# Analysis of Aseismatic Reliability for Gas Pipeline Network System in Large-Scale Gas Field

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**ABSTRACT :** A method for calculating aseismatic reliability of gathering and transferring pipeline network in large-scale gas field is put forward. Taking the maximal seismic intensity S that might occurred during the design service life in the engineering site of gas gathering and transferring pipeline as seismic loads and the fortification intensity ld that is determined during pipelines design as structure resistance, this paper comes up with random reliability analysis model of pipeline to predict the seismic damage. Under the same geological damage environment, pipelines in network are of failure dependency. Aseismatic reliability of pipelines can be expressed with the occurring probability of geological disasters like fault rupture, sand liquefaction, slippage and so forth. For avoiding the NP hard problem caused by the calculation of network reliability, the paper applies breadth first search technology of graph theory to propose the algorithm for determining probability of connectivity reliability for the multi-source and multi-terminal network, and combines it with Monte Carlo simulation to apply to the aseismatic reliability calculation of super-large gas pipeline network. On the basis of the result, the safety of the system will be analyzed and assessed. This method is also able to assess the operation condition of pipeline network after earthquake quickly and constitute reconditioning plan for pipeline network to reduce the earthquake-induced disasters. This paper takes a gas field in western China with 35 pipelines, 4 gas gathering stations and 3 industrial users as example to give the detailed process of the calculation of seismic reliability for pipeline network under the impact of a serious seism at seven magnitudes, analyses the sensitivity and critical importance of pipeline network system and find out the corresponding links of aseismatic weakness. The example demonstrates the simplicity, validity and practicability of this method.

**KEYWORDS:** Natural gas pipeline network, earthquake, fuzzy reliability, fortification intensity, system

The natural gas pipeline network system is usually linear or netlike which exists in a very large space. The seismic damage has some unique characteristics [1] [2][3].

(1) It covers large areas. The earthquake intensity that acts on each section of pipeline or other non-pipe components is different and the threat of earthquake damage as well.

(2) The destruction is multiple. There are numerous unit construction in the gas pipeline network. After the earthquake, many kinds of damage in different degrees will appear. The underground tube lines are vulnerable in the earthquake. Serious damage exists not only in the high intensity area, but also in the low intensity area.

(3) The secondary disaster is serious. The destruction of the pipeline network possibly causes a fire disaster., detonation and so on. The occurrence of the secondary disasters has already been confirmed in many earthquakes.

(4) It is easy to get coupled with other different types of lifeline engineering system (for instance, electrical power system, communication system and so on), and this situation has brought the complexity and difficulty for the disaster prevention of gas pipeline network and the emergent maintenance thereafter.

(5) It has failure dependency. Those functional elements which are included in the gas pipeline network interact with each other and constitute a network system. When the reason that the unit element fails to work holds true to other elements, all expiration events are correlated.

(6) The system rehabilitation is gradual. The destruction position in pipelines after earthquake and the situation of the damage are hard to examine.

According to the above characteristics of seismic damage, the paper carries on a system analysis of the pipeline network. Application of the probability method and the reliability principle, the paper estimates pipeline seismic risk level and the reliability probability of pipeline network in its life service, and also recognizes the links of the aseismatic weakness, so as to provide the scientific basis for safety handling of pipeline network system and the plan for seismic disaster mitigation.

## THE MODEL OF RANDOM RELIABILITY OF GAS PIPELINE SUBJIECTED TO SEISMIC LOADS

For the natural gas pipeline embedded in the soil, earthquake will damage the body and the joint as a result of wave propagation, fault rupture, soil liquefication and so on. The mechanism is complex and the seismic damage degree is affected by many kinds of random factors. Thus, it is very hard to carry on strict mathematics processing. It is quite scientific and reasonable to describe the pipeline seismic resistance reliability by means of the possibility what kind of situation the gas pipeline is at.

### 1. Definition of Working State of Pipeline during the Earthquake

Many cases of earthquake indicate that the primary causes of the failure of the underground pipeline structure include seismic destruction and geological environment destruction[4].

Seismic destruction refers to the destruction when the biggest response value of system unit is bigger than the reaction extreme under the strong seismic wave action. Its characteristic is that pipeline's failure probability depends on the pipeline's fortification intensity $I_d$, seismic intensity $S$ and the damage grade.

The geological damage environment refers to destruction to the pipeline located in seism fault or the saturated sandy soil area, which is caused by fault fracture, sand liquefaction slippage and land subsidence, etc. under the seismic action. Its characteristic is that the pipeline failure probability depends on the destruction probability of the environment where the pipeline is located, and normally the failure probability is higher than the usual structure failure probability of the similar unit under the condition of the corresponding intensity and the field farmland. Thus the unusual area of failure forms.

According to the available results of the study on pipeline under variety of seismic damage action, and the research results of aseismatic property of the partial pipeline, making a reference to three specific standards from of construction aseismatic design standards [5] for building's earthquake resistance fortification, and with the oil (gas) steel pipeline aseismatic design standard SY/T0450-2004, this paper defines the following two kinds of working state of gas pipeline during the earthquake.

(1) Reliable State— The body structure is basically perfect. Certain damages may appear in some different degrees during the earthquake, but after the emergent repair, it resumes the normal service. From the perspective of the force, pipeline's comprehensive anti-disaster ability is higher than the seismatic load, and allows the body structure to enter the non-elastic deformation stage. But pipeline's size of the elastic-plastic deformation has a scope. The permanent deformation after earthquake is not serious, and the pipeline weld joint without fracture phenomenon. The pipeline has no serious flexure destruction under the compression or bending loads during the earthquake, and there is no gas leakage accident Also, after shaking, the pipeline remains in its service.

(2) Failure State— The damage to the body structure is serious. From the perspective of the force pipeline's comprehensive disaster resistance is lower than earthquake load. The body structure is at the plastic deformation stage. The weld joint may present serious fracture phenomenon. The pipeline traversing the earthquake fault zone and the sand liquefaction area may present the shell type destruction or twisted type flexure. The natural gas leakage accidents occur after earthquake, and the tube line fails to work with air supply being cut off.

In view of different types of pipelines failure, the paper establishes the probability model for reliability analysis.

### 2. Reliability Analysis of Pipeline in Seismic Action Destruction

#### *(1) Limit Equation of Pipeline Structure*

Select the gas pipeline project site. During $T$ years of design reference period, the biggest seismic intensity (payload) that may be subjected to is $S$. In pipeline optimization of seismic design, taking the identified fortification intensity $I_d$ (structural resistance) as a basic variable of the performance function of pipeline structure seismic resistance , The performance function

$$Z = f(S, I_d) = S - I_d \tag{1}$$

When $Z < 0$, pipeline is in reliable state; when Z > 0, pipeline is in failure state; when $Z = 0$, pipeline is in limit state. Therefore, pipeline aseismatic reliability and failure probability are:

$$\psi = P(S < I_d) \quad \text{or} \quad F = 1 - \psi = P(S > I_d) \tag{2}$$

The general underground pipeline reliability probability is calculated on the basis of the mechanics model analysis or the statistical model of historical seismic experience. The advantage of the former lies in having grasped the main factors leading to destruction of pipeline, so the aseismatic reliability is established based on a more rational basis. However, it remains hard to fully reflect the various complex factors that lead to the underground pipeline failure. The analysis object and the results have certain limitations. In contrast to the former, to a certain extent, the latter provides a complementary reference, but the integrity of the damage information and the state standards of earthquake damage survey, restrict the application of model to the more difficult and painstaking analysis of the pipeline seismic reliability[6]. The paper takes intensity as the structure resistance unit of the pipeline and the measurement unit of loading, grasps the essence of the issue of pipeline seismic resistance, and makes the problem greatly simplified [7]. Also the study overcomes the shortcomings of pipeline dynamic response calculation which involves the large quantity of calculation, high cost and more difficulties in selecting relevant parameters. Moreover, it avoids insufficiency of the experienced statistical model.

***(2) Probability Distribution of Seismic Intensity***

The occurrence of gigantic earthquake is closely connected with the regional geological environment, and the historical evolution of seismic disasters. For the gas pipeline network system distributed in larger space, its various units suffer different seismic reaction in an earthquake disaster as a result of the spatial distribution. Therefore, the analysis of structural aseismatic reliability can not be separated from the seismic risk analysis of the project site.
The main purpose of seismic risk analysis: to offer the probability distribution $F_S(s)$ or probability density curve $f_S(s)$ of the biggest seismic intensity $S$ (payload) that may be subjected to during $T$ years of design reference period.
Because of deficient information of heavy earthquake, the site seismic risk analysis is still a weak link in earthquake engineering. Generally, the statistical results of seismic risk analysis of earthquakes in China show that the probability distribution of seismic intensity accords with extreme value type III distribution

$$F_S(s) = \exp\left[-\left(\frac{\omega - s}{\omega - \varepsilon}\right)^k\right] \tag{3}$$

In the equation, $\omega$ ——the upper limit value of intensity, take $\omega$=12;
$\varepsilon$ ——modal intensity，in 50 years of design reference period，the intensity with probability above 63.2%;
$k$ ——distribution shape parameter。

Calculating derivation of $F_S(s)$, probability density function $f_S(s)$ of $S$ can be evolved:

$$f_S(s) = \frac{k}{\omega - \varepsilon} \cdot \left(\frac{\omega - s}{\omega - \varepsilon}\right)^{k-1} \cdot \exp\left[-\left(\frac{\omega - s}{\omega - \varepsilon}\right)^k\right] \tag{4}$$

***(3) The Fuzziness of Aseismatic Fortification Intensity*** $I_d$

In decision-making for the pipeline seismic fortification intensity, the majority of designers, use the seismic risk analysis results, and take the intensity value with an agreed probability under the influence of multiple sources of earthquakes. Generally, in the region or sites the intensity above probability of 10% in 50 years is taken [5]. However, this often results in the same level of fortification of a structure within the region, and for different structure with different significance, this standard apparently is unreasonable. In aseismatic design of the pipeline, we believe that the correct approach is the following. Based on the basic intensity offered by national construction department, considering gas pipeline structural features, material properties, application requirements, the importance, economic and social benefits and other factors, we can increase the intensity or improve the aseismatic measures. As a result of uncertainty or inaccuracy of these factors, it is difficult to give a quantitative standard. The fortification intensity determined by designers is bound to attach with a certain degree of subjectivity. In order to prevent $I_d$ from being used as a resistance standard in the assessment of reliability, and to avoid the transformation of two working states of pipeline during the earthquake, the paper introduces the fuzzy mathematics theory to the pipeline reliability model, causes the neighboring intensity to seep mutually. Also the study takes $I_d$ as a fuzzy quantity, considers it fuzzy sector for the real number discourse domain. The membership function is shown in figure 1, the characteristic is

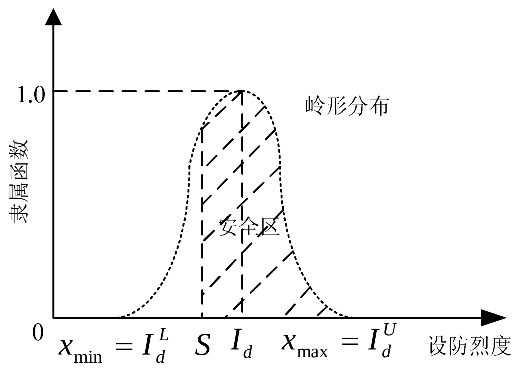


Figure 1 Membership function of fuzzy fortification intensity $\tilde{I}_d$

1） $\mu_{\tilde{I}_d}(I_d) = 1$， $I_d$ is the most representative quantity of $\mu_{\tilde{I}_d}(x)$；

2） $x_{\max} = \sup(I_d) = I_d^U$， recommend $I_d^U = I_d + 1$；

3） $x_{\min} = \inf(I_d) = I_d^L$， recommend $I_d^L = I_d$—1~1.55；

4） $\mu_{\tilde{I}_d}(x)$ curve pattern，can choose triangle, parabola or rhombus distribution.

***(4) Prediction Model of Gas Pipeline Fuzzy Reliability***

Regard the reliable state of pipeline structure as a fuzzy set $\tilde{A}$ in structure state domain of discourse. When the earthquake intensity $S$ is the random variable, fortification intensity $\tilde{I}_d$ is fuzzy quantity, for the limiting condition equation (1), pipeline's fuzzy reliable condition (normal working condition) is

$$\tilde{A} \overset{def}{=} \{S < \tilde{I}_d\} \qquad (5)$$

Apply probability formula of fuzzy event, obtain the fuzzy reliability of pipeline structure

$$\tilde{\psi} = P(\tilde{A}) = \int \mu_{\tilde{A}}(s) f_S(s) ds \qquad (6)$$

Where $\mu_{\tilde{A}}(s)$—membership function of pipeline fuzzy secure state $\tilde{A}$;

$f_S(s)$—probability distribution density function of stochastic earthquake intensity.

In figure 1, when $S$ falls into the abscissa sector, membership function of pipeline fuzzy reliable condition

$$\mu_{\tilde{A}}(s) = \begin{cases} 1 & s < x_{\min} \\ \dfrac{\int_s^{x_{\max}} \mu_{\tilde{I}_d}(x)\mathrm{d}x}{\int_{x_{\min}}^{x_{\max}} \mu_{\tilde{I}_d}(x)\mathrm{d}x} & x_{\min} \le s \le x_{\max} \\ 0 & s > x_{\max} \end{cases} \qquad (7)$$

Rewriting equation (6), the fuzzy reliability

$$\tilde{\psi} = \int_{-\infty}^{x_{\min}} f_S(s)ds + \frac{\int_{x_{\min}}^{x_{\max}} f_S(s)dx \int_s^{x_{\max}} \mu_{\tilde{A}}(x)\mathrm{d}s}{\int_{x_{\min}}^{x_{\max}} \mu_{\tilde{A}}(x)\mathrm{d}x} \qquad (8)$$

## 3. Calculation of the Pipeline Reliability Based on Geological Environmental Damage

In the solution of the system unit failure probability in geological environment destruction, there are extraordinary failure correlation in the same fault or on the same saturated zone [4]. We use the following assumptions: Failure probability of system unit equals the probability of occurrence of fault rupture or soil liquefaction and so on. Clearly, in terms of the assumption, once a fault rupture or a saturated sand liquefaction happens, all the district units in the fault or the saturated sand will fail at the same time.

## CALCULATION OF ASEISMATIC RELIABILITY OF GAS PIPELINE NETWORK SYSTEM

Use natural gas pipe network to simulate a network map. Gas fields, gas-collecting stations, booster stations pipelines interchange and centralized gas points are marked by gas points as the nodes of the map. The pipeline is considered as the boundary of the map. The boundary of air flows in one direction only is directed boundary. For the two-way flow of air, the boundary is undirected boundary. Generally, gas fields or gas-collecting stations are marked as the source points. Users and centralized gas points are terminal points. In the natural gas pipeline network, another peak can be reached from the designated top through alternating sequence of edge and the apex, and then the sequence is called a path between the two vertexes. If any edge is removed, it is no longer a path, and then the path is called the minimum path.

Considering the services of gas pipeline network, the aseismatic reliability of pipeline network refers to the connecting ability of terminal points and source points in earthquake conditions. The measurement is the probability of maintaining connecting between terminal point and source points. The majority of large-scale natural gas pipeline networks belongs to system with multi-source and multi-terminal. Thus, the natural gas pipeline network has reliable events of two kinds in the following

(1) $S_{\mathrm{I}}$ = {source point→terminal points there is at least one minimum path reliable for all the edges. } $= \bigcup_{i=1}^{n} A_i$

(2) $S_{\mathrm{II}}=\{$There is at least one minimum path set for source point→all the terminal points to connect simultaneously$\}=\bigcup_{i=1}^{m} B_i=\bigcup_{i=1}^{m} C_1 \cdots C_l \cdots C_J$

Mark $A_i$ as the minimum path No. $i$ of $n$ minimum paths, $B_i$ as the set No. $i$ of $m$ minimum path sets, $C_l$ as the minimum path $l$ of $i$ minimum path sets, $J$ as the total of terminal points.
Solve all the minimum paths or minimum path sets. Because the same unit may appear in different minimum paths, in terms of Inclusion-Exclusion Principle, reliability of pipeline system.

$$\begin{aligned}\psi_S^{\mathrm{I}}=1-F_S^{\mathrm{I}}=P(\bigcup_{i=1}^{n} A_i)=\sum_{i=1}^{n} P(A_i)-\sum_{1\le i<j=2}^{n} P(A_i A_j)+\sum_{1\le i<j<k=3}^{n} P(A_i A_j A_k)+\cdots+(-1)^{n-1} P(\bigcap_{i=1}^{n} A_i) \\ =\sum_{j=1}^{n}(-1)^{j-1}\sum_{1\le i_1<i_2\cdots i_j=j}^{n} P(\bigcap_{l=1}^{j} A_l)\end{aligned} \tag{9}$$

Because the number of minimum network paths increases with the scale of network in a non-linear pattern, the number of minimum paths of network $n$ is usually large. Expand equation (9) and then there is $2^{n-1}$ sum-of-product. When $n$=20, there is up to $10^6$. From the angle of numerical calculation, more effective algorithms needed searching. Generally $\psi_S^{\mathrm{II}}=1-F_S^{\mathrm{II}}=P(\bigcup_{i=1}^{m} B_i)$, $\psi_S^{\mathrm{I}}\ge\psi_S^{\mathrm{II}}$.

## 1. Principle of Unit Division for Analysis of Aseismatic Reliability

(1)Connected with non-pipe components at both ends. The component whose input and output have no change in diameter is regarded as a unit of calculation, namely arc unit;
(2) Non-pipe component is regarded as a unit of calculation, namely point unit
(3) If a component is connected with sub-tubes, pipes branch, gas source or gas supply point, and the connection is considered as the division, the pipe components can be divided into several calculation units;
(4) Confirm the main types of disaster of pipe section, and regard the pipe sector subjected to one kind of disaster or more kinds together as a unit body.

## 2. Monte Carlo Method of Pipeline Network Reliability Algorithm Based on BFS

Monte-Carlo algorithm is used to obviate the complexity of the calculations in equation (9). The basic idea is to use the destruction probability of the network unit. By means of a large number of random simulations, the damage state of network unit is reproduced approximately. Finally, calculate the frequency of the connecting state between the source point and terminal point and the approximate frequency calculation replaces the analysis of precise probability.
Adopt the technology of Breadth First Search in Graph theory, and simulate the connectivity of two-state network. Take edge weight network as an example, the basic procedure of Monte-Carlo algorithm are concluded as following:
Step1,in terms of evaluation approaches of seismic probability of pipeline units, confirm the probability $\psi_i$ of safe network edges.
Step2, use random number generator to gain random number set in even distribution in $[0,1]$, and match with network edges.
Step3,compare random number $r_i$ falling on the edges and secure probability $\psi_i$ of edges. If $r_i\ge\psi_i$, the edge is secure; if $r_i\le\psi_i$, the edge is in failure. Just like this, gain the damage state in one simulation.

Step4, by means of Breadth First Search, search the simulated network from the source point to the scope around and dye the nodes: for node $i$, if it is connected with source point, dye it with given color(that is, give it a characterizing number); or else do not dye. Repeat the procedure until the dye on the nodes does not change.
Step5,repeat the simulation process in Step 2~ Step 4. Count the frequency of connecting state between nodes and source points, namely the times of nodes to be dyed. Divide the times of being dyed by the times of simulation, and the dye frequency is the approximate estimate value of connecting probability.

## 3. Sensitivity and Critical Importance of the System Components in Pipeline Network

In the system each unit has different contribution to the system reliability. The change in reliability in some unit may lead to a great change of reliability in the whole system, while the change of some other unit may not. In the system reliability theory, sensitivity and critical importance are used to measure the influence to system reliability.
Generally, the sensitivity and critical importance of network system unit $j$ depend on not only the logic construction form, but also unit reliability $\psi_j$ and system reliability $\psi_S^{\mathrm{I}}$ and $\psi_S^{\mathrm{II}}$.

Sensitivity
$$I_{S,j} = \frac{\partial \psi_S^{\mathrm{I}}(\psi_1 \ldots, \psi_j \ldots, \psi_n)}{\partial \psi_j} \tag{10}$$

Critical importance
$$I_{R,j} = \frac{\partial \ln F_S^{\mathbf{II}}}{\partial \ln F_j} = \frac{\partial \psi_S^{\mathbf{II}}}{\partial \psi_j} \cdot \frac{1-\psi_j}{1-\psi_S^{\mathbf{II}}(\psi_1 \ldots, \psi_j \ldots, \psi_n)} \tag{11}$$

Figure 2 shows the general procedure of calculation of aseismatic reliability of gas pipeline network.

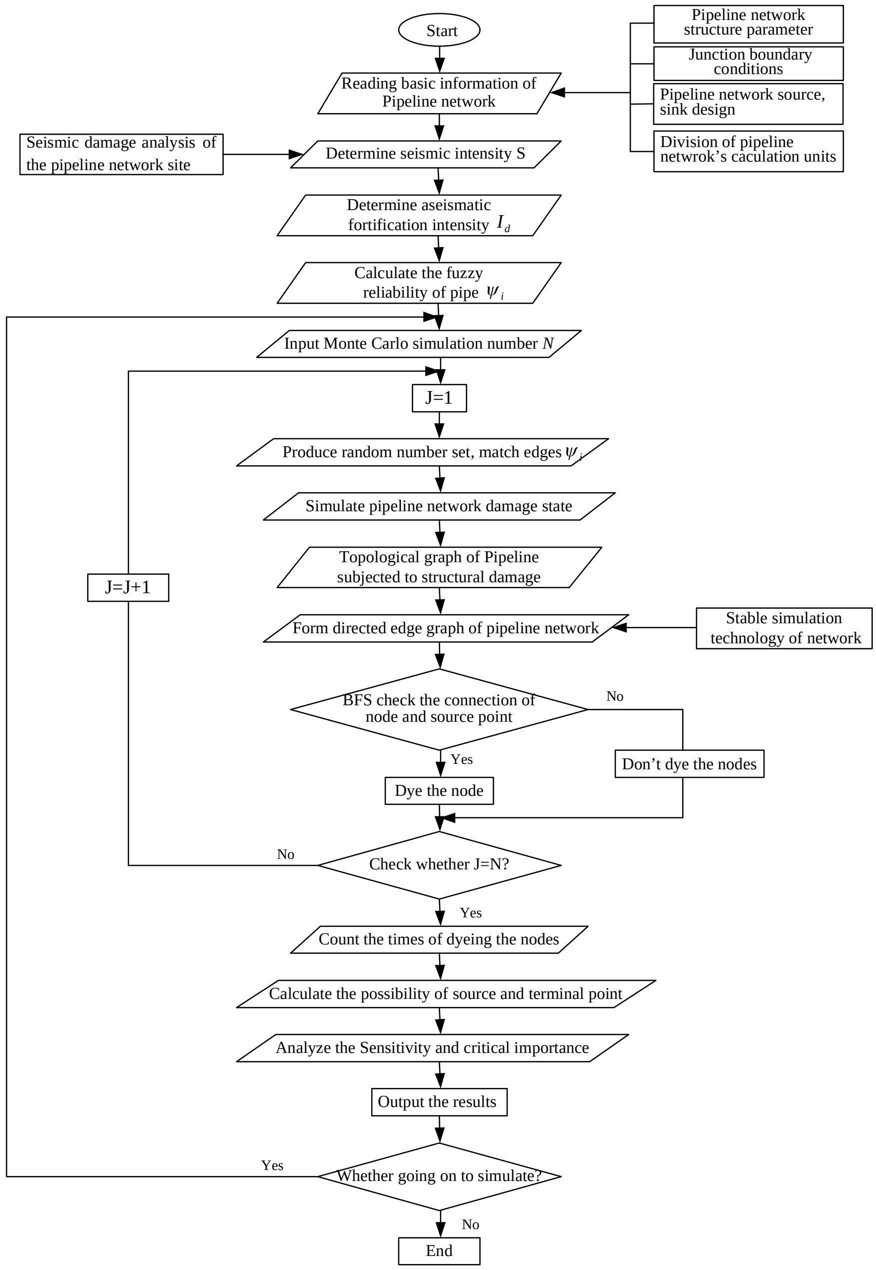


Figure 2 Aseismatic reliability calculation process graph of gas pipeline network

## ANALYSIS OF CALCULATION

Shown in figure 3 is a topological graph of gas centralized transportation pipeline network which contains nodal point of 31, pipe sections of 35. Node①~④represent the four gas gathering stations supplying gas for this pipe network. In the pipe network earthquake resistance fail-safe analysis, they are the four gas sources. Air feed pressure is 4.0~6.4MPa. Quantity of gas supply is 2.45×106Nm3 /d. Node⑤, ⑥ and ㉒ are respectively responsibly for supplying gas for Gas power station, the methyl alcohol factory and the long transmission pipeline. They are three of the biggest gas division stations in proportion of 1:3:6. According to the analysis of the risk of earthquake in the site, there may be heavy earthquakes with the upper limit of level 7 in southwest. The earthquake intensity which various parts of pipeline network possibly suffering can be seen in the region with the dashed line in the charge. The length of pipe 31, 32, 33 are located at the same fracture zone, with the fault fracture probability of 0.20. The length of pipe 18, 22 is in the same sandy soil saturation area. The liquefied probability during

earthquake in this area is 0.15. Then evaluate the aseismatic reliability of the gas pipeline network system.
Aseismatic fuzzy reliabilities of length of pipe 1~35 are listed in Table 1; Under the condition that 4 gas sources are completely reliable, the computing result of reliability in the system that guarantees the connectivity of gas consuming points with different quantity can be seen in Table 2; Table 3 offers the sensitivity, the critical importance and lengths of pipe which rank in the first 10; Table 4 and table 5 provide the connection probability of each node and the source point, and the contribution probability of source point to the terminal point.
Network reliability recursion algorithm in the revised literature [9] realizes 18593 non-cross minimum paths, and calculates the reliability of this pipeline network system which is listed in Table 2. Moreover, the table offers an example of non-cross minimum paths, thus has confirmed the validity of Monte Carlo method.

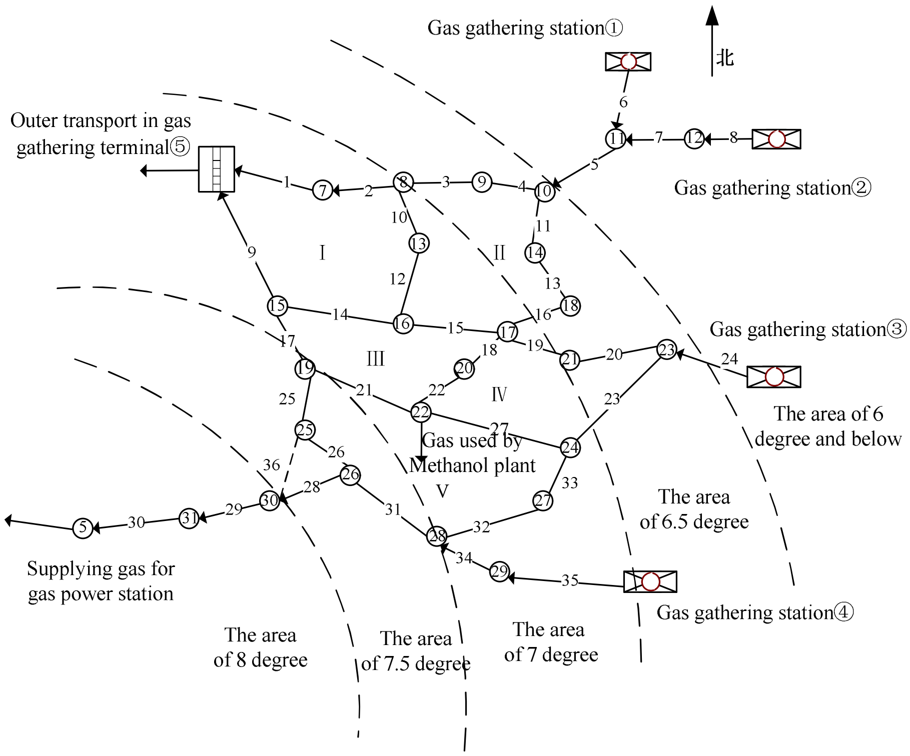


Figure 3 Gas gathering and transportation distribution map

Table 1 Fuzzy reliability of pipeline length in gas pipeline network system

| Pipeline length No. | Fuzzy reliability | Pipeline length No. | Fuzzy reliability | Pipeline length No. | Fuzzy reliability | Pipeline length No. | Fuzzy reliability | Pipeline length No. | Fuzzy reliability |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.9663 | 8 | 0.8756 | 15 | 0.8598 | 22 | 0.85 | 29 | 0.8398 |
| 2 | 0.8598 | 9 | 0.9663 | 16 | 0.9422 | 23 | 0.9422 | 30 | 0.8398 |
| 3 | 0.9422 | 10 | 0.8598 | 17 | 0.9663 | 24 | 0.8756 | 31 | 0.80 |
| 4 | 0.9422 | 11 | 0.942 | 18 | 0.85 | 25 | 0.9366 | 32 | 0.80 |
| 5 | 0.8756 | 12 | 0.8598 | 19 | 0.9422 | 26 | 0.9366 | 33 | 0.80 |
| 6 | 0.8756 | 13 | 0.9422 | 20 | 0.9422 | 27 | 0.8598 | 34 | 0.8598 |
| 7 | 0.8756 | 14 | 0.9663 | 21 | 0.9663 | 28 | 0.9366 | 35 | 0.8598 |

Table 2 Network system reliability

| Output state | The number of nodes at reliable condition | Network system reliability | | Example of non-crossing minimum path |
|---|---|---|---|---|
| | | Monte Carlo | Recurrence algorithm | |
| I | ⑤, ⑥, ㉒ only one of them | 0.02974 | / | 24→23→27→20→19→18 |

| | | | | |
|---|---|---|---|---|
| IV | ⑤, ⑥, ㉒ at least one | 0.99170 | 0.99059 | 32→31→-26→ 28→29→30 |

Table 3 Sensitivity, critical importance of pipeline length

| Pipeline length No. | Sensitivity | Ranking | Pipeline length No. | critical importance | Ranking |
|---|---|---|---|---|---|
| 24 | 0.0462313 | 1 | 30 | 0.684411 | 1 |
| 5 | 0.0393349 | 2 | 29 | 0.652712 | 2 |
| 34 | 0.0181301 | 3 | 28 | 0.604953 | 3 |
| 35 | 0.0116530 | 4 | 27 | 0.180380 | 4 |
| 6 | 0.0097590 | 5 | 26 | 0.178415 | 5 |
| 27 | 0.0097590 | 6 | 25 | 0.161700 | 6 |
| 2 | 0.0088048 | 7 | 24 | 0.147914 | 7 |
| 19 | 0.0088048 | 8 | 9 | 0.137068 | 8 |
| 3 | 0.0078457 | 9 | 23 | 0.116330 | 9 |
| 20 | 0.0078457 | 10 | 18 | 0.108419 | 10 |

Table 4 Connectivity rate of source points and nodes

| Nodes | Connectivity rate | Nodes | Connectivity rate | Nodes | Connectivity rate | Nodes | Connectivity rate |
|---|---|---|---|---|---|---|---|
| 5 | 0.63782 | 12 | 0.88112 | 19 | 0.98702 | 26 | 0.95498 |
| 6 | 0.98274 | 13 | 0.89978 | 20 | 0.92522 | 27 | 0.86322 |
| 7 | 0.78062 | 14 | 0.81626 | 21 | 0.83388 | 28 | 0.87854 |
| 8 | 0.90756 | 15 | 0.98532 | 22 | 0.92424 | 29 | 0.86164 |
| 9 | 0.81438 | 16 | 0.92326 | 23 | 0.87866 | 30 | 0.89790 |
| 10 | 0.85700 | 17 | 0.96724 | 24 | 0.91306 | 31 | 0.75806 |
| 11 | 0.97346 | 18 | 0.77462 | 25 | 0.96814 | | |

Table 5 Contribution rate of source point to terminal point

| Source point / Terminal point | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 5 | 0.42076 | 0.37268 | 0.54142 | 0.44358 |
| 6 | 0.75140 | 0.66572 | 0.84422 | 0.61692 |
| 22 | 0.47764 | 0.42386 | 0.82198 | 0.40986 |

Based on the above simulation results, we conclude as following

(1)When subjected to earthquake with upper limit of level 7, the function of pipeline network doesn't decrease in great extent because it belongs to multiple sources of gas supply and there are five inner rings in pipeline network. The north part and the central part are comparatively distant from the epicenter. The pipeline has good aseismatic property, and the security of supplying gas for ⑥ and ㉒ is high. The weak link of the pipeline is that the southwest part of the pipeline which is located in intense area of the earthquake has a weak geological condition. Node ⑤near to the epicenter and connected with single pipeline as the edge point suffers a lot from the earthquake.

(2) The sensitivity and critical importance offer the measures to improve the aseismatic property of the pipeline network: in order to keep all the gas consuming points in normal state during earthquake, then improve the fortification intensity or aseismatic grade of pipe length 30, 29, 28 and 27 which are connected with the gas consuming points. The length of pipe 24, 5, 34 and 35 connected with gas point are the key components of which at least one is the reliable gas supply in the network.

(3) The pipe length 18, 22 has a little sensitivity and critical importance because they belong to the public edge of inner ring Ⅲ and Ⅳ. Despite the weak aseismatic property, there is no much influence to the system reliability.

(4) The connectivity rates of different nodes and source point in the network further indicate that the damage to the pipeline from the earthquake is not only relevant to the destruction features of pipeline, but also closely connected with the distribution of the damage and the topological structure of the pipeline network.

(5) Affected by power station ⑤, the reliability $\psi_S^{I}$, $\psi_S^{II}$ of the two systems are quite different. Comparing the

connectivity rate of ㉕, ㉘. Thus, adding the pipe length 36 of 15.3km between ㉕→㉚ will improve the aseismatic reliability of system network $\psi_S^{\mathrm{II}}$ in Table 4. Because pipe length 36, 26 and 28 form a new inner ring, and the stable simulation result shows that the inner flow of 36 is zero, it is improper to increase other redundant units in aseismatic improvement, to pursue the system connectivity and to ignore the investment and aseismatic function requirement of the pipeline. So it is better to consider comprehensively in terms of the norm for the evaluated pipeline function during earthquake (pipe flow capacity×pipe reliability).

(6) The aseismatic importance of the gas gathering station 3 is greater than other three stations.

## CONCLUSION

Through rational assumption, the paper sets up a model of random reliability of gas pipeline during earthquake. Aiming at the NP difficulty in reliability analysis of engineering network system, the paper simulates the reliability of system connectivity by Monte Carlo, offers the usual evaluation methods for system aseismatic reliability of the large-scale gas pipeline network. Thus, the evaluation of the aseismatic reliability is made easier and more feasible. The calculated result shows that the method is practical and can be used universally.

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