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Comparison study on qualitative and quantitative risk assessment methods for urban natural gas pipeline network

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ABSTRACT

In this paper, a qualitative and a quantitative risk assessment methods for urban natural gas pipeline network are proposed. The qualitative method is comprised of an index system, which includes a causation index, an inherent risk index, a consequence index and their corresponding weights. The quantitative method consists of a probability assessment, a consequences analysis and a risk evaluation. The outcome of the qualitative method is a qualitative risk value, and for quantitative method the outcomes are individual risk and social risk. In comparison with previous research, the qualitative method proposed in this paper is particularly suitable for urban natural gas pipeline network, and the quantitative method takes different consequences of accidents into consideration, such as toxic gas diffusion, jet flame, fire ball combustion and UVCE. Two sample urban natural gas pipeline networks are used to demonstrate these two methods. It is indicated that both of the two methods can be applied to practical application, and the choice of the methods depends on the actual basic data of the gas pipelines and the precision requirements of risk assessment.

1. Introduction

Natural gas is currently one of the most important sources of energy. In the European Union, more than 20% of the total energy consumption is from natural gas [1]. However, the accidents caused by gas pipeline rupture are great threats to urban public safety. Due to the physical and chemical characteristics of natural gas and the complexity of gas pipeline network topology, accidents occurring in gas pipeline are quite different from other industrial accidents. The broken pipelines may cause numerous fatalities and domino effects, and the derived disasters may cause casualties and property losses. In 2004, fourteen people were killed and more than two hundred people were injured due to the explosion of a natural gas factory in Belgium. In Paraguay, a conflagration caused by gas leakage resulted in more than 250 deaths in 2004. In 2009, an explosion caused by gas leakage induced the greatest conflagration in Moscow ever since the Second World War. Thus, it is very important to assess the risk of natural gas pipeline network.

Risk assessment is defined as a mathematical function of the probability and consequence of an accident. The target of risk assessment is to identify potential accidents, analyse the causations and evaluate the effects of the risk reduction measures [2]. The qualitative and quantitative methods are two aspects of risk assessment. The qualitative method assesses risk by using an index system, which is based on the basic data of gas pipeline network. The basic data includes pipeline length, flow rate, population density, external interference, etc. The outcome of the qualitative method is a qualitative risk value. The quantitative method assesses risk by numerical simulation, including a quantitative calculation of possibilities and consequences of different accidents. The numerical simulation is based on the physical and chemical models as well as the physiological dose–effect relationship of human. The outcomes of quantitative method are individual risk and social risk [2].

Recently, more and more authorities start to be aware of the security problems in natural gas transmission pipelines. For qualitative assessment, numerous approaches were proposed including Analytic Hierarchy Process (AHP), Fuzzy logic method (FL), Fault Tree Model (FTM), Event Tree Analysis (ETA) and Data Envelopment Analysis (DEA), etc. [3–8]. However, these approach focus only on identifying the causes of the accidents, and fail to assess the risk. Besides, the Muhlbauer Pipeline Risk Assessment Method is an approach which using an index system to assess the risks of long-distance transmission pipelines outside city. It has been used for more than ten years and works well [9]. But considering the differences of the located environment between long-distance transmission pipeline and urban gas pipeline, this existing approach is not suitable for the risk assessment of urban gas pipeline. For quantitative assessment, many approaches have been applied to analyse and assess the risk of natural gas pipelines [10–16]. However, these methods fail in general analysing the consequences of various accidents, such as the harms of toxicity,

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Nomenclature

$F(t)$	unreliability function, $(10^3 \text{ km year})^{-1}$
i	accident scenario
L	total length of pipelines, m
N	time of pipelines in used, year
n	total number of objects to be evaluated
M	times of the accidents
m	total number of observation data
$R(t)$	reliability function, $(10^3 \text{ km year})^{-1}$
r	failure rate function, year^{-1}
t	time of the pipelines has been used, year
$Y_i(k)$	sequence of data
ω_i	weight of accident scenario index i
$\xi_{ij}(k)$	grey correlation coefficient
ρ	distinguishing coefficient
$\Delta_{ij}(k)$	sequence of deviation of the reference sequence

combustion and explosion. In fact, these accidents have different physical and chemical effects, which cause different harms to people and influence the spatial distributions of individual risk and social risk in different ways.

In this paper, a qualitative and a quantitative risk assessment methods are proposed. The qualitative method is comprised of an index system, which includes many indices and their corresponding weights. The indices are used to describe the factors that influence the probabilities and consequences of gas pipeline accidents, and the weights describe the significance of the corresponding indices. The quantitative method consists of a probability assessment, a consequences analysis and a risk assessment, in which the analysis for the consequences of different accidents is included.

In the second and third sections of this paper, the qualitative method and the quantitative method are presented, respectively. Section 4 demonstrates the applications of these two methods by using a small and a large sample urban natural gas pipeline networks. Conclusions are given in the last section.

2. Qualitative risk assessment method

This section proposes a qualitative risk assessment method which is suitable for urban gas pipeline network. The qualitative method presented here contains an index system, including three first level indices such as a causation index, an inherent risk index and a consequence index. The selection of indices is based on the characteristics of gas pipeline accidents according to the statistical analysis of historical accident data. And the Reliability Engineering Theory and the Grey Correlation Theory are used to calculate the weights of the corresponding indices. Combining the evaluation values of the indices with the corresponding weights, the criterion and standard of risk management can be constituted.

2.1. Index selection

Based on the historical accidents database, especially the statistical analysis on how accidents occurred and how many incidents were induced, the indices can be selected and the weights can be calculated. In this paper, the database of European Gas pipeline Incident data Group (EGIG) is used for the constitution of the qualitative risk assessment index system [17]. This database indicates the characteristics of gas pipeline accidents: firstly, the causations of gas pipeline accidents can be classified into many categories, such as external interference, corrosion, construction defect/material failure, ground movement, other and unknown causes including incorrect operation and maintenance error; secondly, the occurring probabilities of gas pipeline ruptures depend on the basic characteristic parameters of the pipelines, for instance, pipeline diameter, operation pressure, operation flow rate, service life, wall thickness, and depth of cover; besides, the consequences of the accidents rely on the environmental conditions including the pipelines location, population density, economy conditions and so on. So the index system constituted in this paper can be divided into three groups, i.e. an inherent risk index, a causation index and a consequence index. The first two indices are used to describe the probabilities of gas pipeline accidents including inducements and frangibility, while the last index is used to describe the potential losses. Fig. 1 shows the framework of this index system.

2.2. Index classification

The causation index shows how the natural gas pipeline accidents occur. The failure probabilities of the pipelines vary according to different environmental conditions and inducement mechanism. So the second level indices of the causation index include an external interference index, a corrosion index, a material defect index, an operation error index and a ground movement index. The third level indices include a construction digging index, a ground works index, a public works index, a agriculture index, a drainage works index, a pitting index, a galvanic corrosion index, a stress corrosion index, a internal corrosion index, a material failure index, a incorrect operation index, a incorrect operation index, a maintenance error index, a dike break index, a flood index, a landslide index, a river erosion index and a geologic activity index. All of these indices are the factors that may cause pipeline rupture.

The inherent risk index describes the vulnerability of the pipeline, so the failure probabilities of the pipelines are determined by the inherent conditions of operation and installation. The second level indices of the inherent risk index include an operation index and an installation index. The operation index represents the operating conditions of the pipeline such as flow rate and pressure, and the installation index represents the construction conditions of the pipeline such as depth and diameter. So the third level indices include an operation flow rate index, an operation pressure index, a wall thickness index, a pipeline diameter index, a service life index and a depth of cover index. All of these indices are determined by the basic engineering designs of the pipelines.

The consequence index demonstrates the harms and damages of gas pipeline accidents that include casualties and property losses. Accidents occurred in different environments may lead to different degrees of losses. The second level indices of the consequence index include a leakage hazard index and an effect hazard index. The leakage hazard index represents the fatalness of the substance in the transmission pipelines. The effect hazard index represents the potentially devastating losses in the influence area when transmission pipelines rupture. The third level indices include a medium hazard index, an environment hazard index, a population density index, a property distribution index and an other urban lifeline distribution index. These indices reveal the consequences of gas pipeline accidents, such as casualties, property losses and domino effects in the urban lifeline system.

2.3. Weight calculation

The weights of indices indicate the differences in the impact of the inducements to accidents and the potential loss when accidents occur. For the first level indices, the weight of each index is usually set to 1, which means the causation index, the inherent risk index and the consequence index make equal contribution to the total risk. For the second and third level indices, in order to insure

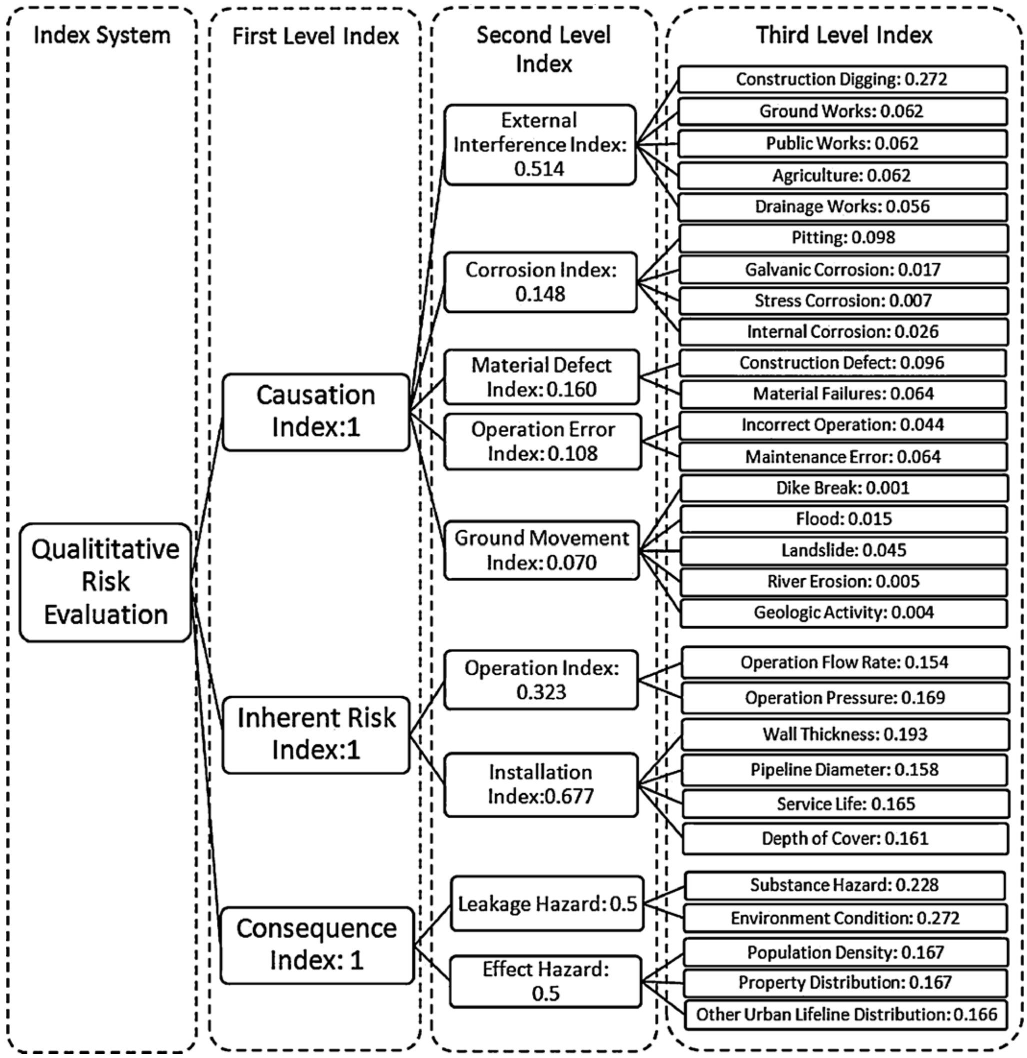

Fig. 1. The framework of qualitative risk assessment index system.

the accuracy and practicability of the index system, the evaluation of weights is based on the real data of gas pipeline network such as operation information, environment information and statistical analysis of historical accident data. And the approaches of weight calculations are the Reliability Engineering Theory and the Grey Correlation Theory.

2.3.1. The weights of the causation index

The weight of the causation index can be calculated by using the Reliability Engineering Theory. Historical records of accidents can be obtained according to the report of EGIG [17], which gives the data on categories and number of accidents during certain time periods. For the natural gas pipelines being used, the unreliability function of pipelines can be estimated in the following equation based on the reliability engineering theory [18,19]:

$$F(t) = 1 - R(t) = 1 - e^{-rt} \tag{1}$$

where $F(t)$ is the unreliability function $(10^3\ \mathrm{km\,year})^{-1}$, $R(t)$ is the reliability function, r is the failure rate function, t is the time of the pipelines has been used. The unreliability of pipelines is also can be expressed as the following equation:

$$F(t) = \frac{M}{N \cdot L} \tag{2}$$

where L is the total length of pipelines, N is the time of pipelines in used, M is the times of the accidents. For the accident scenario i, the failure rate can be expressed as the following equation:

$$r_i(t) = r_i = -\frac{\ln(1 - F_i(t))}{t} = -\frac{\ln(1 - M_i/(N \cdot L))}{t} \tag{3}$$

so the weight of accident scenario index i can be estimated by the following equation:

$$\omega_i = \frac{r_i}{\sum_i r_i} \tag{4}$$

where ω_i is the weight of accident scenario index i.

2.3.2. The weights of the inherent risk and consequence index

For the inherent risk index and consequence index, the information needed for calculating the weights includes the operation flow rate, operation pressure, depth of cover, wall thickness, as well as the population density and economy conditions in the affected area. Usually, it is difficult to obtain the sufficient data [20]. Based on this status, the weights of the inherent risk index and consequence index can be achieved by the Grey Correlation Theory [21–23]. The Grey Correlation Theory aims at finding out the comparability among a mass of dissimilar data. For the risk assessment of urban gas pipeline network, changes of different kinds of basic data

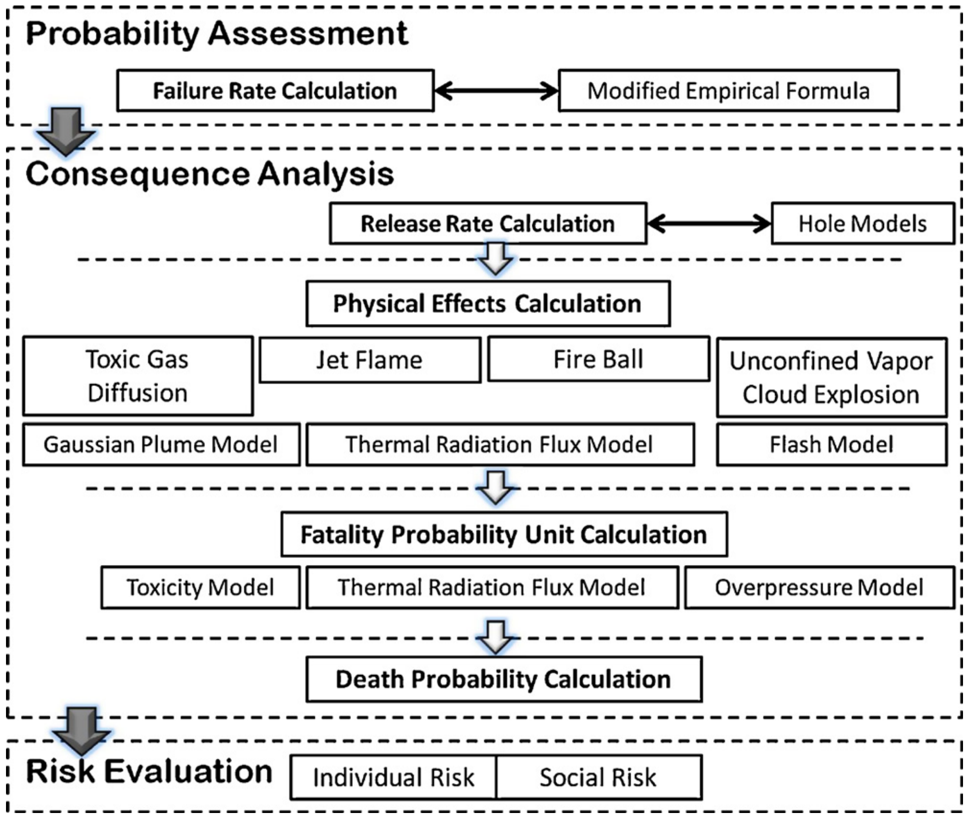

Fig. 2. The framework of quantitative risk assessment method.

influence the evaluation value of risk differently. By using the Grey Correlation Theory, the quantity representing the contribution of each kind of basic data to the total risk value can be evaluated. It is clearly that these quantities of contribution can be used as the weights of the index system in qualitative risk assessment.

The fundamental principle of grey correlation analysis is to determine whether a relationship exists among a series of data based on the degree of similarity among the geometric shapes of the data series' curves. Similar curves indicate a stronger correlation between these series of data. The weights are determined from the grey correlation grades, which measure the degrees of similarity among sequences [22]. According to this method, the actual data depicted as $[X_i(k)]$ for every index of each gas pipeline forms the foundation for the calculation of weights. Then data preprocessing converts the original sequence to a comparable sequence using dimensionless transformation [24]. Usually, each series is normalized by dividing the data in the original series by their average as follows:

$$Y_i = \left(\frac{X_i(1)}{\overline{X_1}}, \quad \frac{X_i(2)}{\overline{X_2}}, \quad \cdots, \quad \frac{X_i(m)}{\overline{X_m}} \right) = (Y_i(1), Y_i(2) \cdots Y_i(k))$$
$$\overline{X_k} = \frac{1}{n}\sum_{i=1}^{n} X_i(k) \tag{5}$$

where $i = 0, 1, 2, \ldots, n$ and $k = 1, 2, \ldots, m$. n is the total number of objects to be evaluated, and m is the total number of observation data, respectively. $Y_i(k)$ is the vector quantities of grey matrix used for the calculation.

After the data have been preprocessed, a grey correlation coefficient is determined by using the preprocessed sequence as follows:

$$\xi_{ij}(k) = \frac{\Delta_{\min} + \rho\Delta_{\max}}{\Delta_{ij}(k) + \rho\Delta_{\max}} \tag{6}$$

where $\xi_{ij}(k)$ is the grey correlation coefficient. ρ is the distinguishing coefficient, $\rho \in (0, 1)$. Generally ρ is taken as 0.5 [21]. $\Delta_{ij}(k)$ is the sequence of deviation of the reference sequence $Y_i(k)$ from the sequence $Y_j(k)$ for comparison. $\Delta_{ij}(k) = \left|Y_i(k) - Y_j(k)\right|$, $\Delta_{\max} = \max\left|Y_i(k) - Y_j(k)\right|$, $\Delta_{\min} = \min\left|Y_i(k) - Y_j(k)\right|$, then the grey correlation grade is an average of the grey correlation coefficients and is defined as:

$$\overline{r_i} = \frac{1}{mn}\sum_{j=1}^{n}\sum_{k=1}^{m}\xi_{ij}(k) \tag{7}$$

and the weights can be calculated by the followed equation:

$$\omega_i = \overline{r_i} / \sum_{i=1}^{n}\overline{r_i} \tag{8}$$

2.4. Risk assessment

According to the actual operation and environment information, the value of each index can be evaluated by comparing with the characteristic parameter of each pipeline and the criterion of risk assessment. Then, based on the index system constituted above, integrating the values of indices and the corresponding weights, the total risk value can be expressed as the following equation:

$$A_t = \sum_{q=1}^{Q} a_{tq}\omega_{tq}$$
$$A = \prod_{t=1}^{T} A_t \tag{9}$$

where A is the total risk value, A_t is the risk value of the first level index t, T is the number of the first level index and in this paper

Table 1
Causation index evaluation for pipeline 1 of small urban natural gas pipeline network.

Third level index	Weights	Characteristic information	Value
Construction digging	0.272	Frequent	7
Ground works	0.062	Extraordinary frequent	10
Public works	0.062	Not frequent	4
Agriculture	0.062	Scarcely	1
Drainage works	0.056	Frequent	7
Pitting	0.098	Corrosion resistant	5
Galvanic corrosion	0.017	Electric potential: −100	5
Stress corrosion	0.007	Pressure drop: 1.728 kPa	10
Internal corrosion	0.026	Without H_2S	1
Construction defect	0.096	Duration of service: 20 year	10
Material failures	0.064	Pipeline length: 113.44 m	4
Incorrect operation	0.044	Possible	5
Maintenance error	0.064	Possible	5
Dike break	0.001	None	0
Flood	0.015	None	0
Landslide	0.045	None	0
River erosion	0.005	None	0
Geologic activity	0.004	None	0
Risk value	5.662		

Table 2
Inherent risk index evaluation for pipeline 1 of small urban natural gas pipeline network.

Third level index	Weights	Characteristic information	Value
Operation flow rate	0.154	10.05 kg/s	0.99
Operation pressure	0.169	9 kPa	10
Wall thickness	0.193	2.2 cm	2.34
Pipeline diameter	0.158	100 cm	2.50
Service life	0.165	20 year	10
Depth of cover	0.161	0.4 m	2.35
Risk value	4.687		

Table 3
Consequence index evaluation for pipeline 1 of small urban natural gas pipeline network.

Third level index	Weights	Characteristic information	Value
Substance hazard	0.228	Comparative denseness	7
Environment condition	0.272	Windy	7
Population density	0.167	Extraordinary denseness	10
Property distribution	0.167	Extraordinary denseness	10
Other urban lifeline distribution	0.166	Extraordinary denseness	10
Risk value	8.500		

Table 4
Quantitative risk evaluation for pipeline 1 of small urban natural gas pipeline network.

Characteristic information			Risk assessment process	
Pipeline diameter	100 mm	$\varphi_d = 7.5 \times 10^{-5}$	Failure rate	3.25×10^{-3}
Depth of cover	0.4 m	2.54	Death probability percentage	0.000307
Wall thickness	2.2 mm	1	Fatality probability unit	2.67
Population density	Town	18.77	Release rate	1.005 kg/s
Prevention method	All methods	0.91	Radius with the individual risk of 10^{-6}	10.6323 m

$T = 3$, a_{tq} is the risk value of the third level index q, ω_{tq} is the weight of index q, Q is the number of the third level index in the first level index t.

3. Quantitative risk assessment method

This section proposes an integrated quantitative risk assessment method, in which the analysis of the consequences of various accidents such as toxicity diffusion, combustion and explosion are combined. This method consists of a probability assessment, a consequence analysis and a risk evaluation [25]. Fig. 2 shows the framework of this method.

3.1. Probability assessment

Probability assessment focuses on the probabilities of accidents, which depend on the failure assumption caused by different inducements [11]. The failure probability of a pipeline varies significantly with design factors, construction conditions, maintenance techniques and environmental conditions, etc. Based on the statistical analysis of historical accidents database, the failure rate of the pipeline for each accident scenario can be estimated by the modified empirical formula [10]:

$$\varphi = \sum_k \varphi_k K_k(a_1, a_2, \ldots) \tag{10}$$

Table 5
Results of the qualitative risk assessment method of small urban natural gas pipeline.

No.	Assessment value	No.	Assessment value	No.	Assessment value	No.	Assessment value
1	225.595	25	235.917	49	279.551	73	211.023
2	329.475	26	249.565	50	276.210	74	220.366
3	314.020	27	237.143	51	272.260	75	225.385
4	278.211	28	242.839	52	278.160	76	226.105
5	218.592	29	227.692	53	235.388	77	221.078
6	265.223	30	253.106	54	253.030	78	260.217
7	262.255	31	232.865	55	257.359	79	325.824
8	225.768	32	236.718	56	227.888	80	314.809
9	213.086	33	251.192	57	231.606	81	346.996
10	255.115	34	229.434	58	265.274	82	263.566
11	220.641	35	236.161	59	227.697	83	244.560
12	186.962	36	286.050	60	262.682	84	251.789
13	220.626	37	242.483	61	204.902	85	266.587
14	204.705	38	256.828	62	245.141	86	244.347
15	217.197	39	281.543	63	205.712	87	269.541
16	233.622	40	244.401	64	248.102	88	357.036
17	235.529	41	222.636	65	266.891	89	400.915
18	268.330	42	259.059	66	254.952	90	406.621
19	244.904	43	226.183	67	318.454	91	353.450
20	273.987	44	252.848	68	322.634	92	359.966
21	287.005	45	220.806	69	213.691	93	402.884
22	270.875	46	227.126	70	227.027	94	242.891
23	286.284	47	252.982	71	210.961	95	270.611
24	278.108	48	254.612	72	219.882		

Table 6
Results of the quantitative risk assessment method (individual risk) of small urban natural gas pipeline network.

No.	Radius with individual risk of 10^{-6}	No.	Radius with individual risk of 10^{-6}	No.	Radius with individual risk of 10^{-6}	No.	Radius with individual risk of 10^{-6}
1	10.63	25	14.41	49	5.49	73	10.40
2	34.86	26	12.15	50	4.40	74	10.40
3	34.82	27	12.17	51	4.40	75	2.37
4	10.54	28	12.15	52	12.04	76	11.97
5	10.58	29	12.15	53	2.97	77	11.97
6	10.58	30	9.42	54	2.97	78	2.04
7	10.58	31	9.42	55	2.96	79	34.62
8	3.06	32	9.42	56	11.02	80	34.56
9	3.06	33	3.06	57	7.24	81	34.56
10	3.06	34	9.43	58	4.40	82	2.35
11	10.59	35	4.48	59	5.49	83	2.35
12	6.53	36	4.40	60	5.49	84	2.93
13	6.53	37	7.89	61	8.08	85	2.93
14	6.53	38	7.89	62	5.58	86	2.93
15	6.53	39	5.49	63	5.58	87	2.93
16	8.08	40	5.49	64	2.98	88	32.64
17	8.08	41	7.24	65	4.37	89	32.64
18	5.58	42	4.40	66	10.55	90	34.39
19	5.58	43	5.49	67	34.82	91	30.88
20	5.58	44	5.49	68	34.82	92	32.64
21	14.39	45	7.24	69	2.67	93	32.64
22	14.35	46	7.24	70	13.36	94	2.97
23	14.35	47	7.24	71	13.36	95	2.95
24	14.39	48	7.24	72	2.07		

where φ is the expected failure rate per unit pipeline length (1/year·km), φ_k is the basic failure rate per unit length of pipeline (1/year·km), K_k is the correction function associated with the failure causes, $a_1, a_2, \ldots$ are the variables of the correction function, and the subscript k denotes the failure causes such as external interference, construction defects, corrosion, ground movement and others.

3.2. Consequence analysis

Consequence analysis focuses on the physical effects of the accidents that are harmful to human beings, including toxic gas diffusion, jet flame, fire ball combustion and UVCE (unconfined vapour cloud explosion), etc. The consequence analysis in this paper is composed of a gas release rate calculation, a physics effects calculation, a fatality probability unit calculation and a casualty percentage calculation [27].

Since the damages of gas such as toxicity, heat and pressure depend on the amount of leakage, the gas release rate should be calculated firstly. The calculation approach of gas release rate adopted in this paper is the Hole Model, which has been widely used in the literatures as a general computational method of quantitative risk analysis [28].

After the gas release rate is obtained, the harms of the accidents are analysed. All the physical effects of the aforementioned physical processes have quantitative descriptions. If the gas leakage does not catch fire, the harm of leakage is related to the toxicity of gas and the concentration distribution around the region where

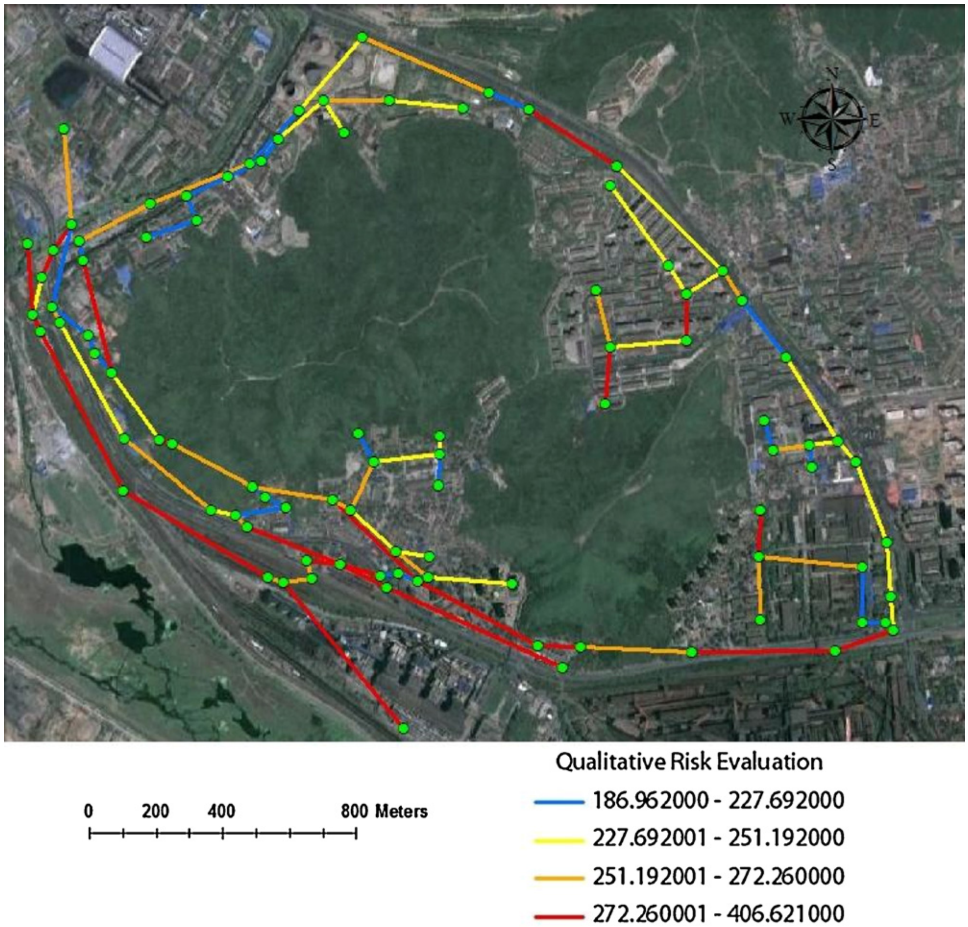

Fig. 3. Results of the qualitative risk assessment method for small urban natural gas pipeline network.

the pipeline ruptures [30–32]. If the gas leakage catches fire at the leakage source, the fire becomes diffusion flame (i.e., jet flame) and poses a threat to people near the leakage source. The risk of jet flame can be quantitatively determined by measuring the thermal radiation flux [33]. If the gas leakage catches fire after it forms a persistent vapour cloud but not intensively mixing with air, a fire ball ensues. The thermal radiation flux of fire ball combustion can be conservatively estimated according to the corresponding fire ball combustion model [34]. If the gas leakage catches fire after it intensively mixes with air and forms a persistent vapour cloud, it will lead to a significant flash fire or unconfined vapour cloud explosion. For the convenience of calculation, the feasible approach for the calculation of explosion overpressure is the modified flash model according to TNT equivalent weight method [32]. The recorded data provided by the API indicated that the probabilities of the accidents after the pipeline ruptures are 0.8 for toxic gas diffusion, 0.1 for jet flame combustion, 0.06 for fire ball combustion and 0.04 for UVCE [29].

To quantitatively describe the level of damages, the fatality probability unit is defined as a mathematical function based on the physiological dose–effect relationship between the dose of harms such as toxicity, heat or pressure and the effects of the recipient such as deaths or injuries. The fatality probability unit of thermal radiation can be calculated according to the damage referring to the third degree burns [35,36]. The fatality probability unit of explosion overpressure can be calculated according to the damage referring to the lung haemorrhage [37]. Then, using the fatality probability unit, the death probability percentage can be obtained by looking up the corresponding table [36].

3.3. Risk evaluation

The results of quantitative risk assessment take the forms of individual risk and social risk [2,26], which quantitatively describe the death probability and critical level. The spatial distribution of individual risk can be calculated by integrating the failure rate, the probability of each accident scenario and the spatial distribution of death probability for the pipeline [10–12]. Social risk can be calculated by integrating the spatial distribution of death probability and population density within the hazard area [2,10,37]. Social risk can be shown in FN-curve [2,25].

4. Applications and comparison

To validate the proposed methods, a small sample urban natural gas pipeline network containing 95 pipelines and a large sample urban natural gas pipeline network containing 5421 pipelines are presented for demonstration. In order to assess the risk using the proposed quantitative risk assessment method, the initial accident hypothesis is assumed that the failure in one pipeline causes an orifice with one-third of the pipeline diameter. For the regional urban gas pipeline network, the experimental conditions can be assumed as following: (1) the recommended values of the exposure time for people referred to overpressure and thermal radiation is 30 s [36]. (2) The toxicity of the gas can be omitted due to a regional urban gas pipeline network carrying nontoxic gas.

For the qualitative risk assessment method, firstly, the index system must be constituted based on the operation information, the environment information and the statistical analysis of histori-

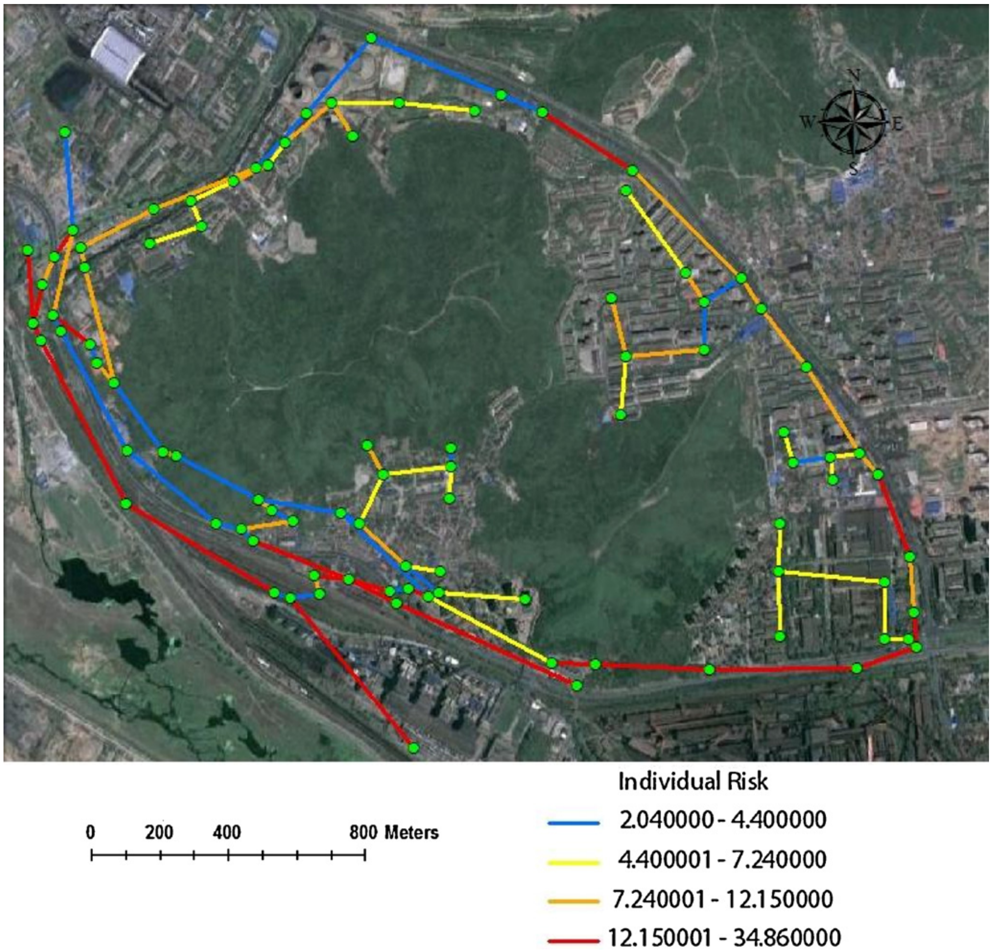

Fig. 4. Results of the quantitative risk assessment method (individual risk) for small urban natural gas pipeline network.

cal accident data. Then the value of each index can be evaluated according to the actual operation, the environment information and the criterion. The result of qualitative risk assessment method can be given by evaluating each index, respectively and integrating the corresponding weight according to Eq. (9). For the quantitative method, the result is given by evaluating the probability and consequence as discussed in Section 3. Detailed process of calculation can be found in Ref. [25].

In this paper, the results of qualitative risk assessment method are compared to those of the quantitative method to validate the feasibility and practicability of these two methods. Since the individual risk of 10^{-6} has been set as a guideline for the boundary between the broadly acceptable and the tolerable regions for the public, the radius with individual risk of 10^{-6} is used as the presented result of the quantitative assessment method in this paper.

4.1. Application in small sample urban gas pipeline network

A small sample urban natural gas pipeline network used here is a part of a whole network in a city, which includes 95 pipelines. For the qualitative risk assessment method, the index system is constructed as shown in Fig. 1.

Based on the methods proposed above, the risk value can be assessed. Taking pipeline 1 as an example. For the qualitative method, the characteristic information and the evaluation value of each index is shown in Tables 1–3, including the causation index, the inherent risk index and the consequence index, respectively. For the quantitative method, the characteristic information and the evaluation process are shown in Table 4. According to the characteristic information, the failure rate can be calculated as 3.25×10^{-3}. So the death probability percentage of the location where the individual risk is 10^{-6} should be $10^{-6}/(3.25 \times 10^{-3}) = 0.000307$. By looking up the corresponding table, the fatality probability unit can be obtained, which is 2.67. The release rate can be calculated as 1.005 kg/s. Then, based on the physical models of jet flame, fire ball combustion and UVCE, the radius with the individual risk of 10^{-6} can be calculated as 10.6323 m.

The results of risk assessment are shown in Tables 5 and 6 and displayed by geographic information system as shown in Figs. 3 and 4. Table 5 shows the results of the qualitative risk assessment method. It is indicated that the average risk value for all of the 95 pipelines is 258.718, and there are 37 pipelines with risk value higher than the average value. Table 6 gives the radius with the individual risk of 10^{-6} as the result of the quantitative assessment method. It is evident that longer radius means higher risk. The average value for all of the 95 pipelines is 10.82 m, and there are 28 pipelines with risk value higher than the average value. Figs. 3 and 4 illustrate the results of qualitative and quantitative risk assessment methods for the small urban natural gas pipeline network, respectively. In these illustrations, the risk values are equally divided into four levels that are depicted by the color of red, orange, yellow and blue. It can be seen that the pipelines of each level of risk in Fig. 3 are almost the same as those in Fig. 4, especially for the levels colored in red and blue.

The analysis result indicates that both the qualitative and quantitative risk assessment methods can be applied to risk assessment

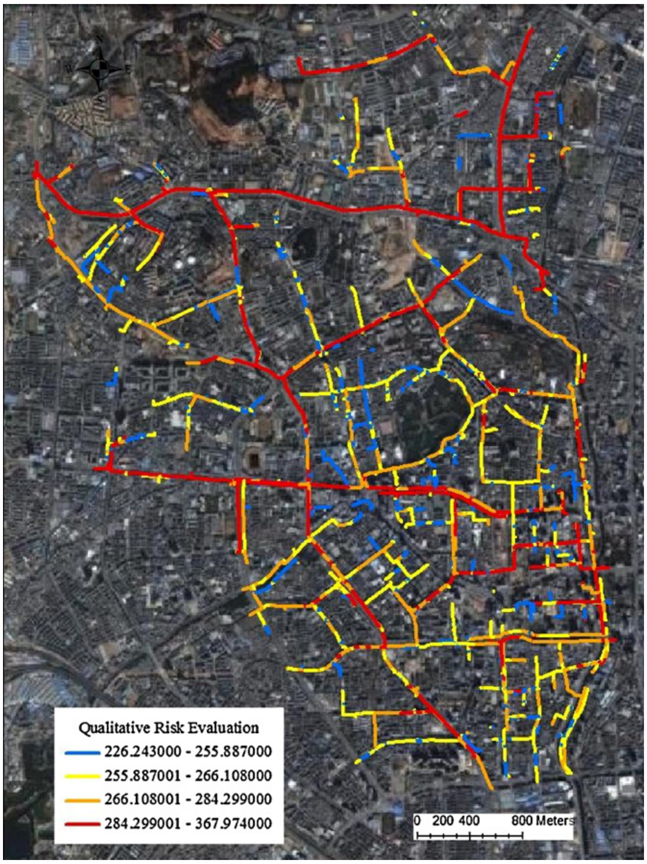

Fig. 5. Results of the qualitative risk assessment method for large urban natural gas pipeline network.

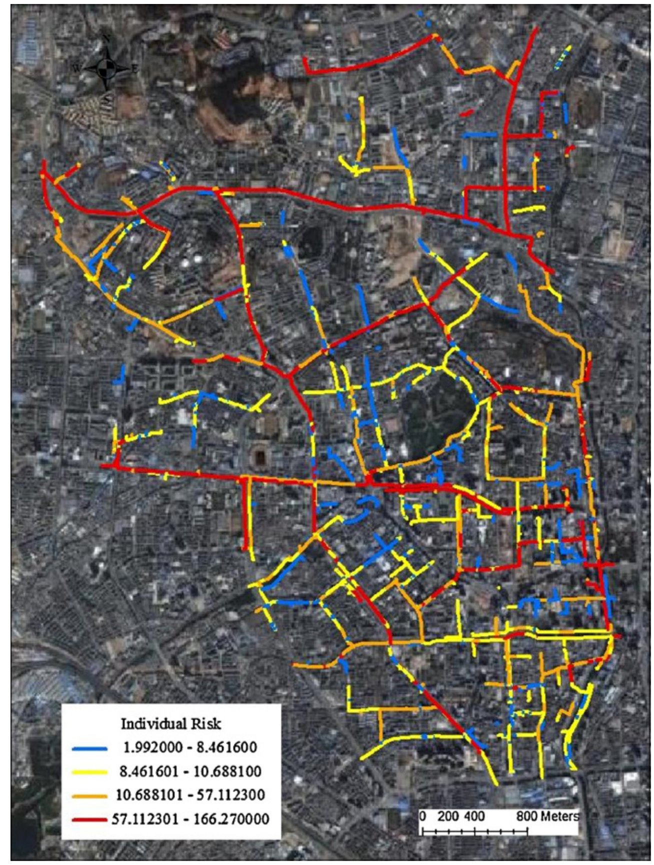

Fig. 6. Results of the quantitative risk assessment method (individual risk) for large urban natural gas pipeline network.

of real small urban natural gas pipeline network, and the evaluation results of the qualitative and quantitative risk assessment methods are similar. For risk management, the pipelines with risk value higher than the average value should be stressed to carry out risk reduction measures.

4.2. Application in large sample urban gas pipeline network

A large sample urban natural gas pipeline network used here is a main part of a whole network in a city, which includes 5421 pipelines. The results of risk assessment are displayed by geographic information system as shown in Figs. 5 and 6. Fig. 5 shows the result of the qualitative risk assessment method. It is indicated that the average risk value for all of the 5421 pipelines is 271.965, and there are 2065 pipelines with risk value higher than the average value. Fig. 6 is the result of the quantitative risk assessment method, i.e. the radius with individual risk of 10^{-6}. It is indicated that the average value for all of the 5421 pipelines is 33.01 m, and there are 1526 pipelines with risk value higher than the average value. Like Figs. 3 and 4, it also can be seen that the pipelines of each level of risk in Fig. 5 are almost the same as those in Fig. 6. The analysis result indicated that both qualitative and quantitative risk assessment methods can be applied to risk assessment of real large urban natural gas pipeline network.

In general, the qualitative risk assessment method is more effective and intuitive than the quantitative method. Comparing with the quantitative method, the qualitative method takes more failure causations into consideration, but it also needs much more basic data. For the quantitative method, it integrates more details of induced accident consequences. So the analysis result of the quantitative method is more accurate, but it takes more time in calculating the risk value. The evaluation results of these two methods for the applications in two sample urban gas pipeline networks are similar. It is indicated that these two methods are feasible and scientific, and can be used in practical application. It is clear that the choice of the methods depends on actual basic data and precision requirements of the risk assessment according to the methods described above.

5. Conclusions

In this paper, a qualitative and a quantitative risk assessment methods for urban natural gas pipeline network are proposed. For the qualitative method, the selection of the indices is based on the statistical analysis of accidents database, and the calculation of corresponding weights is according to the Reliability Engineering Theory and the Grey Correlation Theory. For the quantitative risk assessment method, the possibilities and consequences of different accidents are analysed and integrated. Two sample urban natural gas pipeline networks are chosen to validate the presented methods. The risk assessment results of these two methods are similar. It is indicated that these two methods can be used in practical application for risk assessment of urban natural gas pipeline network, and the choice of the methods depends on actual basic data and the precision requirements of the risk assessment.

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