Risk Assessment System of Spatial City Gas Pipeline

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ABSTRACT
In order to improve the administrative level of pipeline safety among the surrounding environment, this paper proposes a pipeline risk assessment system of space and visualization based on the current situation of the gas pipeline risk assessment. The database of pipeline surrounding natural environment and social environment are established by using GIS. And the scatter grams on the accident severity and the vulnerability of hazard-affected bodies around the pipeline are obtained through spatial analysis and visualization technology. This paper also implements environmental comprehensive risk evaluation, judgment and visualization based on risk superposition principle. Combined with concrete examples, this paper finally introduces the implementation of the environmental risk assessment process under the impact of the risk evaluation system, obtains the spatial distribution results of visualization of environmental risk and provides decision makers with reliable decision basis.

INTRODUCTION
In recent years, many risk assessment methods for city gas pipeline has been proposed [1-2]. The traditional pipeline risk assessment can identify whether there is a risk, and can also evaluate the risk level or grade. But it cannot accurately inform users and decision-makers of the hazard-affected body or its spatial distribution or the level of risk. With the rapid increase in gas pipelines and urban construction, such evaluation methods cannot meet the needs of relevant personnel to pipeline safety and urban safety management. Therefore, introduce the pipeline GIS information technology, and take advantages of its powerful spatial data management, query and analysis capabilities to store and analyze the pipeline and its surrounding environment. It can also obtain the thematic maps which include the pipeline risk analysis and evaluation, pipeline risk distribution and the level of risk. This greatly promotes the development and application of pipeline risk assessment. On this basis, the risks of various surrounding hazard-affected body which caused by pipeline can be further analyzed.
and expressed. And then the comprehensive environmental risk and its spatial distribution features can be found. And it can more scientifically assist relevant departments and enterprises with pipeline maintenance and decisions-making of development planning.

**RISK ASSESSMENT SYSTEM**

Comprehensive risk of pipeline surrounding environment refers to the superposition of all the risk that various hazard-affected bodies surround the pipeline takes. The hazard-affected body mainly includes personnel, vehicles, buildings, soil, vegetation, water and other facilities and equipment. On the GIS platform, using pipeline database can analyze the severity of accidents and the vulnerability of the hazard-affected body. Using spatial analyst tools of GIS can get the quantitative risk and achieve real-time visualization. The block diagram for pipeline surrounding environmental risk assessment system is showed in Figure 1. The output for the results includes data tables, electronic map (hazard, vulnerability, risk distribution and level), the report documents and other forms.

**Environmental Risk Assessment Model**

To facilitate the analysis and comparison of the risk among different hazard-affected bodies and get the analysis and comparison of the risk among them, and at the same time, to obtain the comprehensive risk analysis and statistics, the evaluation and decision by the use of the monetized quantitative risk evaluation, this research established the environmental risk assessment model as in follow [3]:

\[
R = \sum_{i=1}^{n} SV_i C_i
\]

where \( R \) is the environmental risk equivalent, \( S \) is the accident severity, \( V_i \) is the vulnerability of the i-th class of hazard-affected body, \( C_i \) is the monetary value of the i-th class of hazard-affected body.

**Analysis of Severity**

**The Accident Severity Evaluation Model**

The accident severity evaluation model is as follow [4]:

\[
S = \sum_{j=1}^{m} f_j S_j
\]
Figure 1: Pipeline surrounding environment risk assessment system

\[ S_j = \sum_{k=1}^{l} p_{jk} S_{jk} \]  

where \( f_j \) is the failure probability of failure mode \( j \), \( S_j \) is the harm the severity of failure mode \( j \), \( p_{jk} \) is the probability of occurrence of harm mode \( k \), \( S_{jk} \) is the hazard severity of hazards model \( k \). The failure modes for pipeline include leakage, perforation and fracture. Hazard model includes jet fire, flash fire, fire and explosion [5-6]. Among them, jet fire, flash fire or fire affects the surrounding
environment mainly by the thermal radiation [7], while the explosion harms the Hazard-affected Body by the shock wave overpressure [8].

The Hazard Severity of Thermal Radiation

(1) The radiation strength calculation of jet heat is as follow [9-10]:

$$ I = \frac{5qR}{4\pi d^2} \tag{4} $$

where $I$ is the heat radiation intensity, $q$ is the radiation flux of point heat source, $d$ is the distance of point heat source to the target, $R$ is the emissivity which depends on the nature of the burning material.

(2) The radiation strength calculation of fireball or flash fire is as follow:

$$ I = \frac{QT_c}{4\pi d^2} \tag{5} $$

where $Q$ is thermal radiation flux when burning, $T_c$ is the heat conductivity coefficient, $d$ is the distance of point heat source to the target.

(3) Thermal radiation hazard severity is a single-valued function on the thermal radiation intensity [11-12], and the relative relations between them are shown in tab.1. Using linear regression, the relationship between severity and thermal radiation intensity can be obtained as follow:

$$ S = a * I + b \tag{6} $$

where $a$, $b$ should satisfy the following relations:

$$ \begin{cases} 
  a \sum_{k=1}^{5} I_k^2 + b \sum_{k=1}^{5} I_k = \sum_{k=1}^{5} S_k I_k \\
  a \sum_{k=1}^{5} I_k + 5b = 250 
\end{cases} $$

The values of $I_k$ obtained through simulation are shown in Tab.2. And then the severity of thermal radiation intensity function can be obtained as follow:

$$ S = 2.513 * I \tag{7} $$
Table 1: The relationship between severity and thermal radiation intensity

<table>
<thead>
<tr>
<th>Severity S</th>
<th>0</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Radiation Intensity / kW</td>
<td>$I_1$</td>
<td>$I_2$</td>
<td>$I_3$</td>
<td>$I_4$</td>
<td>$I_5$</td>
</tr>
</tbody>
</table>

Table 2: The values of $I_k$ simulated data tables

<table>
<thead>
<tr>
<th>$I_1$</th>
<th>$I_2$</th>
<th>$I_3$</th>
<th>$I_4$</th>
<th>$I_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10.5</td>
<td>19.0</td>
<td>29.5</td>
<td>40.0</td>
</tr>
</tbody>
</table>

The Overpressure Hazard Severity

(1) The calculation of shock wave overpressure is as follow [13]:

$$P = 0.71 \times 10^6 \left[ \frac{d}{3\sqrt{M_{TNT}}} \right]^{-2.09} \tag{8}$$

In this formula, $P$ is the shock wave overpressure, $M_{TNT}$ is the equivalent quality when exploding, $d$ is the distance of the target and the center of vapor cloud explosion.

(2) Explosion hazard severity is a single-valued function on the overpressure[14-16], and the relative relations between both are shown in tab.3. Using linear regression, the relationship between severity and overpressure can be obtained as follow:

$$S = c \ast P + e \tag{9}$$

In this formula, $c$, $e$ should satisfy the following relations:

$$\begin{cases} 
    c \sum_{k=1}^{5} P_k^2 + e \sum_{k=1}^{5} P_k = \sum_{k=1}^{5} S_k P_k \\
    c \sum_{k=1}^{5} P_k + 5e = 250 
\end{cases}$$

The value of $P_k$ obtained by the simulation are shown in Tab.4. And then the severity of the overpressure function can be obtained as follow:

$$S = 0.610 \ast P \tag{10}$$
Table 3: The relationship between severity and overpressure

<table>
<thead>
<tr>
<th>Severity $S$</th>
<th>0</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overpressure $P$ / kPa</td>
<td>$P_1$</td>
<td>$P_2$</td>
<td>$P_3$</td>
<td>$P_4$</td>
<td>$P_5$</td>
</tr>
</tbody>
</table>

Table 4: The values of $P_i$ simulated data tables

<table>
<thead>
<tr>
<th>$P_i$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$P_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40</td>
<td>82</td>
<td>125</td>
<td>165</td>
</tr>
</tbody>
</table>

Vulnerability Analysis Hazard-affected Body

Vulnerability Assessment Factor

Thermal radiation and overpressure are the main harmful patterns for hazard-affected body after the failure of gas pipe [17-18]. So take anti-overpressure and anti-thermal-radiation as vulnerability assessment factors of hazard bearing body.

Vulnerability Assessment Model

The vulnerability of hazard-affected body decreases with thermal radiation and overpressure increases. Vulnerability assessment model is as follow:

$$V = -(K_i\alpha_i + K_p\alpha_p) + 1$$  \hspace{1cm} (11)

In this formula, $V$ is the vulnerability; $K_i$ is the thermal radiation of hazard-affected; $\alpha_i$ is the weight of thermal radiation; $K_p$ is the overpressure resistance of hazard-affected; $\alpha_p$ is the weight of overpressure resistance.

THE STEPS OF RISK ASSESSMENT

Based on the risk evaluation system, determine the steps of risk assessment by the use of ArcGIS software [19].

Data Collection

Collect the study area topographic map; channel design, various technical parameters during the construction and operation maintenance process, every stage of urban gas pipeline system
layout, the regional gas pipe network layout, the plant floor plan and flow stations and pipe network hydraulic calculation chart; Urban gas pipeline system layout during the preliminary design phase, every stage of the network hydraulic calculation chart, the plant floor plan and flow stations and pipe network hydraulic calculation chart, various professional design. Social and natural environmental factors of pipeline surrounding, accident history data, inspection records and maintenance records.

Data Preprocessing

(1) To facilitate the analysis, according to its own characteristics, the hazard-affected body can be divided into two categories, ① Still categories: buildings, roads, soil, vegetation, cables, water pipes, etc; ② Non-stationary categories: Personnel, vehicles and so on.

(2) Set the base layer as regional topographic map we studies and respectively extracts distribution layers of buildings, roads, soil, vegetation, cable, water pipe by the use of ArcGIS Combined with the system arrangement of gas pipe network and remote sensing image.

(3) According to the research on regional topographic map, establish personnel layer. And the area is divided into geographical cells \( (\Delta d \times \Delta h) \) to confirm the cell population density. According to the remote sensing image and statistical data, obtain the population density distribution map. Then according to the method, create a layer density distribution layer of non-stationary class of hazard-affected body such as vehicles \( (\Delta d, \Delta h) \) is the length and width of the geographical cells, which can be valued by the evaluation of accuracy.)

(4) According to the statistics of material, structure, construction time and other attribute data of hazard-affected body, confirm the thermal radiation the overpressure resistance and economic value of hazard-affected body, then add to the attribute table.

(5) Linking local weather website to get real-time weather data in the area we study, including temperature, pressure, and wind direction and so on.

The Evaluation of Accident Severity

(1) According to the above step of basic data, confirm the pipeline failure mode and failure probability by the use of expert scoring method; combined with the real-time meteorological data, confirm the hazard model and probability, and then get the vulnerability grade distribution of hazard-affected body.

(2) According to the pipeline parameters, for example, pressure, diameter, the temperature inside and outside of the pipeline, evaluate the pipeline leakage rate, leakage rate and heat flux and TNT equivalent. And then evaluate the thermal radiation intensity and the shock wave overpressure value taking \( D_i \) as the distance. Get the gradient relationship between severity and distance \( D_i \). And using the buffer analysis capabilities of ArcGIS software to obtain severity distribution map. The value of \( D_i \) is as follow:
In this formula, $\Delta D$ is the width of the gradient, $\Delta D$ is one of the decisive conditions that evaluate the value of accuracy by severity. The precision increases with the value decreases, while it increases the amount of calculation. And $i$ is the gradient series, values 1,2,3,4......

**Vulnerability Assessment of Hazard-affected Body**

1. For stationary hazard-affected body, use the layers of data obtained by data preprocessing and take advantages of the corresponding thermal radiation resistance, super-pressure. And according to vulnerability assessment model, calculate the vulnerability of each hazard-affected body, and then add it to the attribute table.

2. For non-static hazard-affected body, according to the vulnerability assessment model, confirm the average vulnerability of the individual, and add it as a kind of vulnerability to the hazard-affected body attribute table;

3. Classify the vulnerability based on the vulnerability assessment data, and then obtain the level of vulnerability map of hazard-affected body.

**Risk Assessment of Hazard-affected Body**

According to the risk evaluation model, obtain and show the risk of each hazard-affected body by the use of the accident severity distribution and the vulnerability grade distribution of hazard-affected body above.

**Environmental Risk Assessment**

According to the risk evaluation model, take the currency as risk equivalent value and use the risk value for each hazard-affected body obtained by the above analysis. According to the results of environmental comprehensive risk assessment obtained by overlay analysis, reclassify it to generate the risk classification map.

**EXAMPLES AND ANALYSIS**

**Instance Data**

Regional main pipe layout is shown in Figure 2. The diameter of the pipe is DN80, and the texture of it is steel. The pressure level of the pipeline is medium pressure system, and the pipe pressure is 0.4MPa. The construction time and the operation situation of the regional pipeline have been given, as well as the regional environmental activities in this area. Based on the experience, confirm the rate of three failure modes ——leakage, perforation and fracture. And the rate of
them is respectively 54%, 29% and 17% [20]. The rate of persistent jet fire, fireball or flash fire and explosion is respectively 0.1, 0.08 and 0.06 [21-22]. And then, conduct a comprehensive risk assessment.

The Evaluation Results of Accident Severity

The evaluation results of accident severity are shown in Figure 3. According Pipe Properties, confirm the radius of injury severity of three levels. And then by means of the analysis of the buffer in ArcGIS, draw the Injury severity distribution diagram. In the diagram, the red cover area is for the first level. With the linear distance of the pipe increases, the severity of injury is decreased, and the Injury severity also gradually reduces. They are respectively defined as second level and third level.

Figure 2: Study area and the distribution network

Figure 3: The accident severity distribution
Vulnerability Assessment Results of Hazard-affected Body

According to the anti-overpressure, thermal radiation index selected, obtain the vulnerability assessment results of hazard-affected body. Using the "natural discontinuities grading method", exhibit the classification of hazard-affected body’s vulnerability, which is showed in Figure 4. The comparative analysis shows that the vulnerability assessment results are consistent with the actual situation.

![Figure 4: Vulnerability grade distribution](image)

The Assessment Results of Environmental Risk

Using risk evaluation method established, overlay and analyze the vulnerability of hazard-affected body, and then obtain the Comprehensive environmental risk. Show the visual results in Figure 5.
According to the analysis of environmental risk distribution, draw the following conclusion: (1) There is a certain risk within the scope of coverage to gas pipeline environment, and it obeys the regular that the environmental risk increases along with the decreasing distance; (2) There is a large flow of vehicle and personnel in the main road because the gas pipeline is paved along the main road. The environmental risk is the highest in this area. Thus the decision makers should fully consider the factors; (3) The vegetation, lakes and other hazard-affected body have the characteristics of high vulnerability, risk and failure which are not easy to recover, the environmental issues are outstanding, and the responsibility of environmental protection is much more heavy, so that it is of great significance to strengthen the safety management of this kind of hazard-affected body.

**CONCLUSIONS AND REFLECTIONS**

Taking the hazard-affected body around the pipeline as the object of study and using the ArcGIS, constructed the city gas pipeline environment risk assessment system of space and visualization. The risk evaluation system can not only realize the existence of risk assessment and identification of pipeline risk levels and other traditional risk method, but also confirm the risk of the hazard-affected body, environment risk, rapid positioning the risk of pipeline and the real-time visualization during the process of comprehensive risk evaluation; At the same time, reduced the influence of subjective factors in traditional evaluation and made the evaluation results more objective and reliable. Using the ArcGIS, obtained a comprehensive risk evaluation of the environment and environmental valuation of various hazard-affected body around the pipeline. It provided the relevant departments and enterprises with reliable basis of more scientific city management, confirmation of safe area and the optimal evacuation path.
However, further improvement in this area has a lot of work to be done. Here are some aspects should be studied right now: (1) For the risk of hazard-affected body around the pipeline, the study only considered the direct damage, but did not evaluate the secondary damage which caused by roads, cable, water pipe network. And it should be improved in the further study; (2) The vulnerability assessment of hazard-affected body is the important part of risk determination while the vulnerability assessment system is not perfect enough, and it needs further study for establishing more scientific and more accurate vulnerability assessment system.

CONFLICT OF INTERESTS

All the authors declare that there is no conflict of interests regarding the publication of this paper. All the authors do not have a direct financial relation with the commercial identities mentioned in their paper that might lead to a conflict of interests for any of the authors.

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