A novel method of quantitative risk assessment based on grid difference of pipeline sections

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ABSTRACT

The growing demand of the urban natural gas pipeline makes the security problem of in-use pipelines attract more and more concern. Risk assessment and management for urban natural gas pipeline network is the effective way to guarantee its safety running. This paper focuses on a method for quantitative risk assessment for urban natural gas pipeline network based on grid difference of pipeline sections (GDPSs), introduces the city gas pipeline network model, defines the pipeline fatal length and analyzes gas network accident probability and accident consequence of unconfined vapor cloud explosion (UVCE), fire ball combustion, jet flame. The outcome of the quantitative method is the risk contour line and then can get corresponding protective area according to risk acceptable criteria. Finally, the proposed method is applied to an urban pipe network. It is proved that is suitable for the urban natural gas pipeline network and can provide decision support for risk management of urban natural gas pipeline network.

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1. Introduction

Natural gas pipeline network is an important part of a city's infrastructure for energy transmission. With the development of modern cities, natural gas has currently become one of the most widely used sources of energy. At present, the consumption of natural gas is more than 20% for the total energy in the European Union (Montiel et al., 1996). In China, there are 246 prefecture cities having gas pipeline facilities and the length of natural gas pipeline has reached 6.35×10^4 km by the year of 2004. However, with the gas pipeline network becoming vaster and more complex, accident caused by the leak of gas pipeline network occur. Accident consequences caused by gas pipeline rupture are often fire and explosion, directly threatening the safety of persons and property (Mercedes et al., 2008). In 2006, ten people were killed and injured due to the explosion caused by gas pipeline rupture in Sichuan province; In Paraguay, a conflagration resulted in more than 250 deaths in 2004, caused by gas leakage. In Moscow, an explosion caused by gas leakage induced the greatest conflagration in 2009 ever since the Second World War (Han and Weng, 2011). On March 15, 2010, a natural gas explosion resulting from the road construction of the Huangpu Road in Wuhan damaged the main natural gas pipelines, set nearby residents' houses on fire, and interrupted natural gas supply to 4000 households. On June 8, 2010, a natural gas pipeline explosion in Lipscomb County, a small town in Northern Texas on the border with Oklahoma, caused two deaths and three heavy injuries. Thus, it is clear that the risk assessment of natural gas pipeline network is very important.

Generally, risk is defined as a mathematical function of the probability of a pipeline failure occurring and the magnitude of death. Risk management control the probability of risk, casualties, property loss, economic loss and environment damage at acceptable level according to the reference data of gas pipeline network. Recently, the quantitative risk assessment has become one of the important approaches for risk management of gas pipeline network (Han and Weng, 2010). Generally, the outcomes of quantitative method are individual risk and social risk (Jonkman et al., 2003), which is the main work in this paper. Generally, the numerical simulation method is used for assessing the risk, including a quantitative calculation of possibilities and consequences of different accidents, which is based on the physical and chemical models as well as the physiological dose–effect relationship of human (Mark et al., 1998; Jonkman et al., 2003).

As for gas pipeline quantitative risk assessment, numerous researchers have been done by academics from home and abroad (Arnaldos et al., 1998; Joel and Duncan, 2003; Muhlbauer, 2004; Metropolo and Brown, 2004; Jo and Ahn, 2005; Sklavounos and Rigas, 2006; Xu et al., 2008; Jo and Crowl, 2008; Liu and Liu, 2009; Jaffee et al., 2009). However, many researches mainly used the quantitative risk assessment method of long-distance transmission pipeline to analyze the urban gas pipeline network. The located environment between the long-distance transmission pipeline

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and urban gas pipeline is quite different. Moreover, urban gas pipeline network is more complex than long-distance transmission pipeline, which is comprised of dendritic pipeline network and looped pipeline network. Consequently, a limitation can be observed regarding the existing method for the quantitative risk assessment of urban gas pipeline network (Han and Weng, 2011). In addition, basic data, corrosion monitoring and inspection data have been paid more attention for assessing the risk value by quantitative method, and the location and multi-segments impacts factors are ignored (Xing et al., 2009; Jing et al., 2009; Xiang et al., 2011; Zhang et al., 2011). However, the location and multi-segments impacts factors should be brought to the forefront, due to complexity and very high density of the urban pipelines. Considering the pipeline fatal length, gas network accident probability and accident consequence, an integrated approach for dynamic safety assessment and prognosis needed to be improved (Hu et al., 2010).

In this paper, a novel method of quantitative risk assessment based on grid difference of pipeline sections (GDPSs) is proposed for urban natural gas pipeline network, to assess the risk of gas pipeline network. Combining gas pipeline failure probability with the consequences of various accident impacts, this method can calculate risk value for specific position (x, y) under the influence of pipeline sections, to simulate the risk distribution. In the second section of this paper, urban gas pipeline network model is presented. The quantitative method is presented in Section 3. In Section 4, a sample urban gas pipeline network is applied to demonstrate the method. Conclusions are given in the last section.

2. Methodology

Risk can be expressed in different ways: individual risk, social risk, maximum individual risk, average individual risk of total population, average rate of death. Generally, individual risk (IR) and social risk (SR) are used to describe risk (Liu and Liu, 2009). The former usually uses risk contour line to show risk while the latter is presented with frequency–number (F–N) curve (TNO, 1999). Individual risk can be evaluated by synthesizing possibility assessment and consequence analysis and mainly involves casualty, which is defined as the probability of death at any particular position without protection. Social risk is defined as the relationship between the frequency of an incident and the number of casualties (John et al., 2001). In the following section, individual risk and social risk for urban gas pipeline will be analyzed in detail.

2.1. Urban gas pipeline network model

From the standpoint of the map projection, the structure of urban gas pipeline network characteristically has the features of point and line. To traverse pipeline sections which have an influence on the risk of special position (x, y), it is reasonable to use the graph theory method to analyze the risk impact (Ying and Zhang, 2006). Gas pipeline network can be defined as the network in graph theory, and Gas pipelines can be defined as edges in network, and pressure-regulator boxes and values can be defined as junctions in network. From the standpoint of data structure, gas pipeline is abstractly comprised of nodes and arcs. After the topology is created, the relationship between nodes and arcs, nodes and nodes, arcs and arcs can be got, to generate the geometric network for gas pipelines network. Relationship between nodes and arcs can be conveyed by adjacency list (see Table 1).

Relationship between nodes and arcs, nodes and nodes, arcs and arcs for gas pipeline network model is represented as follows:

Storage structure in adjacency list as follows:

```
Struct ArcNode
{
    int AdjVertex; // Edge point to the vertex positions
    Arc ArcInfo; //Information of the edge
    ArcNode *NextArc;} //Point to Next edge
Struct VNode{
    Vertex VertexInfo; //Information of the node
    ArcNode *FirstArc; //Point to first attached edge
}
Storage structure of pipeline information as follows:
    Struct PipelineEdge
    {
        int nId; //Pipeline ID
        int nNode1;
    int nNode2; //Ends of pipeline ID
        double nLength;//Length of pipeline
    }
Facilities information (values, pressure-regulator boxes,
    Source, Sink, etc.) as follows:
    Struct PipelineNode
    {
    int nId; // Facilities nodes ID
    string nType; // Facilities nodes style
    Ipoint xy; //Geographic coordinates
    }
```

2.2. Quantitative risk assessment model

Individual risk is calculated by multiplying the probability of pipeline failure occurring by the magnitude of death at any particular position (x, y). As for urban gas pipeline network, failure position is unknown and failure rate may vary along the pipeline. Moreover, risk is influenced by more than one sections of pipeline due to the complexity of the urban gas pipeline network. It can be estimated by integrating the probability of pipeline failure multiplied by the magnitude of death at any particular position from different accident scenarios. It can be expressed as the following equation (Jo and Ahn, 2005):

$$IR(x, y) = \sum_i \sum_{Consequence} \int_{l_-}^{l_+} \phi_i P_i(x, y) dL \tag{1}$$

where the subscript i denotes the accident scenarios, (x, y) the specified location of individual risk value, ϕ_i the failure rate per unit length of the pipeline associated with the accident scenario i, L the pipeline length, P_i the lethality associated with the accident scenario i and $l_{\pm}$ represents the ends of the interacting section of the pipeline in which an accident pose hazard to the specified location (see Fig. 1).

By assuming a constant failure rate to simplify calculation of individual risk, the individual risk can be written as the following equation:

$$IR(x, y) = \sum_i \phi_i \sum_{Consequence} \int_{l_-}^{l_+} P_i(x, y) dL \tag{2}$$

Table 1
The relations of nodes-edge.

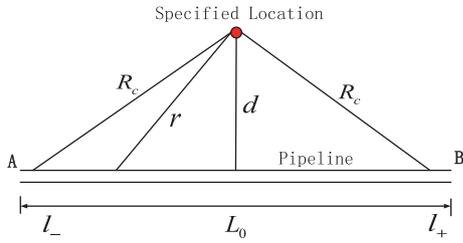| Vertex	AdjArc
V1	L1,L2,L4
…	…
Vn	Li, Lj, Lk

Fig. 1. Individual risk geometric model. It shows the relation of variables (Jo and Ahn, 2005).
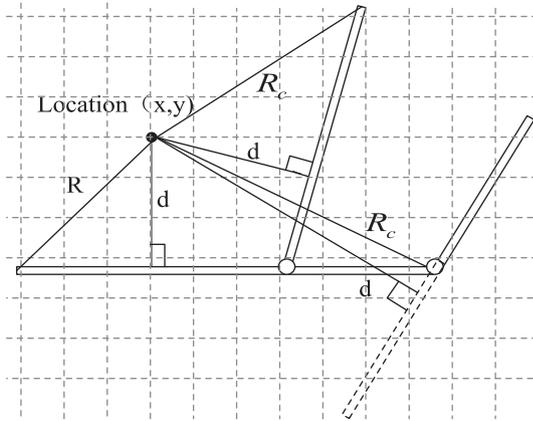

Fig. 2. Geometric model of individual risk impacted by multi-sections.

By defining fatal length as the integrate value of the probability of death in Eq. (2), that means a weighted length of pipeline within which an accident has a fatal effect on a person at a specified location. Then, the individual risk can be estimated simply with the following equation:

$$IR(x,y) = \sum_i \phi_i \sum_{Consequence} L_{FL,i} \tag{3}$$

where $L_{FL,i}$ is the fatal length associated with accident scenario i. A simpler method for estimating the fatal length will be discussed later (see Section 2.4.6).

According to geometric characteristics of urban gas pipeline network, pipeline sections can be searched by using GIS related algorithm, which have had influence on risk calculation at particular location (x, y). The total individual risk is estimated by stacking each individual risk produced by each pipeline section. Specific points is created by dividing the area of urban gas pipeline network into grids (see Fig. 2.) and the risk of any point is estimated by interpolation of specific points.

$$IR(x,y) = \sum_{s=1}^N \sum_i \phi_i \sum_{Consequence} L_{FL,i} \tag{4}$$

where N is the number of pipeline sections, which generate risk impact on target point.

Structured Grid is defined as that each node in network has the same number of adjacent points, which is easy to realize and convenient for interpolation processing. The area of urban gas pipeline network is divided into uniform spacing girds by using Structured Grid, which covers the area of the assessment pipeline in Cartesian coordinate system. Risk at each grid point is calculated produced by each pipeline section. The total individual risk at grid point is estimated by adding each individual risk produced by each pipeline section. The risk of any point is estimated by interpolation of grid points. And the approaches of interpolation are the Kriging or Inverse Distance Weighted (IDW). Risk contour line at different risk level is obtained by connecting each point with the same risk value in the area of urban gas pipeline network.

2.3. Pipeline failure rate

The pipeline failure rate refers to the unit of the number of failures per year and per unit length of the pipeline because of the rupture induced by external influence or inner risk. For pipeline failure assessment, numerous approaches are proposed including Analytic Hierarchy Process (AHP), Fault Tree Model, Event Tree Analysis and modified empirical formula based on historical data, etc. However, the calculation of above methods is complex and is not accurate enough except modified empirical formula based on historical data. The failure rate of the pipeline for each accident scenario can be estimated by using empirical formula based on historical data. The failure rate caused by third party activity depends on several factors, such as pipe diameter, depth of cover, population density and prevention methods, which can be obtained easily by using the information of urban gas pipeline network of geographic information systems (GISs). HSE recommends a method to calculate the failure rate caused by external interference (John et al., 2001), it could be expressed as following equation:

$$P_{i,EI} = P_{i,EI,D} Q_E F K_{dc} K_t K_\rho K_p \tag{5}$$

where i is the assumed failure type, is generally categorized as one of the following: small hole, medium hole, and great hole. F is the correction factors for age pipe. $P_{i,EI,D}$ is the failure rate varying with pipe diameter due to external interference. K_{dc}, K_t, K_ρ, K_p are the correction factors of depth of cover, wall thickness, population density and prevention method, respectively. Q_E is the correction factor related welding line of the pipeline, which can be estimated by following equation.

$$Q_E = A \times N \times 1.75 \tag{6}$$

where A is welding vulnerability coefficient (usually 0.5), N is the account of pipeline welded in all of pipeline network.

The total failure rate is calculated by adding each failure rate from other causes, such as construction defects, corrosion, ground movement and unknown causes, which is estimated by using EGIG data (2008). The total failure rate is given by:

$$P_{i,EI} = P_{i,EI,D} + P_{i,CD} + P_{i,C} + P_{i,GM} + P_{i,OR} \tag{7}$$

where $P_{i,CD}$, $P_{i,C}$, $P_{i,GM}$, $P_{i,OR}$ respectively depict construction defect, corrosion, ground movement and unknown causes contribute the value to the risk.

2.4. Consequence analysis

Urban gas pipeline network is generally comprised of low pressure pipeline and high pressure pipeline. Once a pipeline leak, it may cause catastrophic fire and explosion, which cause great damage to the human being and building, due to the gas characteristics of inflammable and explosive and high-density of urban area. Failure consequence of pipeline concentrates on the physical effects of the accidents including toxic gas diffusion, jet flame, fire ball, and UVCE (unconfined vapor cloud explosion). According to the historical data by API (1990, 2001), the probability of each kind of accidents is 0.8, 0.1, 0.006 and 0.004 when the pipeline ruptured (Sklavounos and Rigas, 2006). However, for the urban gas pipeline network, leakage gas is generally natural gas. Methane is the main components of natural gas, which accounts for more than 90%. And the toxic of methane can be ignored (Han and Weng, 2010). Here, we mainly discuss the physics effects of the fireball, fire, unconfined vapor cloud explosion (UVCE). Consequence analysis of fire and explosion is based

on the release rate and mass of the leakage. Combined with the lower burning limit of natural gas, diffusion area can be estimated by using Gauss diffusion model. And fuel mass can be obtained, which is contribute to the explosion and fire.

2.4.1. Gas release rate

The process of leakage is a isentropic adiabatic expansion process and the release rate can be calculated by leakage model for different failure style, including small hole model, pipe model and approximate fitting algorithm, etc. For risk assessment, the small hole model have been widely used as an engineering calculation method to fit the need of pipeline quantitative risk analysis, and it is discussed in the paper to compute to gas release rate. The value of the release rate at the orifice depends on whether gas flow is sonic or subsonic. This will be decided by relationship between $\frac{P_0}{P_1}$ and $\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$ (Dong et al., 2003).

When $\frac{P_0}{P_1} \leqslant \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$, gas flows sonically in the pipeline. Therefore, according to the continuity equation of gas flow, gas release rate can be calculated by:

$$Q = C_0 A P_1 \sqrt{\frac{kM}{RT}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \tag{8}$$

When $\frac{P_0}{P_1} > \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$, gas flows subsonic in the pipeline. Therefore, according to the continuity equation of gas flow, gas release rate can be calculated by:

$$Q = C_0 A P_1 \sqrt{\frac{2M}{RT}\left(\frac{k}{k-1}\right)\left[\left(\frac{P_0}{P_1}\right)^{\frac{2}{k}} - \left(\frac{P_0}{P_1}\right)^{\frac{k+1}{k}}\right]} \tag{9}$$

where Q is the gas release rate in kg/s, A is the area of the leakage opening in m², M is the molecular weight of gas in kg/mol (usually 0.016 kg/mol), R is the gas constant (8.314 J/mol K), T is the temperature of the gas inside the pipeline in K, k is the adiabatic index or the ratio of the isobaric specific heat capacity to the isovolumetric specific heat capacity (1.28 for natural gas), P_0 is the environmental pressure in Pa, and P_1 is the pressure inside the gas pipeline in Pa.

The gas release rate from a hole of the pipeline varies with time. In order to engineering calculation the effective gas release rate can be estimated by using decay factor, which is refers to is the ratio of the effective gas release rate and peak gas release rate. The decay factor λ varies from 0.2 to 0.5 and a conservative value of 0.3 is adopted here for calculation. The effective gas release rate is given for the risk analysis by (Stephen, 2000; Jo and Ahn, 2005):

$$Q_{effect} = 2\lambda Q_{Peak} \tag{10}$$

where λ is the decay factor. Q_{effect} is effective rate of gas release from a hole in kg/s. Q_{Peak} peak initial rate of gas release from a hole in kg/s.

2.4.2. Leakage mass

The concentration of the hazardous material for diffusion section is gauss distribution in homogeneous turbulence. And the dispersion for hazardous materials can be describe by Gauss Dispersion model, which is simple, established early and widely used in the research of atmospheric pollution. With the release for the natural gas pipeline taken into account, the height of the dispersion source can be estimated as 0. So according to Gauss Dispersion model, where coordinates origin is assumed as the leak source, X axis is assumed as the downwind direction of the average wind speed and Y axis is assumed as the crosswind direction, the dispersion concentration can be calculated by the following equation:

$$C(x, y, z) = \frac{Q}{\pi\mu\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}\right)\right] \tag{11}$$
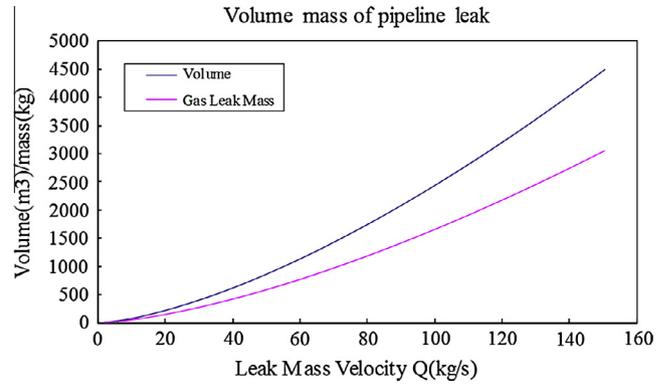

Fig. 3. The relationship between volume mass of pipeline leak and leak mass velocity (Dong et al., 2003).

where $C(x, y, z)$ is the density in kg/m³; Q is the mass flow rate of leakage in kg/s; μ is the average wind speed in m/s; and σ_x, σ_y, and σ_z are the diffusivities of the tailwind, crosswind, and vertical wind respectively in m and are calculated according to the level of atmospheric stability.

As the natural gas is flammable, the shape of the LEL (lower explosive limit) contour can is calculated, which will act as the size of the burning cloud and the explosive mass by computer programming. The explosive mass is then transferred to the explosion model to calculate the overpressures (see Fig. 3).

2.4.3. Thermal radiation of jet fire

A Jet fire is formed by the immediate ignition of a high-velocity release of a gas in the case of pipeline rupture and poses a threat to the people near the leakage. For risk analysis, a jet flame is generally composed of a series of point source along the flame. The risk of the jet flame can be judged by the measure of the thermal radiation. Therefore, the heat flux at a certain distance forming the leakage source can be calculated as the following equation:

$$I = \frac{\eta\Delta H_c Q\tau}{4\pi R^2} \tag{12}$$

where I is the thermal radiation flux in W/m² at the specific position, η is the ratio of radiation heat to the heat released by the fire (0.2 for methane), τ is the atmospheric transmissivity (value = 1) (Han and Weng, 2009), ΔH_c is the combustion heat of natural gas in J/kg, and R is the distance between the target and the center of the flame zone.

2.4.4. Thermal radiation of fire ball

A fireball would result from immediate ignition of a release resulting from the gas leak accident. A fire ball occurs in case of delayed ignition of releases of natural gas when the leakage of gas forms a persistent vapor but is not intensive with air. The diameter of the fire ball can be estimated as the following equation:

$$R_f = 2.665M^{0.327} \tag{13}$$

where R_f is maximum radius of fire ball, M is inflammable goods mass. The relationship between the time and fuel mass can be described by the following equation:

$$t_f = 1.089M^{0.327} \tag{14}$$

where M is inflammable goods mass. The equation to calculate thermal radiation flux at a specific position is as follows: The heat

radiation with distance from the fireball can be calculated as the following equation (Stephens, 2000):

$$I = \frac{F_r \Delta H_c m \tau}{4\pi R^2 t_f} \tag{15}$$

where I is the thermal radiation flux in W/m² at the specific position, F_r indicates the percentage of radiation for flammable gas (normally 90%), τ is the atmospheric transmissivity (value = 1), ΔH_c is the combustion heat of natural gas in J/kg, m is the mass of the gas combustible gas cloud in kg, and R is the distance between the target and the center of the flame zone.

2.4.5. Explosion overpressure

In case of a confined flammable vapor cloud intensively mixing with air, upon ignition a vapor cloud explosion may occur. Overpressures caused by the explosion can be calculated with the vapor cloud explosion model (multi energy method), based on the explosive mass in the flammable vapor cloud calculated with the dispersion model. For convenience of calculation, TNT equivalent weight method is adopted to calculate the explosion overpressure, which compares the explosion of TNT with that of gas vapor cloud. TNT absorptivity is defined as gas cloud volume percentage participating in explosion. Generally, there is no more than 10% of the vapor cloud occurring explosion. And TNT absorptivity is assumed as 10%. Therefore, 10% of the vapor cloud is addressed to analyze the consequence for risk assessment. The explosion energy of flammable vapor cloud can be expressed as the following equation:

$$E_{EX} = 1.8 \alpha_{TNT} m_d \Delta H_d \tag{16}$$

where E_{EX} is total energy of explosion, α_{TNT} is equivalent coefficient of combustible gas vapor (usually 4%), m_d is the mass of the gas involved in the explosion in kg, and ΔH_d is the explosion heat of the gas in J/kg (usually 5.002×10^7 J/kg). The overpressure at certain distance is given as below (Xu et al., 2008):

$$\Delta P = P_0 \left(0.137 \left(R \left(\frac{P_0}{E_{ex}} \right)^{\frac{1}{3}} \right)^{-3} + 3.99 \left(R \left(\frac{P_0}{E_{ex}} \right)^{\frac{1}{3}} \right)^{-2} + 12.6 \left(R \left(\frac{P_0}{E_{ex}} \right)^{\frac{1}{3}} \right)^{-1} \right) \tag{17}$$

where ΔP is incident overpressure of the explosive wave in Pa, R is the distance between some point in the explosion field and the source of the explosion in m, and P_0 is the environmental pressure in Pa.

2.4.6. Lethality calculation

The dose–effect of the consequences for people can be expressed by the probability unit. A probit (probability unit) function relates the doses of such harmful load as pressure, heat or toxicity to the proportion of affected people.

$$P_r = a + b \ln D \tag{18}$$

where a and b are empirical constants that reflect the hazard specifics of a harmful load studied and the susceptibility of recipients to the load, and D is the dose of the load for a given exposure time.

For the exposure to heat radiation, the vulnerability model (probit function) is given by (TNO, 1989):

$$P_r = -14.9 + 2.56 \ln \left(\frac{t I^{\frac{4}{3}}}{10^4} \right) \tag{19}$$

where I is the thermal radiation flux, and t is the time of the target exposed to the thermal radiation. Generally, the exposure time in urban is assumed to be maximum 30 s.

As for probit function of jet fire radiation, replacing I by Eqs. (12) and (19) is converted to (Han and Weng, 2010):

$$P_r = 16.61 + 3.4 \ln \left(\frac{Q}{R^2} \right) \tag{20}$$

where Q is the mass flow rate of leakage in kg/s, R is the distance between the target and the center of the flame zone in m.

For the probit function of fire ball radiation, the expression of fire ball probit function can be obtained by substituting Eqs. (14), (15) into (19).

$$P_r = 12.74 + 2.56 \ln \left(m^{1.224} \times R^{\frac{8}{3}} \right) \tag{21}$$

where m is the mass of the gas combustible gas cloud, and R is the distance between the target and the center of the flame zone.

For the exposure to explosion in the case of a vapor cloud explosion, the vulnerability model (probit function) is given as follows (Cui et al., 2008):

$$P_r = -77.1 + 6.9 \ln P \tag{22}$$

where P is the overpressure of explosive shock wave in Pa.

The probit value P_r varies between 2 and 9 (HSE, 2010). To convert the probit value to a percentage of mortality, the equation below is used:

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{P_r - 5} e^{-\frac{s^2}{2}} ds \tag{23}$$

For the consequence calculations, 100% lethality, 50% lethality and 1% lethality are assumed within the explosion overpressure and heat radiation dose. The pipeline fatal length is defined as the pipeline length weighted by the corresponding average value of lethality in the zones, 1–50%, 50–99%, 99–100% lethal. The radius of fatality 99%, 50% and 1% for pipeline failure consequence are calculated simply from Eqs. (20)–(22), by using the probability unit, 7.33, 5 and 2.67.

Therefore, the radius for jet fire can be estimated as the following equation:

$$r_{jet,99} = 3.891\sqrt{Q}, \quad r_{jet,50} = 5.498\sqrt{Q}, \quad r_{jet,1} = 7.767\sqrt{Q} \tag{24}$$

where Q is the mass flow rate of leakage in kg/s. The radius for fire ball can be estimated as the following equation:

$$\frac{(r_{Fireball,99})^{\frac{4}{3}}}{m^{1.106}} = 2.855, \quad \frac{(r_{Fireball,50})^{\frac{4}{3}}}{m^{1.106}} = 4.518, \quad \frac{(r_{Fireball,1})^{\frac{4}{3}}}{m^{1.106}} = 7.149 \tag{25}$$

where is the mass of the gas combustible gas cloud in kg. The radius for explosion can be estimated as the following equation:

$$\frac{r_{explosion,99}}{\sqrt[3]{m_{TNT}}} = 2.718, \quad \frac{r_{explosion,50}}{\sqrt[3]{m_{TNT}}} = 2.861, \quad \frac{r_{explosion,1}}{\sqrt[3]{m_{TNT}}} = 3.017 \tag{26}$$

where $m_{TNT} = \frac{m_d \Delta H_d}{Q_{TNT}}$ is the TNT equivalent in kg. The length in each zone can be estimated by using individual risk geometric model.

$$l_{i,100-99} = 2\sqrt{(r_{i,99})^2 - h^2}, \quad l_{i,99-50} = 2\sqrt{(r_{i,50})^2 - h^2}, \quad l_{i,50-1} = 2\sqrt{(r_{i,1})^2 - h^2} \tag{27}$$

where the subscript i denotes the small, medium and great hole on the pipeline.

The average fatalities of those three zones for all consequences are given, respectively.

$$\frac{\int_0^{3.891} P dr}{\int_0^{3.891} dr} = 1, \quad \frac{\int_{3.891}^{5.498} P dr}{\int_{3.891}^{5.498} dr} = 0.805, \quad \frac{\int_{5.498}^{7.767} P dr}{\int_{5.498}^{7.767} dr} = 0.172 \tag{28}$$

Average fatalities for jet fire are shown from Fig. 4.
Average fatalities for fire ball are shown from Fig. 5.
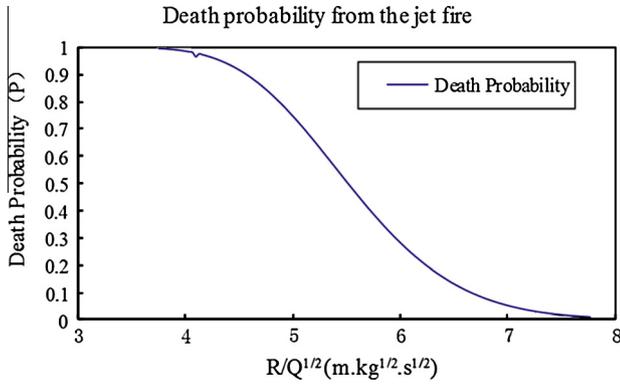Average fatalities for explosion are shown from Fig. 6.

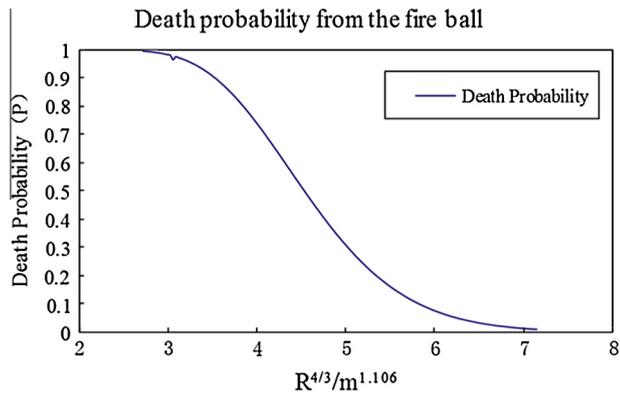Fig. 4. Death probability from the jet fire.

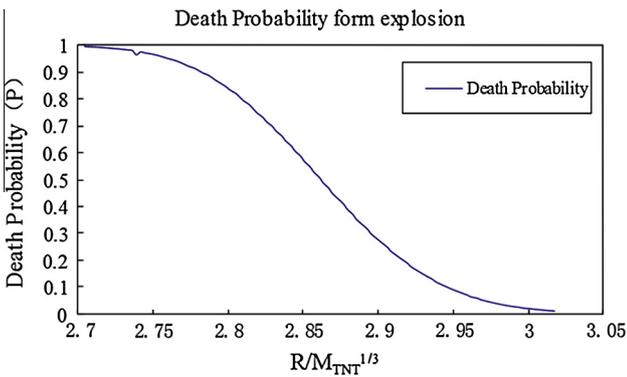Fig. 5. Death probability from the fire ball.

Fig. 6. Death probability from explosion.

Therefore, the fatal length for all consequences can be calculated from the length of pipeline within each zone as the following equation:

$$L_{FL,jet} = \int_0^L P_{jet}(x,y)dL$$
$$\approx l_{jet,100-99} + 0.805 l_{jet,99-50} + 0.172 l_{jet,50-1} \qquad (29)$$

$$L_{FL,fireball} = \int_0^L P_{fireball}(x,y)dL$$
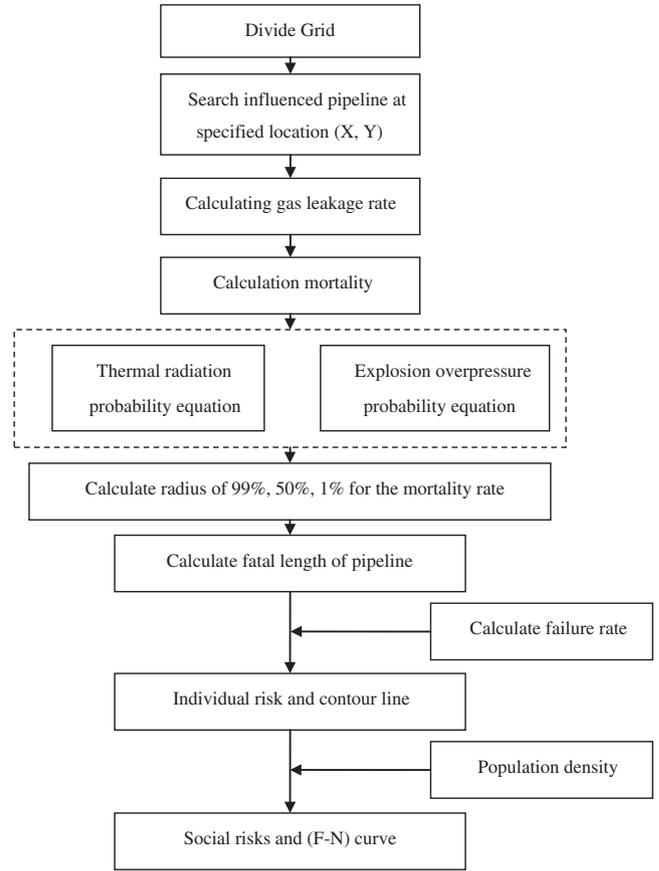$$\approx l_{fireball,100-99} + 0.831 l_{fireball,99-50} + 0.161 l_{fireball,50-1} \qquad (30)$$

Fig. 7. Procedure to calculate the risk of natural gas pipeline for quantitative risk assessment.

$$L_{FL,exposion} = \int_0^L P_{exposion}(x,y)dL$$
$$\approx l_{jet,100-99} + 0.828 l_{exposion,99-50} + 0.168 l_{exposion,50-1} \qquad (31)$$

where $L_{FL,jet}$ is fatal length of jet fire, $L_{FL,fireball}$ is fatal length of fire ball, and $L_{FL,exposion}$ is fatal length of explosion.

Individual risk under multiple pipeline section can be estimated by adding the fatal length multiplied with corresponding values of weight for consequences.

$$IR(x,y) = \sum_{s=1}^N w_i \sum_{Consequence} P_{EI} L_{FL,i} \qquad (32)$$

where w_i is values of weight for consequences, which can be approximated by historical data provided by the EGIG (2008).

$$w_i = u_i / \sum u_i \qquad (33)$$

where u_i is the probability associated with accident scenario i.

Therefore, social risk at certain location can be estimated by multiplying the average population density with the individual risk and the procedures of individual risk and social risk evaluation are shown in Fig. 7.

3. Results and discussion

To validate the proposed methods in the above sections, a sample urban natural gas pipeline network operating at 0.1 Mpa, temperature at 288 K is presented for demonstration. For risk analysis, the experimental condition is assumed as following: the failure of pipeline causes an orifice with the pipeline diameter. The local

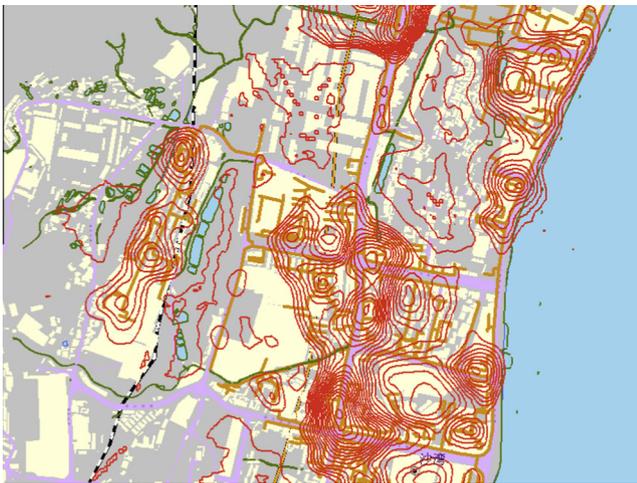**Fig. 8.** Construct grid of natural gas pipeline map.

Fig. 9. Risk contour line map.

average wind speed is 5 m/s. A plane model geometry grid as shown in Fig. 8 is generated to accurately model the distribution of risk through areas of interest. The generation of these grid models requires the use of ArcGIS' internal pre-processor or external CAD software. According to our test experience, here we set grid cell size as 25 m for the selected sample urban natural gas pipeline network, to construct grid as shown in Fig. 8.

Based on the calculation procedure (see Fig. 7), individual risk value of each grid cell point can be calculated. Then risk contour line at different risk level is obtained by connecting each point with the same risk value within the area of urban gas pipeline network as shown in Fig. 9. And it can be seen that many risk contour lines with the individual risk above 10^{-5} (Si et al., 2012) cross the research area and is not acceptable due to the density and old age of the pipeline network. In addition, in the risk contour line map, it is easy to distinguish the area of high risk from low risk, because the density of the pipe line network is higher, and the risk contour line is denser, for example, the risk contour line in center city is more than one in the suburb of city (see Fig. 9). Obviously, the value of risk contour line associated with the pipeline network density is reasonable, and the further application can be expected for manager.

Although this study presented a number of practical applications, a number of limitations need to be addressed. First, because

of the cross-sectional nature of the study, we cannot provide predictive validity evidence for the safety pipeline risk measure. Second, the study uses data from only county-level city for validation of the measure, and the data rely on self-report, which may result in artificially inflated correlations among variables. Third, here we only choose the scale according to the experience, what may be only suitable to the sample data. Regardless of this issue, to reduce possible bias in this study, future research may include what scale should be chose, and how to choose the suitable scale automatically.

4. Conclusions

In this paper, a method for quantitative risk assessment for urban natural gas pipeline network base on grid difference of pipeline sections (GDPSs) is proposed. The structure of the pipeline network, the failure probability and the consequence of accidents are analyzed. The total individual risk at special point is estimated by adding each individual risk produced by each pipeline section. A sample urban gas pipeline network is adopted to demonstrate the presented method. The results indicated that the method can be used in practical application. It may be useful for risk management during the planning, modification and building stages of pipeline and can provide basic theory and technology for risk assessment.

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