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Decision of Optimal Fortification Intensity for Natural Gas Pipeline Network System

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ABSTRACT: The model of optimal decision on fortification intensity for natural gas pipeline network is established, and it takes the sum of the construction cost of natural gas pipeline network, the failure loss expectation of pipeline structure in future seism and the failure loss for the service after the disaster as minimal objective function. Restriction of the models are project investment, the seismic reliability for pipeline network, the special requirement of fortification for part of pipelines and the balance equation of nodal flow. The cubical algorithm for disjoint of Boolean function that is applicable for reliability calculation of network system is put forward and is used as the tool of seismic reliability analysis for multi-source and multi-terminal network system. Combing the reproduction strategy of differential evolution algorithm with the cross and variation of genetic algorithm, a new hybrid genetic algorithm is applied to the optimization solution for fortification intensity of natural gas pipeline network. This paper took a natural gas network with 22 pipelines, 2 gas sources and 2 gas users under the condition of seven magnitude seism as example, and makes the decision on the optimal fortification intensity for gas pipeline. Meanwhile, influence of the topology of pipeline network, the structure importance of pipeline, the fortification level of system, and the engineering investment on the fortification intensity of pipeline was analysed. The result of the example demonstrates the practicability of the established model and algorithm.

KEYWORDS: Gas pipeline network, Fortification intensity, Optimization, Genetic algorithm, Differential evolution

Gas pipeline network is a unique lifeline system with network characteristics that existed in a great spatial scope in reticular or linear and easily suffered natural disaster like earthquake. In aseismatic research of lifeline engineering network system, scholars at home and aboard emphasis on aseismatic reliability analysis and seismic damage prediction. However, at the early period of the design on lifeline system, there is little report has been seen in published literature for the research on how to layout and determined pipe structural parameter in anti-seismic optimal design on the basis of quantitative evaluation in network system's aseismatic performance. Because of the double dimensionality curse like mathematical programming and the system reliability calculation, during the process of lifeline system's optimization design which based on system reliability analysis, most researches stay on reliability optimization design of simple series-parallel system. Therefore, no significant development has been gained in this filed in recent years. This research uses the theory at early period of gas pipeline network system design that aseismatic fortification intensity characterized the effect of pipeline structure resistance and establishes whole life aseismatic fortification intensity decision model of gas pipeline network to guideline pipeline structure aseismatic design. In this way this paper plans related aseismatic factors during design stage in whole-life process of pipeline network system to make pipeline network's total cost and lost of suffered earthquake in the future reach the lowest.

1. DECISION-MAKING MATHEMATICAL MODEL OF OPTIMAL FORTIFICATION INTENSITY FOR PIPELINE NETWORK SYSTEM

Under the condition that process program, topology structure and structural size of new pipeline network system have been identified in Preliminary design process, the pipeline aseismatic optimal design, which uses aseismatic fortification intensity to characterize the effect of pipeline structure resistance carried out. As pipe diameter, value of tube wall, and construction mode of gas pipeline structure design are related to resistance, this paper builds relationship among fortification intensity, pipeline network construction investment, loss expectation of pipeline network and after disaster pipeline network service function loss. Satisfy all the constraints and requirements of regulation; this paper explores a pipeline fortification level, which combined investment in the near future with long-term benefits to make sure pipeline structure parameters which is an optimization problem.

1.1 The Determination of Objective Function

This paper uses fortification intensity vector $[I_{dn}]$ of every pipeline that composed gas pipeline network as optimization variable to characterize pipeline fortification level. It takes the minimum sum of gas pipeline network total cost $C_{总}[x(I_d)]$, loss expectation when pipeline network suffered earthquake $L[x(I_d)]$, pipeline network post-earthquake performance failure loss $F[x(I_d),\psi_S]$ as evaluation index[7]. Therefore the objective function is:

$$W_{总}[x(I_d)] = C_{总}[x(I_d)] + L_{总}[x(I_d)] + F[x(I_d),\psi_S] \rightarrow \min \tag{1}$$

In this formula, $W_{总}[x(I_d)]$ is the sum of gas pipeline network system's current total cost and the overall loss under seismic load in the future. $x(I_d)$ is pipeline structure design which based on fortification intensity I_d . ψ_S is seismic reliability of gas pipeline network system connectivity.

(1)The calculation of gas pipeline network system total cost

Gas pipeline network system's total cost is the minimum cost of every pipeline structure, which based on pipeline optimal fortification intensity:

$$C_{总}[x(I_d)] = \sum_{n=1}^{N} C_{\min,n}[x(I_{dn})] \tag{2}$$

Obviously, the total cost of network system increase with the improvement of pipeline fortification intensity I_{dn} .As far as the pipeline under the condition of seven magnitude seism, it can not increase investment, therefore, the total cost of natural gas pipeline can be written as follows form:

$$C_{总}[x(I_d)] = \sum_{n=1}^{N} [1+\omega_1 \times \omega_2^{(I_{dn}-6)}]C_6 \tag{3}$$

In this formula, ω_1、ω_2 are determined by actual investment data of pipeline network project, C_6 is pipe cost when basic seismic intensity is 6.

(2)This is the loss expectation calculation when pipeline suffered multiple failure criteria

According to the standards in reference literature [8], seismic damages of gas pipeline network structure are divided into five levels:

$[B_1, B_2, B_3, B_4, B_5]$=[the basically well-remained, slight destruction, moderate destruction, serious destruction and destroy]

As pipeline fortification intensity is I_d , the failure probability of suffering every level damage B_i is

$$\begin{aligned} P_f[B_1, x(I_d)] &= 1 - P_f[B_1^*, x(I_d)] \\ P_f[B_i, x(I_d)] &= P_f[B_{i-1}^*, x(I_d)] - P_f[B_i^*, x(I_d)] \quad i = 2,3,4 \end{aligned} \tag{4}$$

$$\mathrm{P}_f[B_5, x(I_d)] = P_f[B_4^*, x(I_d)]$$

Where $P_f[B_i, x(I_d)]$—$x(I_d)$ is the failure probability when happened B_i level damage.

$P_f[B_i^*, x(I_d)]$—$x(I_d)$ is the failure probability when happened greater than B_i level damage.

Depends on the research results of seismic risk analysis; given the condition that pipeline passed the site during the design reference period T years and probability densities curve $f_s(S)$ of its probably suffering the maximum earthquake intensity S, we can get out:

$$P_f[B_i^*, x(I_d)] = \int_0^{12} f_s(S) P_f[B_i^*, x(I_d)|S]ds \qquad (5)$$

In this formula, $P_f[B_i^*, x(I_d)|S]$ is conditional probability when seismic intensity is S. According to the principle of the three-level design criteria against earthquake, it can get the curve of conditional failure probability in figure 1. In the following figure: small earthquake intensity $I^{\mathrm{L}} = I_d - 1.55$,large earthquake intensity $I^{\mathrm{U}} \approx I_d + 1$。

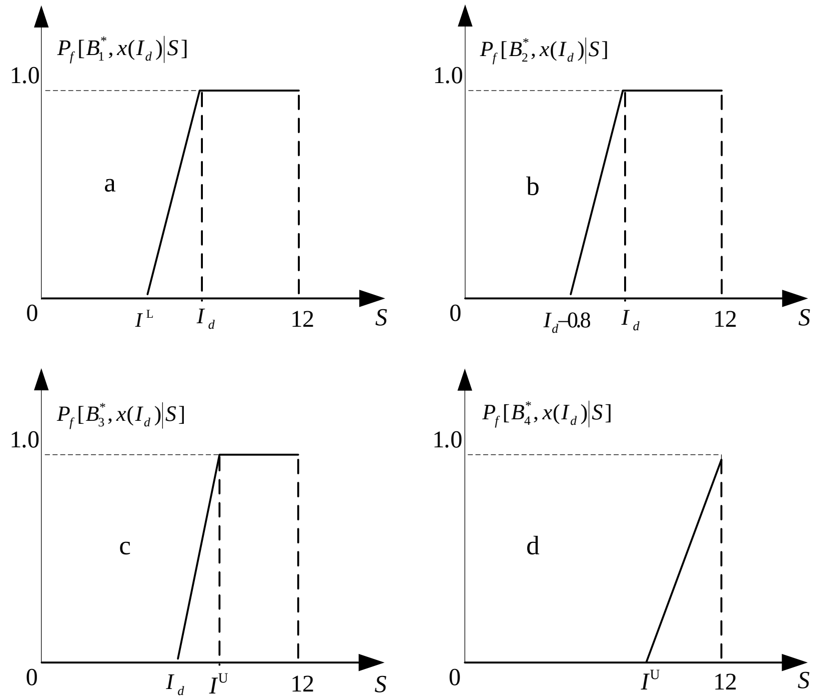

Figure 1 Curve of conditional failure probability

Because there are few records of strong earthquake, the site seismic risk analysis is still a weakness in earthquake engineering. The results of seismic risk analysis and statistics of each area in our country indicate that probability distribution $F_S(s)$ of seismic intensity S accord with the distribution of extreme value III, the probability density function is $f_S(s)$

$$f_S(s)=\frac{k}{\omega-\varepsilon}\cdot\left(\frac{\omega-s}{\omega-\varepsilon}\right)^{k-1}\cdot\exp\left[-\left(\frac{\omega-s}{\omega-\varepsilon}\right)^{k}\right] \tag{6}$$

In this formula, ω is intensity upper limit value, take ω=12; ε is intensity cell value which refers to seismic intensity with probability of exceedance as 63.2% in design reference period of 50 years. k is distribution shape parameter.
From formula (4)、(5)、(6) and figure 1, we can calculate pipeline's failure probability and relevant reliability when pipeline suffered seismic intensity S, under different conditions of I_d and B_i

$$\psi=1-P_f[B_i^*,x(I_d)] \tag{7}$$

As pipeline suffered the B_i level seismic loss, we can calculate from the following formulae

$$D_{ni}=D_{ni}^{(1)}+D_{ni}^{(2)}+D_{ni}^{(3)} \qquad i=2,3,4,5 \tag{8}$$

In this formula, $D_{ni}^{(1)}$ is the direct loss of pipeline's structure damage; $D_{ni}^{(2)}$ is the causality loss which initiated by pipeline's structure damage; $D_{ni}^{(3)}$ is the loss of pipeline network system operation caused by pipeline's structure damage.
Taking I_d as fortification intensity, this paper takes the loss expectation of pipeline's structure design of aseismic design $x(I_{dn})$.

$$L_n[x(I_{dn})]=\sum_{i=2}^{5}P_{fn}[B_i,x(I_{dn})]D_{ni} \tag{9}$$

Total loss expectation of gas pipeline network which corresponds pipeline structure failure:

$$L_{总}[x(I_d)]=\sum_{n=1}^{N}\sum_{i=2}^{5}P_{fn}[B_i,x(I_{dn})]D_{ni} \tag{10}$$

Formula (10) takes multiple failure criterion of seismic code into consideration. The higher of pipeline fortification intensity I_{dn}, the lower of loss expectation.

(3)the calculation of performance failure loss expectation of pipeline network system service
For gas pipeline network system, earthquake not only bring pipeline structure damage by ground motion and geological effect, but also cause disaster consequence of the service function loss and economic loss by services objects' stop production. Gas pipeline network's service function refers to make sure users' needed gas amount and gas pressure in the ordinary work environment . Under the earthquake environment, connectivity failure caused by every source may bring the breakup loss in pipeline network service. In gas pipeline network system, the k point refers to the system loss caused by connectivity failure:

$$D_k=D_k^{(1)}+D_k^{(2)}+D_k^{(3)} \tag{11}$$

In this formula, $D_k^{(1)}$ is the loss of operation benefit caused by gas user k and the breakup of gas source's connection service.

$D_k^{(2)}$ is the industrial, political and economic loss of customers in gas user k which brought by the breakup of gas supply
$D_k^{(3)}$ is the loss of secondary damage runaway in the service of gas user k caused by source to connectivity failure.
$D_k^{(1)}$ can be assessed by operation benefit of gas user k by the following formula:

$$D_k^{(1)} = q_k \times ¥_k \times \tau \tag{12}$$

In this formula, q_k is the gas supply of gas user k under a regular working environment, $10^4 \times Nm^3/d$; $¥_k$ is gas price of gas user k, yuan/Nm^3; τ is the repair time of post-earthquake, d. $D_k^{(2)}$ can be evaluated by the manufacturing, economic state and social influence of customers in gas user k. $D_k^{(3)}$ can be evaluated by occurrence rate of secondary damage, the loss of relieve delay and disaster go out of control when source k caused disconnected. The loss of service function's declining caused by gas connectivity failure between source and gas user or sink of pipeline network system is

$$F[x(I_d),\psi_S^{(k)}] = \sum_{k=1}^{K}\sum_{j=1}^{3}(1-\psi_S^{(k)})[x(I_{dn}),\psi_S]D_k^{(j)} \tag{13}$$

In this formula, $\psi_S^{(k)}$ is the connectivity reliability between gas user k and gas source , K is the total number of gas users. It is one of most effective way of caculating network connectivity reliability by disjoint principle. The basic idea of disjoint principle is changing an assemble of a minimal pathway into disjointed events assemble and logic operation into arithmetic operation. The expression method of pipeline network system logic relation's Boolean cube matrix and operation method of Boolean cube can be found in literature [9,10]. This paper uses multiplication operator ⊗、addition operator ⊕ and disjoint operator ＃ in Boolean cube matrix to achieve Boolean cube matrix （BCM）disjoint algorithm of multi-source and multi-terminal network system. Since the pipeline network topology structure has been established, the more system service function improved, the less fortification intensity (pipeline reliability) loss decreased.

1.2 Constraint condition

(1)Connectivity reliability of pipeline network system is an important synthetically index which depends on each pipeline's reliability (fortification intensity) and pipeline network topological structure and reflects pipeline network's economy and security. Therefore, pipeline network system seismic reliability is needed to improved to a set-point, in this way to control the economic loss at acceptable level

$$\psi_S^{(k)}[x(I_{dn}),\psi_S] \geq \left[\psi_S^{(k)}\right]_0 \quad \text{or} \quad \psi_S \geq [\psi_S]_0 \tag{14}$$

In this formula, $[\psi_S]_0$ and $[\psi_S^{(k)}]_0$ are pipeline network system and the least acceptable anti-seismic connectivity reliability by gas user.

(2)For gas pipeline network large coverage, part of pipelines maybe located in unique geologic environment. Because of their failure probabilities which caused by fault fracture, sand liquefaction, landslip, land collapse are higher than the same pipelines under the relevant intensity and space, the structure scheme design need improve its fortification intensity level to assure the safely operation of gas pipeline:

$$[I_{dn}]^{\mathrm{L}} \le I_{dn} \le [I_{dn}]^{\mathrm{U}} \qquad n \in [1, N] \tag{15}$$

In this formula, $[I_{dn}]^{\mathrm{U}}$ and $[I_{dn}]^{\mathrm{L}}$ are upper limit and lower limit of special pipeline fortification intensity.

(3)Gas amount of gas pipeline network should satisfy balance equation of pipeline network nodal flow rate. The flow rate's algebraic sum of flowing in and out of every node in pipeline network must be 0.

$$\sum_{k \in S_i} a_{kl} Q_{kl} + q_k = 0 \qquad k = 1,2,\cdots, N_P \tag{16}$$

In the formula, Q_{kl} is the flow rate's absolute value by element l which connected with node k flowing in.(out) node k. The flowing in is minus while flowing out is plus. a_{kl} means factor. When the flow rate of element l flowing is -1 and the flowing out is +1 in node k, N_p is the number of pipeline network node.

1.3Gas pipeline network seismic optimal model

According to the above study, optimum allocation model of gas pipeline network system reliability can be established. Obtains optimum fortification intensity vector $[I^*_{dn}] = [I^*_{d1}, I^*_{d2}, \cdots, I^*_{dN}]$,

$$\begin{gathered}\sum_{n=1}^{N} C_{\min,n}[x(I_{dn_i})] + \sum_{n=1}^{N}\sum_{i=2}^{5} P_{fn}[B_i, x(I_{dn})]D_{ni} + \sum_{k=1}^{K}\sum_{j=1}^{3}(1-\psi_S^{(k)})[x(I_{dn}), \psi_n]D_k^{(j)} \to \min \\ \text{s.t.} \quad \psi_S[x(I_{dn}), \psi_n] \ge [\psi_S]_0, [I_{dn}]^{\mathrm{L}} \le I_{dn} \le [I_{dn}]^{\mathrm{U}}, \sum_{k \in S_i} a_{kl}Q_{kl} + q_k = 0\end{gathered} \tag{17}$$

In formula (17)optimization problem can make in ordinary form:

$$\begin{aligned}&\min_{x \in R} f(x) \\ &\text{s.t.} \quad h_n(x) = 0 \quad n = 1,2\cdots, p \\ &g_n(x) \le 0 \quad n = 1,2\cdots, m\end{aligned} \tag{18}$$

2 .GENETIC DIFFERENCE HYBRID ALGORITTHM'S PRINCIPLE AND STEP

Genetic algorithm based on random search algorithm of gene genetics principle. It brings a basic evolutionary principle that survival of the fittest, into bunch structure and also uses selection, intercrossing and variation among bunches to interchange information organically and randomly. The plan that survival of the fittest generates a new individual and makes continuous evolution of the whole race. Difference evolution algorithm is a global optimization method that depends on evolution algorithm foundation. Its principle is generating new individual by weighting vectorial difference of two or more individuals in race then make linear combination with the third individual (for example the best fitness individual) according to certain principle [11].
This research learns the difference evolution basic principle and genetic algorithm basic frame in documents published [11] and fuses the each advantage of two optimization methods to design a hybrid optimization algorithm.

This algorithm uses in resolution of formula （18）. Its main idea is chromosome intercrossing in genetic algorithm and chromosome reproduce strategy in difference evolution algorithm. The fundamental path is figure 2. It adopts real number coding system where fitness function is made by alteration of object function and uses penalty function method treat constraint condition. Concrete form of fitness function is

$$F(x)=\begin{cases} f(x) & if \quad g(x)\le 0 \quad and \quad h(x)=0 \\ f(x)+\alpha(\sum_{n=1}^{m}[\max\{0,g_n(x)\}]+\sum_{n=1}^{p}|h_n(x)|) & \text{else} \end{cases} \tag{19}$$

Where $F(x)$—fitness function；

α—penalty factor.

Progeny chromosomes created through the gene value difference calculation of parent chromosomes

$$u_i^{G+1}=x_t^G+\rho[x_k^G-x_l^G] \tag{20}$$

In this formula, t、k、l are three parent chromosomes by random selection, ρ is a random number among 0~1 to control individual alternation level caused by two variables difference.

In order to increase the race diversification, when we adopts difference evolution operator as
Reproduce device of new chromosome, we make chromosome as assistant operator. Generally speaking, there are 20%～30% chromosomes created by gene intercrossing of parent chromosome.

There is little change for progeny chromosome to randomly select genes in this way to add new genetic information through variation operation. The chance is about 1% which is higher than variation chance of average genetic algorithm 0.01%-0.1% but lower than variation chance of evolutionary algorithm. In order to make sure the optimum result, we should assure the optimum chromosome can't be broken in the variation.

The constringe principle of genetic algorithm can't adopt pre and post time of optimal fully approaching principle, stopping in figure 2 ends algorithm through combined two principles of counting fixed max evolutionary generations, difference sufficiently small among groups.

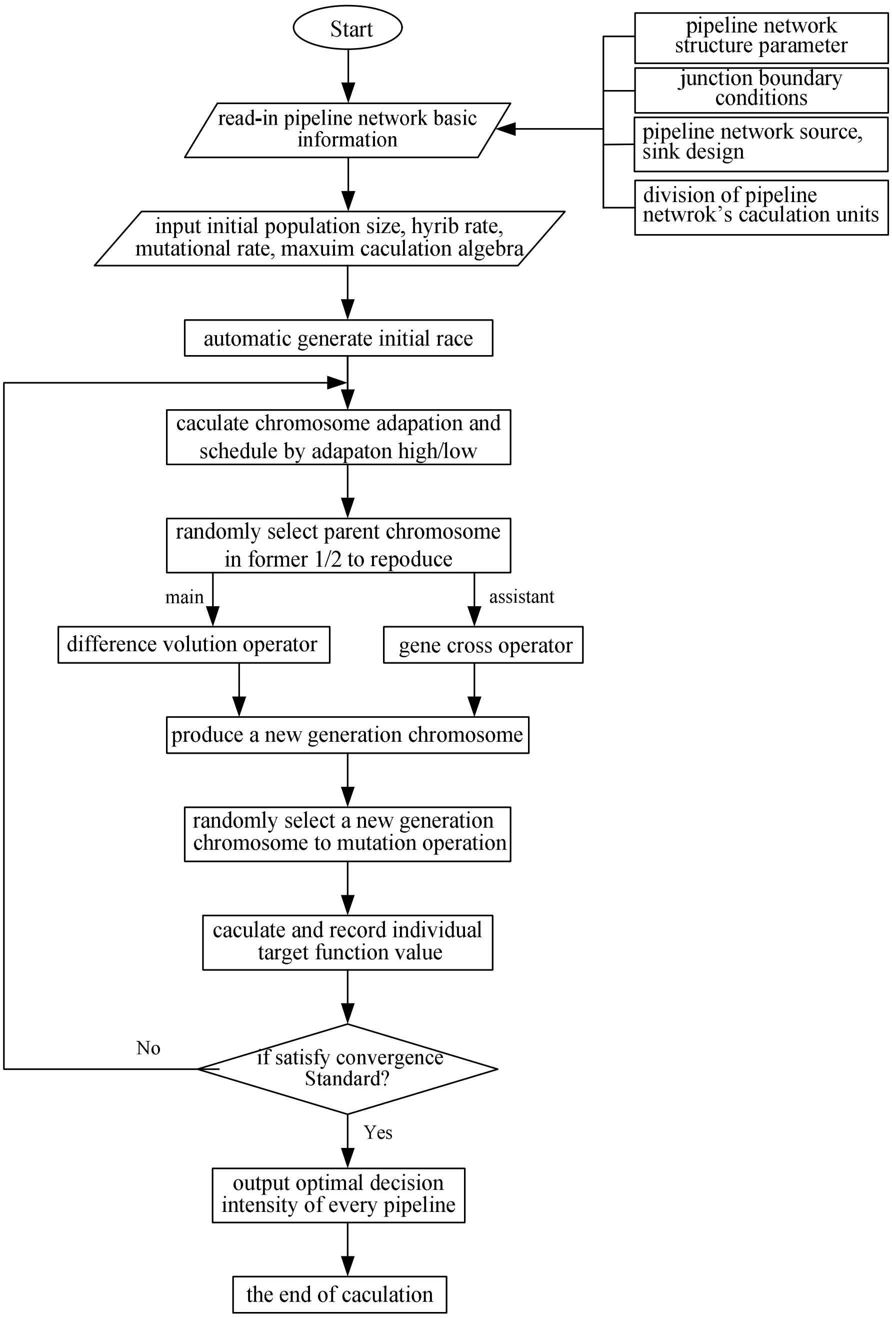

Figure 2 Basic flow of genetic difference mixed algorithm

3. ANALYSIS EXAMPLES

Figure3 is gas gathering pipeline network at some area, the number of nodes is 15, pipe section number is 22. 12, 16 denotes gas gathering station which supply gas the pipeline network respectively. In aseismatic reliability analysis, as two gas sources , the gas collection pressures are 8.3 MPa、7.5Mpa. 5, 15 take the duty of supplying gas to gas power station, long-distance transmission pipeline with gas supply mount are $775\times10^4Nm^3$ /d、$145\times10^4Nm^3$ /d and gas supply prices are $0.5yuan/Nm^3$、$0.8yuan/Nm^3$. Other parameters of pipeline network are ignored. When gas pipeline network suffered earthquake with Ms=7, the post-earthquake repair time is 5 days. As pipeline 19、20 located in sand liquefaction area, fortification intensify level is needed higher than 8. When system connectivity reliability $\psi_s \geq 0.85$, we can determine every pipeline's optimum fortification intensify.

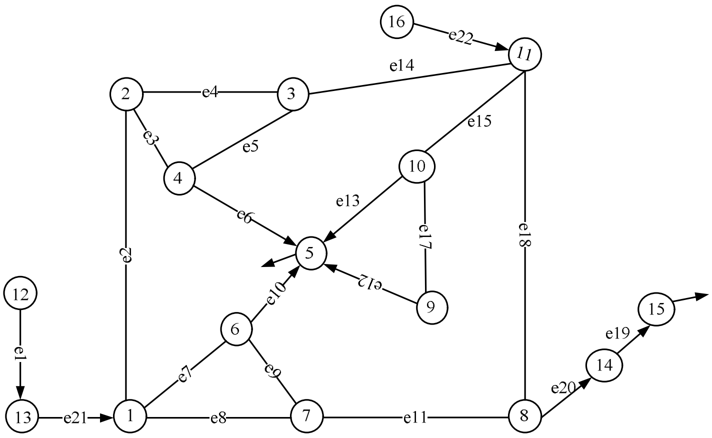

Figure 3 Diagram of gas pipeline network

Table 1 Optimal fortification intensity of pipeline network without constraints of ψ_S

Pipe section	Optimal Fortification intensity	Optimal reliability	Pipe section	optimal fortification intensity	Optimal reliability
e1	6.93	0.93737	e12	6.612	0.90054
e2	6.636	0.90369	e13	6.603	0.89935
e3	6.63	0.90291	e14	6.639	0.90408
e4	6.618	0.90133	e15	6.615	0.90094
e5	6.615	0.90094	e16	6.624	0.90212
e6	6.621	0.90173	e17	6.615	0.90094
e7	6.606	0.89975	e18	6.633	0.90330
e8	6.666	0.90755	e19	8.003	0.98031
e9	6.621	0.90173	e20	8.001	0.98029
e10	6.618	0.90133	e21	6.993	0.94323
e11	6.66	0.90679	e22	6.618	0.90133

W=16103.8million yuan,C=10754.7 million yuan,L= 4925.08 million yuan,

F=423.962 million yuan, $\psi_s = 0.81654$

Table 2 Optimization result of pipeline network without constraints of ψ_S (Million)

Evolutionary algorithm	Pipeline total cost	Loss expectation when pipeline suffered damage	Pipeline network function loss after damage	Total cost and total loss of pipeline network system
Genetic algorithm	10814.8	4915.15	412.82	16142.7
Differential evolution	10764.5	4918.1	420.315	16102.9
Genetic	10746.5	4937.46	419.529	16103.5

Table 3 Optimal fortification intensity of pipeline network system（$[\psi_S]_0 \geqslant 0.85$）

Pipe section	Optimal	Optimal	Pipe section	Optimal	Optimal

	Fortification intensity	reliability		fortification intensity	reliability
e1	7.186	0.95792	e12	6.612	0.90054
e2	6.713	0.91343	e13	6.609	0.90015
e3	6.609	0.90015	e14	6.672	0.90831
e4	6.666	0.90755	e15	6.624	0.90212
e5	6.612	0.90054	e16	6.618	0.90133
e6	6.621	0.90173	e17	6.618	0.90133
e7	6.615	0.90094	e18	6.63	0.90291
e8	6.717	0.91392	e19	8.009	0.98037
e9	6.606	0.89975	e20	8.013	0.98042
e10	6.633	0.90330	e21	7.135	0.95451
e11	6.778	0.92118	e22	6.609	0.90015
W=16153.2million yuan ,C=11068.5 million yuan ,L=4743.31 million yuan , F=341.3393 million yuan, ψ_s =0.85					

From the calculation and analysis of this formula, we can get the following conclusion:

(1)Pipeline optimal fortification intensity is related to its structure importance in pipeline network. The greater of structure importance, the higher of fortification intensify. Under the precondition of confirming the pipeline network topology structure, as system reliability improved, the pipeline fortification intensify correspond added.

(2)When ψ_S in table 3 is more than 0.81654 in table 1, gas pipeline network meets system reliability requirement through raising pipeline network cost, declining loss expectation when pipeline network suffered damage and pipeline network failure loss post-damage.

(3)Table 2 lists calculation results of different optimisation methods. Although genetic algorithm has some special advantages that traditional plan doesn't have during solving the global optimization problems, compared with traditional genetic difference, it has some characters like large group size, easily falling into partial lowest point, poor mountain climbing ability, premature convergence, heavy computation.

4. CONCLUSION

This paper is based on fortification intensify to establish mathematic model of pipeline network seismic cost and related pipeline design parameter, combines with some related seismic factors like geological condition, laying mode in pipeline passed area. It is applied in optimal decision on fortification intensity for natural gas pipeline network, under the constraint of pipeline network system seismic reliability by genetic difference. After solving optimum fortification intensify, it corrects pipeline size and wall thickness of preliminary design to satisfy seismic requirements in the future. Computation result shows embedded difference algorithm and fixed genetic algorithm of reproductive strategy in iterative process have advantages like getting out local minimum point, escaping group evolution stagnation to solve some complex optimization problems like pipeline network.

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