Structure damage of facilities	3.Explosion, fire, and gas supply cut
		Distribution factory or storage station	Structure damage of facilities	4.Explosion, fire, and gas supply cut
		Pressure regulating stations or devices	Device damage	5.Gas leak and gas supply cut
	Poor reliability of external supporting system, unclear device marks, and low degree of equipment and facility automation	Gate or master station	Pressure monitoring system out of control	1.Explosion or fire due to high pressure 2.Gas shortage due to low pressure
		Distribution factory or storage station	Pressure and temperature monitoring out of control	3.Explosion of storage tanks, and fire
		Pressure regulating stations or devices	Pressure and temperature monitoring out of control	4.Unstable internal pressure in pipelines
		Valve well	Pressure monitoring system out of control	5.Unstable internal pressure in pipelines
Corrosion	Service time beyond design life, improper protection of cathode, surface coating falling off, soil erosion, stray currents, corrosion, insufficient internal protection, and tress corrosion	High-pressure pipeline	Breaking pipeline	Gas leak and explosion

es; ④ gas entrances in neighborhoods; ⑤ entrances of heavy loads. The connection between two nodes is called pipeline section.

For a pipeline section in the natural gas pipeline network, the loss of friction resistance was calculated based on the Code for Design of City Gas (GB50028-2006), in order to identify the breaking points in the section. For the entire network system, the nodes with the maximum or minimum loss of flow were identified by evaluating the vulnerability of the network using the Flow Interdiction Model (FIM). The identified nodes are the critical nodes with the maximum or minimum vulnerability in the network.

Flow Interdiction Model

The FIM is proposed by Murray et al. and used to evaluate the importance of nodes or sections in facilities with network structure (Li, 2010; Zhou, 2010). The core idea is: there are the nodes and sides in a network; when a certain number of network nodes have been blocked, which is nodes or adjacent nodes and sides may also lose services, the nodes with the maximum or minimum loss of flow were identified by evaluating the vulnerability of the network using FIM; the node set is selected, which make the network vulnerability being highest or lowest key node combinations.

The maximize or minimize loss of flow is

$$\sum_{o} \sum_{d} f_{od} Z_{od} \quad , \tag{1}$$

which subjects to the following:

$$\sum_{k \in N_{od}} Y_k + Z_{od} \geq 1 \qquad \forall o, d \quad , \tag{2}$$

$$Z_{od} \leq (1 - Y_k) \quad \forall o, d, k \in N_{od}, k \quad , \tag{3}$$

$$Y_k \geq 1 - \sum_{j \in \Phi_k} X_j \qquad \forall k \quad , \tag{4}$$

$$Y_k \leq (1 - X_j) \quad \forall k, j \in \Phi_k \quad , \tag{5}$$

$$\sum_{j} X_j = p \quad , \tag{6}$$

$$\begin{aligned} X_j &= \{0,1\} \quad \forall j \\ Y_k &= \{0,1\} \quad \forall k \\ Z_{od} &= \{0,1\} \quad \forall o, d \quad . \end{aligned} \tag{7}$$

In the above equations, k is the set of paths, j is the set of facilities, o is the set of origins, d is the set of destinations, N_{od} is the set of paths between origin and destination pairs, f_{od} is the flow between origins and destinations, p is the count of interdicted facilities, and ϕ_k is the set of facilities constituting path *k*.

Related to the variables：

$$X_j = \begin{cases} 1 & \text{When the facility } j \text{ is interdicted} \\ 0 & \text{Other} \end{cases}$$

$$Y_k = \begin{cases} 1 & \text{When the count of interdicted facilities is } p\text{, the path } k \text{ is still connected} \\ 0 & \text{Other} \end{cases}$$

$$Z_{od} = \begin{cases} 1 & \text{When the set of paths between origin and destination pairs is not connected} \\ 0 & \text{Other} \end{cases}$$

The *p*-value is an important variable in the FIM and the number of the interdiction nodes, which the value is from 1 to the total number of nodes. Each *p*-value represents the interdiction situation. The key node combinations of *p*-value can be obtained by the FIM.

The equation (1) is the objective function of the Flow Interdiction Model, which is the product of the flow values and connectivity about all nodes. The nodes with the maximum or minimum loss of flow were identified by the restrictions of (2) to (7).

The equation (2) to (7) is the restrictions of the Flow Interdiction Model. X_j , Y_k and Z_{od} are variables, whose value can be either 0 or 1. When the facility *j* is interdicted, X_j is 1. When the count of interdicted facilities is p, the path *k* is still connected, Y_k is 1. When the set of path between origin and destination pairs is not connected, Z_{od} is 1.

The equation (6) restricts the number and combination of the node. The *p* value controls the number of nodes.

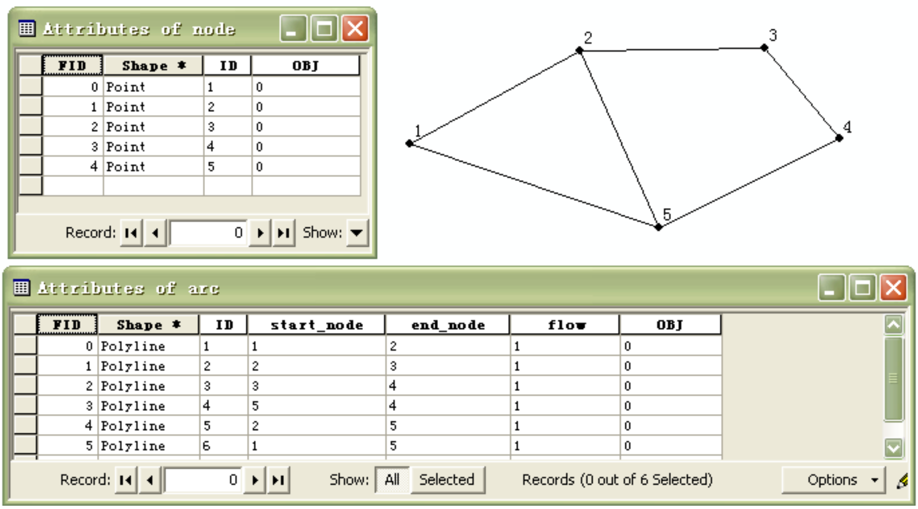
In this paper, with geological information system ArcGIS, Java programming language, and Lingo optimization software, the FIM model was implemented.

Calculation Process of Flow Interdiction Model

The calculation process of FIM is to implement the model through geographic information system (ArcGIS), Java programming, and Lingo optimization software, based on a virtual network with five nodes.

(1) Digitalization by ArcGIS

Firstly, topological attributes of the nodes and lines are saved in ArcGIS, as shown in Fig. 2. The OBJ value of a node is a dummy variable with the value set as 1 when the node is interdicted and selected, and otherwise set as 0. The OBJ value of a line is also a dummy variable with the value set as 1 when the line is adjacent to an interdicted node, and otherwise set as 0. The automatic attribute value update of nodes by the VBA language embedded in ArcGIS makes possible the application of FIM in large-scale networks (as shown in Fig. 3). The VBA outputs the data of nodes in text format as the input of the next step of calculation by Java.



Attributes of node

FID	Shape *	ID	OBJ
0	Point	1	0
1	Point	2	0
2	Point	3	0
3	Point	4	0
4	Point	5	0

Attributes of arc

FID	Shape *	ID	start_node	end_node	flow	OBJ
0	Polyline	1	1	2	1	0
1	Polyline	2	2	3	1	0
2	Polyline	3	3	4	1	0
3	Polyline	4	5	4	1	0
4	Polyline	5	2	5	1	0
5	Polyline	6	1	5	1	0

Figure 2: Schematic diagram of the recording of attributes of points and lines in a virtual network.

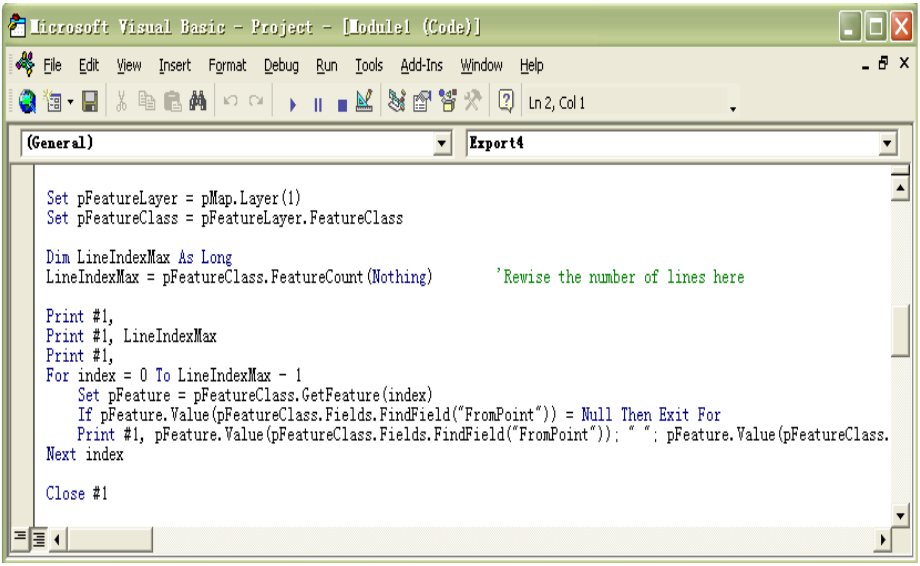


Figure 3: Code section for exporting topological information of the network by VBA language.

(2) Path enumeration algorithm by Java

After the digitalization, the paths between origins and destinations (o-d) are enumerated through Java language. For a small-scale network, it is possible to enumerate the paths between all o-d pairs. However, such enumeration has inestimable time complexity for a large-scale network, creating extreme difficulties for solving the problem. According to the definition of valid path in pipeline networks, a path's contribution is close to 0, which is negligible, when the number of steps between an o-d pair is greater than a certain threshold value. In the actual path enumeration, a method of "shortest path + N paths" was adopted, which means to calculate the number of steps on the shortest path between each o-d pair, add N steps to this number and set the result as the upper limit (threshold) of the number of steps. With this threshold, all paths between the o-d pairs were enumerated. Fig. 4 presents the code section that adopts the threshold of "shortest path +2 steps". The path enumeration result can be exported in text format as the input of the next step – Lingo optimization.

```
        System.out.println();
        vis[i]=false;
        return;
}
for(int j=0;j<total;j++){
        if(matrix[i][j]==1&&vis[j]==false){
                if(step>=weightmatrix[path[0]][end]+2) break;
                search(matrix,vis,path,weightmatrix,total,end,j,step+1,bw1,bw2,se);
        }
}
vis[i]=false;
```

Figure 4: Code section for path enumeration between o-d pairs by Java language.

(3) Optimization by Lingo

The final step of the FIM calculation process is to find the optimal solution with the Lingo software. During programming for the model, the attribute of each node is set as a dummy variable with initial value of 0. If this attribute value of a node became 0 in the result report, it means the node is selected as a key node. The optimization result can be displayed in the text file, which is automatically generated to store the final attribute values of nodes, and input as the OBJ values of nodes, through VBA language, in AricGIS platform to realize the visualization.

Figure 5 shows the code section for the Lingo optimization of FIM. The code is written in the embedded programming language of Lingo to convert the expression of FIM to recognizable code of Lingo. With an assumed number of interdicted nodes (*p* value), for example *p*=2 in this case, the report window and text file obtained are as illustrated in figures 6 and 7, respectively.

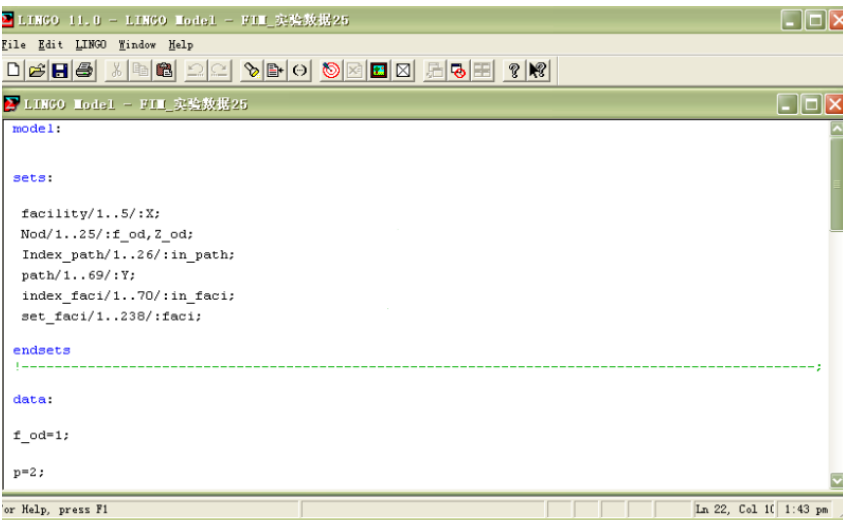


Figure 5: Code section for Lingo optimization of FIM.

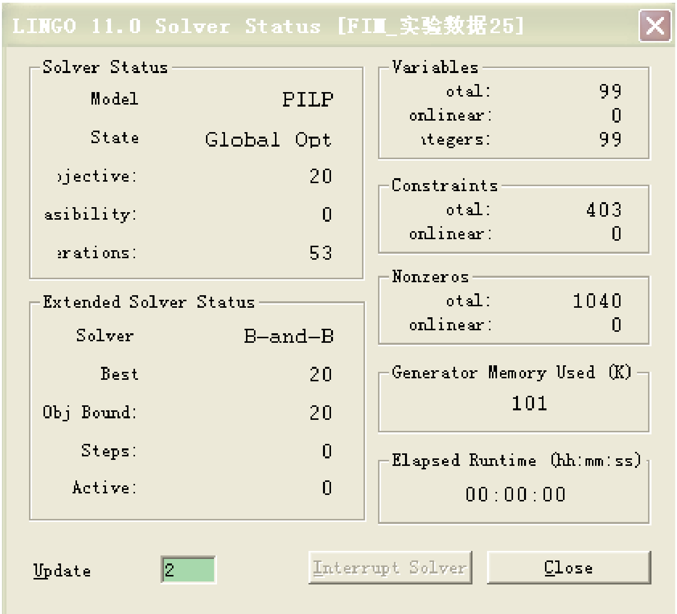


Figure 6: Result window of Lingo optimization of FIM.

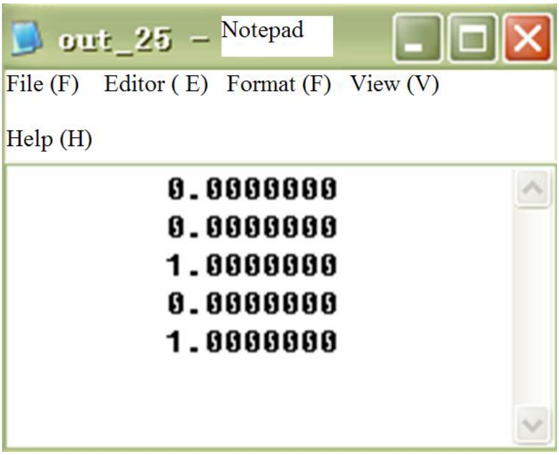


Figure 7: Result window in text format of Lingo optimization of FIM.

The report window of Lingo shows the type of the model, calculation status, target value, number of iterations, adopted algorithm, numbers of variables and constraints (linear, nonlinear or integer), nonzero coefficients, occupied memory, and calculation time. As shown in Fig. 6, FIM can be treated as an integer planning problem. Through calculation, the obtained optimal solution adopts the branch and bound algorithm with 53 iterations, costs one second for calculation and has a target value of 20. That is to say, when the two nodes corresponding to the two values of 1 in the result window in Fig.A.7 are damaged, the resulting damage of the network is the most serious, and the degree of damage is 20.

The result report window in Fig. 7 displays the target values of nodes sorted by IDs of the nodes. When the target value of a node is 1, this node is a key node; otherwise the node is not in the set of key nodes. It can be seen that in the five-node virtual network, when *p*=2, i.e. there are two interdicted nodes, interdicting nodes 3 and 5 will cause the maximum loss of flow for the whole network, which means causing the most serious adverse impact on the function of the network. Table 2 shows the sets of key nodes corresponding to *p* values of 1, 2, 3, 4, and 5.

Table 2：Optimal solutions for interdictions in a five-node virtual network.

p	Objective	Node Interdicted	Times（s）
1	9	2	00：00：01
2	20	3，5	00：00：01
3	23	2，4，5	00：00：01
4	24	1，2，4，5	00：00：01
5	25	1，2，3，4，5	00：00：01

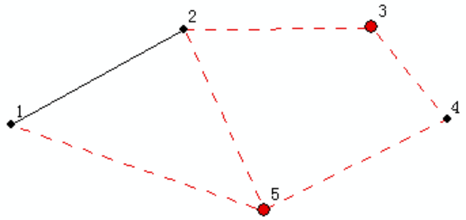
(4) Visualization by ArcGIS

Figure 8 shows the result of visualization by ArcGIS. Through the interface of VBA language imbedded in ArcGIS, the target values in Figure 7 are input as the OBJ field of the attributes of nodes. As shown in Figure 8, the target values of nodes are displayed in the OBJ field, nodes 3 and 5 are the key nodes with target values of 1, and they compose the key node set. Accordingly, OBJ values of the lines adjacent to those two key nodes are set to 1. The key nodes in the network are highlighted, with the adjacent lines shown in dotted lines, and the resulting network structure is the most vulnerable with two interdicted nodes.

Attributes of node

FID	Shape *	ID	OBJ
0	Point	1	0
1	Point	2	0
2	Point	3	1
3	Point	4	0
4	Point	5	1

Record: 0 Show:



Attributes of arc

FID	Shape *	ID	start_node	end_node	flow	OBJ
0	Polyline	1	1	2	1	0
1	Polyline	2	2	3	1	1
2	Polyline	3	3	4	1	1
3	Polyline	4	5	4	1	1
4	Polyline	5	2	5	1	1
5	Polyline	6	1	5	1	1

Record: 0 Show: All Selected Records (0 out of 6 Selected) Options

Figure 8: Schematic diagram of key nodes identification result in a virtual network (p=2).

(5) Identification of the important indicators of interdicted nodes

Based on the enumeration of optimal solutions, the indicators for sorting the importance of nodes are determined, as Eq. (8) shows. According to those indicators, all the interdicted nodes are sorted.

$$IM_i = \sum_{p=1}^{n} \frac{OBJ_p}{p} \times N_{pi} , \qquad (8)$$

Where, IM_i is the value of the importance of node i, Σ denotes every interdiction condition, n is the total number of nodes, p is the count of all interdicted nodes, OBJ_p is the target value for a specific interdiction, N_{pi} is the count of node i in all optimal solutions under a specific interdiction, and $\frac{OBJ_p}{p}$ means that the target value for a specific interdiction is generated by p nodes, thus the target value can be equally assigned to each key node.

Taking a five-node virtual network as example, the importance of each node is as shown in Fig. 9. Nodes 2 and 5 have the highest importance 82, followed by nodes 3 and 4, which have the importance of 64. Node 1 has the lowest importance of 54.

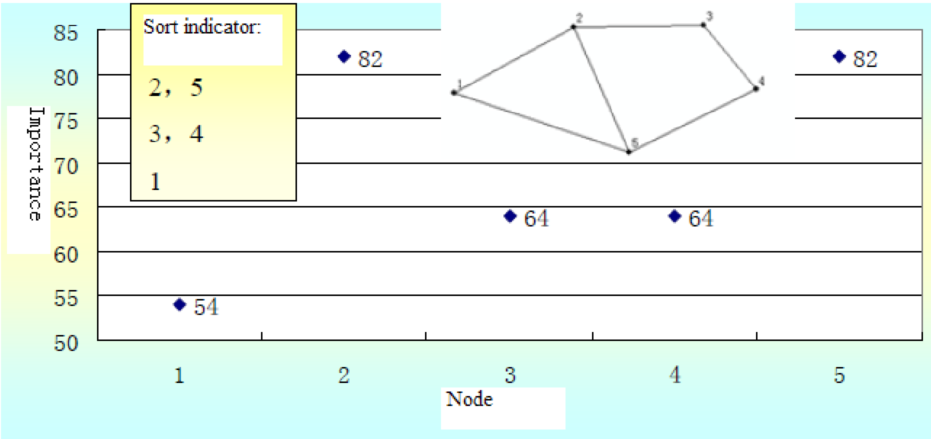


Figure 9: Scatter diagram of the importance of the nodes in the five-node virtual network.

According to the topological structure of the five-node virtual network, the dimensions of node 2 and node 5 are three, which means node 2 and 3 each has three lines connected to them. The dimensions of the other three nodes are two. Comparing with other nodes, nodes 2 and 5 have more connections and higher connective class. This is consistent with the sorting result calculated by Eq. (8), further validating the established importance indicators.

Vulnerability Analysis of Natural Gas Pipeline Network – A Case Study of Beijing

Considering the data security of natural gas pipeline network, only the backbone pipeline network in Beijing was studied (Zhao, 2010), as shown in Figure 10. The studied network includes 73 pressure regulating stations and gate stations. The fine lines in Fig. 10 denote the 0.8 MPa high-pressure pipelines, including the 3rd Ring line, the 4th Ring line, the Beiyuan branch line, and the Yongfeng branch line; the thick lines denote the 2.5 MPa high-pressure pipelines, which are the external high-pressure gas transmission lines.

The 3rd Ring pipeline and 4th Ring pipeline have minimum buried depths of 2.1 m to 2.5 m, pipe diameters of 200 m – 500 m, and regular pressure of 0.77 MPa. They are hypo-high-pressure pipelines made by iron with service life of 10-15 years, and are inspected twice a week, with fully equipped emergent supplies. The studied pipeline network is located at a high-density population area with heavy morning and evening crowds and traffics, and relatively highly educated residents. The area also hosts a number of important institutions such as government organizations and embassies. There are also high-end shopping malls, higher education institutions, and high-rise office and residential buildings. Once a natural gas accident happened in the area, there would be serious consequences and large area of gas supply cut.

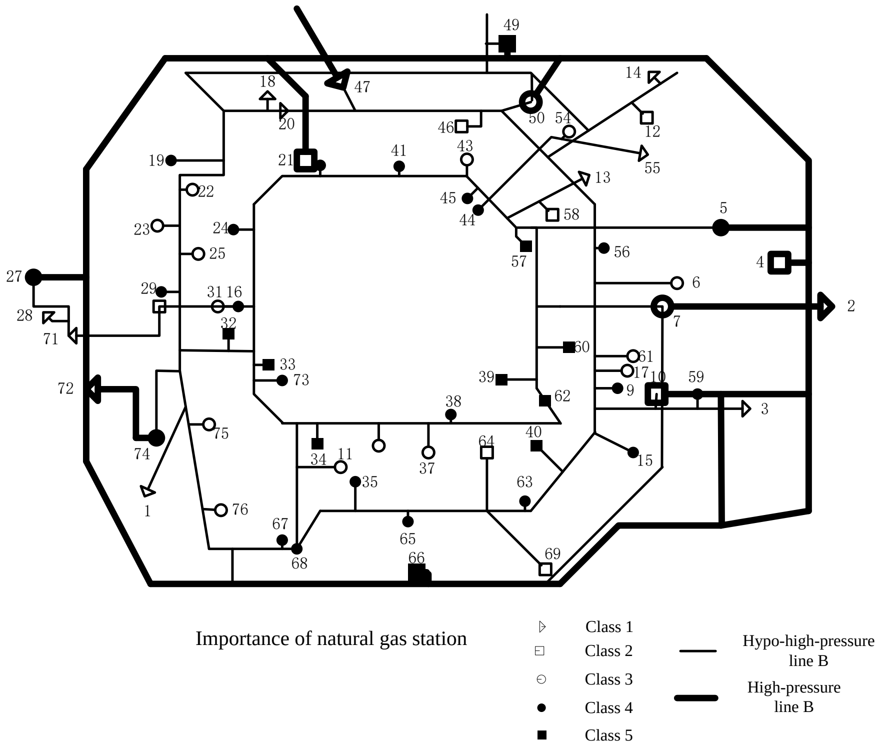


Figure 10: Importance assessment result for key nodes in the studied natural gas pipeline network in Beijing.

With FIM and GIS network analysis, the importance of the key nodes (pressure regulating stations and gate stations) in the studied natural gas pipeline network were assessed.

The studied network has a complex, conjoint and interdependent structure. Accidents at the important nodes, such as gas regulating stations or gate stations, would inevitably affect the gas supply security of local areas and even larger area (You et al., 2011; Xiong, et al., 2008). Therefore, it is important to assess the importance of key nodes based on the topological structure of the network, and monitor and inspect the key nodes with higher importance during daily operation, in order to reduce natural gas accidents and consequential damage.

(1) Algorithm implementation

① The studied natural gas pipeline network was digitalized in ArcGIS9.3, and the topological structure was extracted through Java programming. (Considering that the Yongfeng region is independent of other regions, it was not considered in the assessment.)

② The pressure regulating stations and gate stations were defined as key nodes and assigned weighted values based on the pressure in their connected pipelines. The weighted value assignment was done in an upward manner, where the highest pressure in the connected pipeline was used as the weighted value of a key node.

③ The line between two adjacent nodes was defined as an arc. In the model, the capacity of a natural gas pipeline section was considered the flow of the corresponding arc. For example, an 0.8 MPa-arc has a flow of 0.8 MPa, while a 2.5 MPa-arc has a flow of 2.5 MPa.

④ It was defined that the importance of a node is the target value, OBJ value, of the node. The value refers to the sum of the products of the number of times the node occurs in each set of interdicted nodes and failure loss. A larger target value indicates higher importance of the node.

⑤ A importance model was established for each of the 73 key nodes, and solved by Lingo10.0. The calculated importance were classified into five categories and colored accordingly in ArcGIS9.3. The results are presented in Figure 10. Higher class of a node indicates higher importance of it.

(2) Analysis of assessment result

Based on the assessment result in Figure 10, the following trends can be seen.

① High-pressure regulating stations generally have higher importance. For example, stations 49, 5, 59, 66, 74, 27, etc. in Fig. 10 are all class 4 or 5 stations. In fact, since the supply of natural gas is from high-pressure stations to low-pressure stations, the flow direction of natural gas is inevitably from high-pressure regulating stations to the 3rd Ring and 4th Ring lines. The disruption of a high-pressure regulating station would impact the natural gas supply in a large area. On the other hand, high-pressure regulating stations are usually located at suburban area far from other types of gate stations, thus they are seldom impacted by the accidents at other gate stations. Therefore, the high-pressure regulating stations do not always have the highest importance. Moreover, when two or more pressure regulating stations are close, they act as backups for each other. This explains the reason that station 10 has low importance.

② In general, the regions with complex network structure or high density of pressure regulating stations and gate stations have high importance. For example, stations 60, 39 and 62 at the East 3rd Ring, stations 16, 29, 32, 33 and 73 at the West 3rd Ring, stations 34 and 35 at the South 3rd Ring and stations 22, 41, 45 and 44 at the North 3rd Ring with high importance are either in complex network structures such as ring, branch or star structures, or located at human, financial and material high-density areas of key nodes, which the importance was higher. The point is more vulnerable point of the system. Therefore, the part of higher importance was monitored and supervised, which can help reduce the incidence of accidents pipe network system, reduce accident losses.

Conclusion

The vulnerability analysis of natural gas pipeline network is both the emphasis and difficulty of the safety management. In this study, the Flow Interdiction Model (FIM) was introduced into vulnerability analysis, in order to determine the importance of the key nodes in natural gas pipeline network by mathematic theories, and identify the vulnerable nodes in advance to implement preventive measures so as to improve the safety of the entire natural gas supply system in a city. The study provides theoretical guidance for the planning, redevelopment, disaster prevention and reduction, and priority configuration of pipeline network facilities. Based on interviews with experts and field investigation, the vulnerability analysis approach for natural gas pipeline network in urban areas with high-density population was explored thoroughly.

1. Vulnerability analysis was applied to the urban natural gas pipeline network system based on features of the system. An analysis concept of the vulnerability analysis of urban natural gas pipeline network system was proposed to support the safe operation of pipeline networks.

2. The causes of natural gas accidents were determined. Based on the network structure, the threats to the natural gas pipeline network system were analyzed and the vulnerable parts of the system were identified.

3. The calculation process of FIM was detailed. The process includes node and line storage and topological structure construction by ArcGIS, numeration of origin-destination paths and formation of input matrix by Java, matrix optimization by Lingo, and visualization by ArcGIS.

4. The criteria for selecting nodes were identified based on the composition of urban natural gas pipeline network system. A method was formed for the calculation of the structural threats from the network itself. First, the interdicted point of single pipeline sections was identified through the calculation method for friction resistance loss. Then, with the FIM, the key nodes with the maximum or minimum vulnerability of

the entire network were identified. The point-to-net analysis of the pipeline network was realized through these two steps.

5. Using a natural gas pipeline network in Beijing in a high-density population area as an example, combining FIM and the topological features of the network, vulnerability analysis was carried out for the network to identify the nodes with high importance, and determine the most vulnerable key nodes in the network. The analysis provides technical support for the accident prevention, construction and reconstruction of urban natural gas pipeline networks.

Acknowledgement

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