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Quantitative risk analysis of urban natural gas pipeline networks using geographical information systems

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ABSTRACT

This paper presents a novel quantitative risk analysis process for urban natural gas pipeline networks using geographical information systems (GIS). The process incorporates an assessment of failure rates of integrated pipeline networks, a quantitative analysis model of accident consequences, and assessments of individual and societal risks. Firstly, the failure rates of the pipeline network are calculated using empirical formulas influenced by parameters such as external interference, corrosion, construction defects, and ground movements. Secondly, the impacts of accidents due to gas leakage, diffusion, fires, and explosions are analyzed by calculating the area influenced by poisoning, burns, and deaths. Lastly, based on the previous analyses, individual risks and social risks are calculated. The application of GIS technology helps strengthen the quantitative risk analysis (QRA) model and allows construction of a QRA system for urban gas pipeline networks that can aid pipeline management staff in demarcating high risk areas requiring more frequent inspections.

1. Introduction

The unprecedented increase in urbanization, especially in large cities, has led to a growing demand for natural gas, thus giving rise to a dense urban natural gas pipeline network. This translates into a corresponding increase in potential safety hazards and risks. In the event of an accident, the concentration of urban population and the dense distribution of buildings are likely to complicate the evacuation of residents, and thus, result in great loss of life and property. In recent years, numerous natural gas accidents have occurred at home and other countries. On April 20, 2004, natural gas leakage led to an explosion in Naxi District, Luzhou City of Sichuan Province in China, causing 5 deaths and 35 grievous injuries. On January 20, 2006, the explosion of natural gas pipelines and the subsequent large fires in the Renshou Fujia Gas Transmission Station of the Transmission Department of Southwest Oil and Gas Branch caused 10 deaths, 3 grievous injuries, and 47 minor injuries. On April 6, 2007, Shenyang City of Liaoning province also witnessed a large power failure on account of natural gas leakage and subsequent fires, which impacted production and the life of local residents. 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. Clearly, prevention is better than cure. Therefore, in order to prevent accidents and reduce damages resulting from such accidents to the extent possible, it is necessary to propose a systematic quantitative risk analysis assessment framework for natural gas pipeline networks. Such a framework would help predict regions where natural gas accidents are likely to occur and those that are likely to be influenced by natural gas leakage and diffusion, so that potential accidents can be nipped in bud, and where needed, rescues can be performed immediately Tables 1–4.

Risk is generally defined as a measure of human death in terms of two quantities: the probability of a pipeline failure occurring and the magnitude of death that arises as a result (Jo & Ahn, 2005). Risk analysis has already been extensively applied to safety science, environmental science, economics, sociology, and so on. It aims at uncovering the probability of potential accidents and analyzing the causes as well as the improvements needed to reduce the risk. It is also important to realize that decision-making regarding risk does not concern technical aspects alone; rather, political, psychological, and societal processes all have a role to play (Han & Weng, 2010).

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Table 1
Correction factors for third party damages (Jo & Ahn, 2005).

Correction factors	Correction value	Conditions
Minimum cover depth	2.54	$D_c < 0.91$m
	0.78	0.91m $\leq D_c \leq$ 1.22m
	0.54	$D_c >$ 1.22m
Wall thickness	1	$t = t_{\min}$ or $d > 0.9$m
	0.4	6.4 mm < t ≤ 7.9 mm and 0.15m < d ≤ 0.45m
	0.2	$t > t_{\min}$
Population density	18.77	Urban areas
	3.16	Suburbs
	0.81	Rural areas
Precautionary measures	1.03	Warning signs only
	0.91	All other measures

Therefore, it is significant to clearly identify the risk and analyze the effects of possible risk reduction measures through a quantitative risk analysis (QRA) (Jonkman, Gelder, & Vrijling, 2003).

For quantitative risk analysis in the natural gas industry, most researchers tend to use software such as Matlab, GAMBIT, and FLUENT to conduct safety simulation research. Progress in geographical information systems (GIS) has kept pace with the rapid developments in information technology. Apart from the traditional numerical simulation methods, safety management technologies also include GIS monitoring technology, where methodological land computer-based support has been provided to personnel responsible for disaster emergency management (Si, Ji, & Zeng, 2012). Thus, it is worthwhile to study how a combination of GIS technology and urban gas pipeline network risk assessment models may be effectively applied to urban natural gas pipeline safety and management (Cozzani et al., 2006). This study integrates a considerable number of research results to summarize a number of advanced quantitative risk analysis models (e.g., leakage and diffusion of poisonous materials, jet fire and explosion model, etc.) and then uses these results in tandem with GIS. Based on ArcEngine and C# programming techniques, a complete risk analysis system for natural gas pipeline networks is designed, thus enabling a quantitative risk analysis of urban natural gas pipelines in the GIS environment, and bringing new thinking to safety management of urban gas pipelines.

2. Related work

Researchers around the world have studied and proposed various GIS applications in safety analysis. For example, risk analyses based on numerical modeling and GIS have been conducted for sewer systems (Mark, Wennberg, Wennberg, Rabbi, & Albinsson, 1998). A GIS platform has been interfaced to software developed for the quantitative assessment of the domino effect (Cozzani et al., 2006). In 2008, China Safety Science Research Institute of Dangerous Chemicals Safety Institute of Technology (2008) developed the CASST-QRA assessment software (Version 1.0) for major dangerous regions. Castanedo et al. (2009) performed a GIS-based assessment of an offshore oil spill, while Ba (2009) proposed an ArcEngine-based emergency response system for sudden air pollution accidents, which simulated the diffusion of poisonous gases by using Visual Basic 6.0 and ArcEngine platforms. Meanwhile, Yin, Lin, Fu, and Chen (2009) also built a GIS-based early warning system for the Tianjin gas pipeline network in china, and Chen and Qi (2010) further combined GIS with early warning models composed of gas leakage, diffusion, fire and explosion to construct the gas accident early warning system. Then a generic framework and decision tools for real-time risk assessment on Emergency Environmental Decision Support System were developed for responding to chemical spills in a river basin (Jiang, Wang, Lung, Guo, & Li, 2012). To city traffic safety, Gundogdu (2010) developed methods to obtain maps to determine traffic Hot Spots in Konya, Turkey, by applying linear analysis supported by Geographical Information Systems (GIS), and the traffic accidents could be prevented.

Table 2
Corresponding diameter and minimum wall thickness (Jo & Ahn, 2005).

d(mm)	–150	150–450	450–600	600–900	900–1050	1050
$t_{\min}$(mm)	4.8	6.4	7.9	9.5	11.9	12.7

Table 3
Examples of different causes of failure and the corresponding rates of failure types (EGIG, 2008).

Failure causes	Failure rate (1/year km)	Percentage (%)	Rates of occurrence of different hole sizes (%)		
			Small	Medium	Large/ Fracture
External interference	1.8×10^{-4}	49.6	25	56	19
Construction defects	6.5×10^{-5}	16.5	69	25	6
Corrosion	6.0×10^{-5}	15.4	97	3	<1
Ground movement	2.5×10^{-5}	7.3	29	31	40
Other factors	4.0×10^{-5}	11.2	74	25	<1
Total failure rate	3.7×10^{-4}	100.0	48	39	13

It is clear that these studies have, by and large, met the needs for risk analysis and emergency response to some extent for dangerous situations in urban areas. However, none of these have considered the effects of gas leakage, diffusion, fires, and/or explosions. In addition, they are not relevant to urban natural gas pipeline networks, do not consider atmospheric stability, and have no unified standards for setting relevant parameters. While the CASST-QRA assessment software (Version1.0) is the integrated analysis software for dangerous urban situations, it lacks the emergency response and decision-making parameters applicable to a natural gas pipeline network. In addition, most research systems focus on limited areas, mainly on local dangers, and attempt an impact analysis of the accident's consequences alone, instead of providing conclusions about the failure rate of pipeline networks, and the resulting individual and societal risks. Gas pipeline networks throughout the city require a consideration of the impacts of local accidents as well as the risk management of whole urban pipeline networks. Therefore, currently, it is difficult to undertake an urban risk assessment and plan for risk management on a macro scale. Furthermore, sufficient early warning systems in the context of pipeline networks are still under development. This study attempts to fill in the abovementioned gaps.

3. Methodological approach

This paper begins with a risk analysis and quantitative risk assessment framework for urban gas pipeline networks, and

Table 4
some international F–N curve standards (Jonkman et al., 2003).

Countries	n	C
Britain	1	10^{-2}
Hong Kong	1	10^{-3}
Holland	2	10^{-3}
Denmark	2	10^{-2}

enhances the said framework by combining it with GIS technology. The first step includes summarizing known risk analysis models, including the concepts and calculation methods for the failure rate of pipeline networks; compiling QRA models to evaluate accident consequences; and reviewing risk analysis indexes according to the failure rate and accident impacts, including respective standards and calculation methods of individual risk and societal risk. All of the works aim at determining whether the individual risk and societal risk exceed acceptability of risk to operate the maintenance, for example, 1E-06 per year is recommended as the minimum individual acceptable risk (Jonkman et al., 2003), and the society risk acceptable range is judged, based on the risk-benefit trade-off for the total population (Dawotola, Trafalis, et al., 2012; Dawotola, Van Gelder, & Vrijling, 2012) (see Section 4.2.3 (2)). Then the minimized total cost and the maximized benefit-to-cost ratio may be expected for maintenance (Dawotola et al., 2012b). A quantitative risk analysis system for the pipeline network is constructed in the second step. This includes the introduction of the system function structure under a GIS environment, followed by accident simulation and studying their consequences using the QRA model. Finally, using the analysis results of the failure rate of the pipeline network, an analysis of individual and societal risks is attempted.

Natural gas pipeline accidents are usually caused by leakage. Various methods have been proposed to conduct a quantitative risk analysis to develop early warning systems for natural gas pipeline networks. This section briefly reviews the practical role of risk assessment models in early warning systems for urban natural gas pipeline networks. Fig. 1 shows the operating flow chart of the quantitative risk analysis system of a proposed urban pipeline network. First, the failure rate of each pipe segment at different times is calculated. Using the value of the failure rate and the failure rate tendency chart of the same pipe segment at different times, we decide whether the pipeline is to be revised or directly replaced. If the failure rate meets the requirement (i.e., below the norm), then the physical effects caused by all kinds of possible accidents can be calculated and the fatality rate of different physical effects can be deduced. The failure rate of this pipe segment is employed to calculate the individual risk value of the affected sample point (Jo & Ahn, 2005). Risks are assessed using the interpolated risk isoline and by calculating the societal risk curve of the given area. According to the historical tendency chart of the failure rate of the same pipe section at different times, we decide whether the pipeline is to be revised or directly replaced. If the statistical tendency chart is normal, the risk assessment is conducted by calculating the fatality rate. In addition, when analyzing the physical effects caused by leakage, we expand and implement the analog module of accident consequences in GIS, which includes forecasting the explosion impact range and the analyzing the gas diffusion simulation.

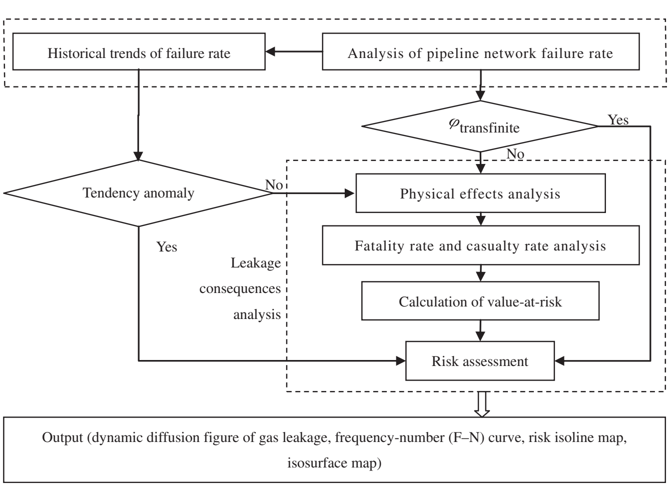


Fig. 1. Flow chart of quantitative risk analysis for an urban gas pipeline network.

3.1. Calculation of failure rate of the pipeline network

The failure rate of the natural gas pipeline network refers to the fracture in the network resulting in leakage due to external interference or inherent risks. The main factors include corrosion, construction defects, ground movement, and external interference. Fault tree analysis is usually adopted to analyze pipeline network failure rates. Unlike gas valves, pressure regulating boxes, and other single-point facilities, the failure rate φ of the network is usually defined as the number of times the pipeline failure occurs per unit length every year (Jo & Ahn, 2005). Thus,

$$\varphi_i = \sum_j \varphi_{i,j,0}\kappa_j(a_1, a_2, a_3, \ldots) \tag{1}$$

where φ_i is the failure rate of the pipeline network that is caused by failure type i(1/year km). i, the assumed failure type, is generally categorized as one of the following: small hole (size not exceeding 2 cm), large hole (size between 2 cm and the pipe diameter), and fracture (complete fracture with size exceeding the pipe diameter).j depicts the reasons for the failure (including external interference, construction defects, corrosion, ground movement, and others), while $\varphi_{i,j,0}$ is the probability of different failure types resulting from specific failure causes, κ_j is the modifying equation of corresponding failure causes (weight factors can be deduced using expert assessments), and a_k are the parameters of the modifying equation (external interference including cover depth, wall thickness, ground population density, and precautionary measures).

Let us consider an example for failure rate calculation with external interference. $\varphi_{i,EI}$ is calculated as follows:

$$\varphi_{i,\mathrm{EI}} = \varphi_{i,\mathrm{EI},d}\kappa_{\mathrm{DC}}\kappa_{\mathrm{WT}}\kappa_{\mathrm{PD}}\kappa_{\mathrm{PM}} \tag{2}$$

where κ_{DC}, κ_{WT}, κ_{PD}, and κ_{PM} refer to the effect weight of the cover depth, wall thickness, ground population density, and precautionary measure, respectively, which will be used to modify $\varphi_{i,\mathrm{EI},d}$. According to the statistics from the European Gas Pipeline Incident Data Group (EGIG) (2008), $\varphi_{\mathrm{small,EI},d}$, $\varphi_{\mathrm{medium,EI},d}$, and $\varphi_{\mathrm{great,EI},d}$ could be summarized as:

$$\varphi_{\mathrm{small,EI},d} = 0.001e^{-4.18d-2.18562} \tag{3}$$

$$\varphi_{\mathrm{medium,EI},d} = 0.001e^{-4.12d-2.02841} \tag{4}$$

$$\varphi_{\mathrm{great,EI},d} = 0.001e^{-4.05d-2.13441} \tag{5}$$

where d is the diameter of the pipe in m.

D_c is the depth of cover, t is the wall thickness of the pipeline, and d is its diameter. “Rural” refers to a population density not exceeding 2.5 persons/ha, “town” refers to the central areas of towns or cities, “suburbs” refers to an area intermediate in character between rural and town areas, and $t_{\min}$ is the minimum wall thickness.

In general, compared to external interference damages, other impact factors exert a relatively small influence on the failure rate of the pipeline network. As a result, Eqs. (3)–(5) are usually employed to undertake simple analysis and calculation of the failure rate. If conditions permit, 3.7×10^{-4}/year km could be used directly as the failure rate of the pipeline network (Jo & Ahn, 2005). A regular risk assessment of pipeline failure rate helps derive the tendency chart of the failure rate risk, and in turn, provides early warnings.

3.2. Risk assessment

Almost any human endeavor carries some risk—some much than others—and safety serves as a dynamic balance between "relative risk" and the economic input. Our purpose of conducting this research is to reduce risks to the extent possible. Our aim is to locate the most suitable point between the probability of accidents occurring and the losses caused by these accidents by establishing an early warning system. In general, several different indexes are used to measure risks, such as individual risks, societal risks, economic risks, environmental risks, and so on. The first two—individual risks and societal risks—are the most relevant to our study.

3.2.1. Individual risk

Individual risk refers to frequency of particular damages borne by an average unprotected person who is permanently present at a particular location. Generally speaking, the individual risk in our context means the risk of death. Any point in the gas pipeline network will be impacted by the risks in a certain range of pipeline network. Therefore, the individual risk at every point will include the risk of the adjacent segments of the pipeline network. Thus, the individual risk for the failure of an urban gas pipeline network is expressed by the following equation (Jo & Ahn 2005; Jo & Crowl, 2008):

$$\mathrm{IR} = \sum_i \varphi_i \int_0^L P_i dL \tag{6}$$

where i is the assumed failure type, φ_i (see Section 3.1) is the number of times there is a failure per unit length each year for the failure accident i (1/year km), L is the length of pipeline in m, and P_i (see Section3.3.7) is the fatality rate of failure accident i.

A suitable individual risk is selected to judge whether the risk within a certain area is acceptable, based on the relevant individual risk acceptance criteria depending on the country in question and the overall features of the pipeline network. Common individual risk acceptance criteria typically pay heed to the ALARP (as low as reasonably practicable) principle, the AFR value, the risk matrix, and the AI value. In general, we adopt IR $< 10^{-6}$ as the standard (Jonkman et al., 2003). Inspired by Gundogdu (2010), we obtain enough sample points depicting individual risk values, then the individual risk isoline can be interpolated easily (Mitas & Mitasova, 1999), to make the risk distribution map (Implemented Section 4.2.3). This isoline and gas pipeline networks maps make it easy to plan the corresponding protection area for the urban gas pipeline using GIS.

3.2.2. Social risk

Social risk is used to describe the relationship between the probability of accidents and the casualties caused by the accidents. It refers to the risk of disastrous accidents that influences many people at the same time. Such accidents attract attention and exert a great impact on society. Social risk is not only related to the individual risk but also has a close relationship with the regional population density, as seen below.

$$N_i = \int_{A_i} \rho_p P_i dA_i \tag{7}$$

where A_i is the affected area of the assumed failure accident i, ρ_p is the population density of this area, and P_i is the fatality rate of failure accident i. The frequency-number (F–N) curve is also used to formulate social risk (Jonkman et al., 2003).

$$1 - F_{\mathrm{N}}(x) = P(N > x) = \int_x^\infty f_{\mathrm{N}}(u)\mathrm{d}u \tag{8}$$

In several countries, an F–N criterion curve limits the risks of various hazardous activities. This standard could be formulated as follows (Jonkman et al., 2003).

$$1 - F_N(x) < \frac{C}{x^n} \tag{9}$$

where $F_N(x)$ is the probability that annual fatalities will be less than x, n is the power of the standard curve, and C is a constant (see Table 5).

3.3. Quantitative analysis model of accident consequences

In order to conduct a quantitative risk analysis and develop an early warning system, a quantitative calculation of the estimates of individual risks and societal risks is required. φ_i and P_i thus need to be calculated first for Eq. (6) pertaining to individual risk (see Section 3.2.1). Similarly, A_i and P_i need to be calculated first for Eq. (7) pertaining to societal risks (see Section 3.2.2). Thus, it is clear that the calculation model of the affected area A_i in failure accident i and the fatality rate P_i of failure accident i are needed for quantitative calculation of the value-at-risk for the pipeline network. The method is shown in Fig. 2.

3.3.1. Small hole model

All gas leakages are divided into two states: sonic speed and sub sonic speed (Dong, Gao, Zhou, & Feng, 2002; Han & Weng, 2010; Montiel, Vılchez, Casal, & Arnaldos, 1998; Yin et al., 2009). To simplify calculations, a unified model (equation (10)) is adopted to calculate the leakage caused by small and medium-sized hole failures.

$$Q = A_{\mathrm{or}} P_2 \sqrt{\frac{2M}{RT_2} \cdot \frac{k}{k-1} \left[\left(\frac{P_a}{P_2}\right)^{\frac{2}{k}} - \left(\frac{P_a}{P_2}\right)^{\frac{k+1}{k}} \right]} \tag{10}$$

where Q is the flow rate of gas leakage in kg/s, A_{or} is the area of the leakage opening in m^2, 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_2

Table 5
Thermal radiation exposure effects.

Thermal radiation (kW/m^2)	Effect
1.2	Received from the sun at noon in summer
2	Minimum to cause pain after 1 min
Less than 5	Will cause pain in 15–20 s and injury after 30 s' exposure
Greater than 6	Pain within approximately 10 s; rapid escape only is possible
12.5	• Significant chance of fatality for medium duration exposure • Thin steel with insulation on the side away from the fire may reach thermal stress level high enough to cause structural failure • Wood ignites after prolonged exposure
25	• Likely fatality for extended exposure • Spontaneous ignition of wood after long exposure • Unprotected steel will reach thermal stress temperatures that can cause failure
35	• Significant chance of fatality for people exposed instantaneously. • Cellulosic material will pilot ignite within 1 min's exposure.

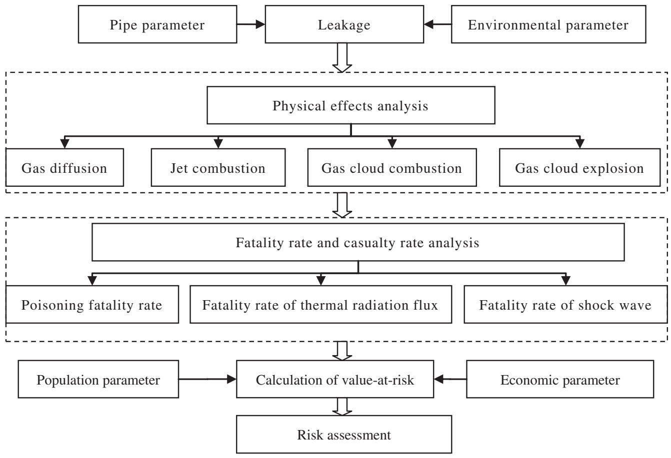


Fig. 2. Flow chart of quantitative risk prediction of accident consequences.

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_a is the environmental pressure in Pa, and P_2 is the pressure inside the gas pipeline in Pa.

3.3.2. Fracture model (Han & Weng, 2010)

Refer to Eq. (11) for the fracture model.

$$Q = \sqrt{\frac{2M}{RT_2}\cdot\frac{k}{k-1}\cdot\frac{T_2 - T_1}{\left|\frac{T_1}{P_1}\right|^2 - \left|\frac{T_2}{P_2}\right|^2}} \tag{11}$$

where T_1 is the temperature at the beginning of the pipeline in °K, P_1 is the pressure at the beginning of the pipeline in Pa, T_2 is the gas temperature at the fracture of the pipeline in °K, and P_2 is the gas pressure at the fracture of the pipeline in Pa.

3.3.3. Gaussian diffusion model

The Gaussian diffusion model is of two types: the puff diffusion model and the plume diffusion model. Under the condition of instantaneous leakage and partial continuous source leakage or breeze (<1 m/s), the Gaussian puff diffusion model is adopted. On the other hand, with continuous source leakage or when the leakage exceeds or is equal to the time of diffusion, it is more appropriate to adopt the plume model. The concentration distribution patterns of the Gaussian diffusion models are as follows (Ding, Wang, & Xu, 1999; Lines, Deaves, & Atkins, 1997).

(1) For the Gaussian plume model:

$$c(x,y,z,H) = \frac{Q}{2\pi\sigma_y\sigma_z\overline{u}}\cdot\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\cdot\left\{\exp\left[-\frac{(z-H)^2}{2\sigma_x^2}\right] + \exp\left[-\frac{(z+H)^2}{2\sigma_x^2}\right]\right\} \tag{12}$$

where $c(x,y,z,H)$ is the density in kg/m^3;Q is the mass flow rate of leakage in kg/s; H is the height of effective sources in m; (x,y,z) is any point in the downwind area; $\overline{u}$ 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 (Huang, 2004).

(2) For the Gaussian puff model:

$$c(x,y,z,T) = \frac{Q}{2\sqrt{2\pi}^{2/3}\sigma_x\sigma_y\sigma_z}\cdot\exp\left[-\frac{(x-\overline{u}T)^2}{2\sigma_x}\right]\cdot\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\cdot\left\{\exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+H)^2}{2\sigma_z^2}\right]\right\} \tag{13}$$

where T is the runtime of the puff from the source to the calculation point (x,y,z) in s.

3.3.4. Fire

As identified in the Consequence Modeling datasheet (OGP, 2010a), several different types of fire are potentially of concern depending on the release material and scenario (OGP, 2010b):

(1) Fireball model

A fireball would result from immediate ignition of a release resulting from the gas leak accident. The equation to calculate thermal radiation flux at a specific position is as follows:

$$q(x) = \frac{Q_{\text{total}}T_c}{4\pi x^2} \tag{14}$$

where q is the thermal radiation flux in W/m^2 at the specific position, T_c is coefficient of heat conduction, x is the distance between the target and the center of the flame zone.

(2) Jet fire model

Gas jets from the opening of the fracture or from the pipeline and ignites fire, forming jet fire (Sun, Zhong, & Zhang, 2006). The equation to calculate thermal radiation flux at a specific position is as follows:

$$I = \frac{\eta\gamma_a QH_c}{4\pi r^2} \tag{15}$$

where I is the thermal radiation flux in W/m^2 at the specific position, η is the ratio of radiation heat to the heat released by the fire (0.2 for methane), γ_a is the atmospheric transmissivity (value = 1) (Han & Weng, 2010), H_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.

(3) Flash fire model

A great quantity of gas would produce vaporous cloud in the air. However, the vaporous cloud is named the flash fire with mass deficiency or the low power of source of ignition. The equation to calculate thermal radiation flux for the flash fire in specific position is the same to the fireball, but low heating value of gas should be adopted.

(4) Fire accidents effects

Humans are vulnerable to fire in the following ways: Engulfment by fire, Thermal radiation, People inside buildings.

To engulfment by fire, the following lethality levels are recommended for the purposes of QRA: 100% lethality for people outdoors engulfed by a jet fire, pool fire or fireball. 100% lethality for members of the public outdoors engulfed by a flash fire. 50–100% lethality, depending on ease of escape, for workers wearing fire resistant clothing made from fabrics meeting the requirements of NFPA 2112 (2007) or equivalent.

To thermal radiation, HSE (2010) summarizes thermal radiation exposure effects over a range of radiation fluxes (Table 5). HSE (2010) also sets out thermal radiation criteria applicable to longer fire durations, i.e. to jet fires or pool fires (Table 6). Thermal Dose Fatality Criteria is used for fireballs (HSE, 2010), to flash fire here, too (Table 7).

To people inside buildings, people inside buildings may be vulnerable to the building catching fire if combustible building material is exposed to the fire. Personnel inside a building are vulnerable to the building catching fire if they cannot escape in sufficient time. This will depend on the time to ignition as compared to the time to alert the people inside to the source fire and evacuate them. People inside a building are also vulnerable if escape routes are exposed to thermal radiation: in this case the criterion of 6 kW/m2 given in Table 5 can be applied.

3.3.5. *Overpressure explosion model*

A vapor cloud is formed when a large amount of leaked gas diffuses rapidly into the air. If the vapor cloud is ignited and its density reaches the explosive limit, an explosion will occur and generate a shock wave. When an explosion takes place on the ground, the overpressure of the shock wave in the explosion field can be calculated using the following equation.

$$\Delta P = 0.71 \times 10^6 \left| \frac{R}{\sqrt[3]{m_{\mathrm{TNT}}}} \right|^{-2.09} \quad (16)$$

where ΔP is incident overpressure of the explosive wave and R is the distance between some point in the explosion field and the source of the explosion.m_{TNT} is calculated using the following equation:

$$m_{\mathrm{TNT}} = \frac{m_{\mathrm{d}} \Delta H_{\mathrm{d}}}{Q_{\mathrm{TNT}}} \quad (17)$$

where m_{TNT} is the TNT equivalent in kg, m_{d} is the mass of the gas involved in the explosion in kg, ΔH_{d} is the explosion heat of the gas in J/kg (usually in terms of combustion heat), and Q_{TNT} is the calorific value of the standard TNT explosion source (4.2 MJ/kg).

Knowing the different carrying threshold of human body overpressure ΔP (Yin et al., 2009), the damage semidiameter can be back-calculated using Eq. (16) and an isoline map of the damages caused by the overpressure explosion can be drawn (see 4.2.2).

3.3.6. *Explosive blast model*

The explosive blast model is provided by Eq. (18).

$$\Delta P = k_1 \lambda^{k_2} \times 10^5 \quad (18)$$

Table 6
Thermal radiation criteria (use for jet/pool fires).

Thermal radiation (kW/m^2)	Effect
35	Immediate fatality (100% lethality)
20	Incapacitation, leading to fatality unless rescue is effected quickly
12.5	Extreme pain within 20 s; movement to shelter is instinctive; fatality if escape is not possible. Outdoors/offshore: 70% lethality Indoors onshore: 30% lethality
6	Impairment of escape routes
4	Impairment of TEMPSC embarkation areas

Table 7
Thermal Dose fatality criteria (use for fireballs).

Thermal dose units ($(kW/m^2)^{4/3}$ s)	Effect
1000	1% lethality
1800	50% lethality, members of the public
2000	50% lethality, offshore workers
3200	100% lethality

where ΔP is the pressure of the explosive shock wave in Pa, λ is the equivalent distance in $m/kg^{1/3}$, k_1 and k_2 are the coefficients relevant to the value of ΔP and λ respectively (see Table 8). Moreover, λ can be estimated with the following equation:

$$\lambda = \frac{R_{\mathrm{L}}}{\sqrt[3]{Q}} \quad (19)$$

where R_{L} is the distance to the explosion center in m and Q is the explosion equivalent at the explosion center in kg (Huang, 2004).

3.3.7. *Calculation of the fatality rate*

The impact of leaked gas on human beings (poisoning, thermal injury, and blast damage) can be presented by a probability. The percentage of the injured people exposed to the leakage is used to measure this probability. It is related to the injury factors used to measure all kinds of physical effects intensity (Huang, 2004). Probability P_{T} is a probit, usually ranging from 1 to 10 and is directly related to the percentage of fatality, and OGP (2010b) shows the percentage affected (fatality) for a calculated probit value. P_{T} is expressed as the following equation:

$$P_{\mathrm{T}} = a + b \ln I_{\mathrm{f}} \quad (20)$$

where P_{T} is the probability of the percentage of damages suffered by exposed people (or the environment),it is the probit (or the probability measure without unit), I_{f} is relevant to the factors causing the damages (seen in Eqs. (21) and (22)), and a and b are constants.

(1) For damages caused by thermal radiation, the commonly used methods are introduced by Eisenberg, Lees, Tsao and Perry and TNO, and it is proved that the Lees probit provide the most optimistic consequences (HSE, 2010).

$$P_T = -10.7 + 1.99 \ln\left(I^{\frac{4}{3}} \times 10^{-4} \times t\right) \quad (21)$$

(2) where I is the intensity of the thermal radiation in W/m^2 (30 s is the typical recommended exposure time in urban areas (Jo & Ahn, 2005)). The overpressure levels necessary to cause injury to the public are typically defined as a function of peak overpressure, without regard to exposure time. Persons who are exposed to explosion overpressures have no time to react or take shelter; thus, time does not enter into the relationship. For fatalities caused by explosion overpressure (HSE, 2010),

Table 8
Explosion effect equivalent to k (Huang, 2004).

λ	2–3.676	3.676–7.934	7.934–29.75	29.75
ΔP	3–0.65	0.65–0.2	0.2–0.036	0.036–0.0025
k_1	11.535	6.9064	3.233	4.21
k_2	−2.0597	−1.9673	−1.3216	−1.3988

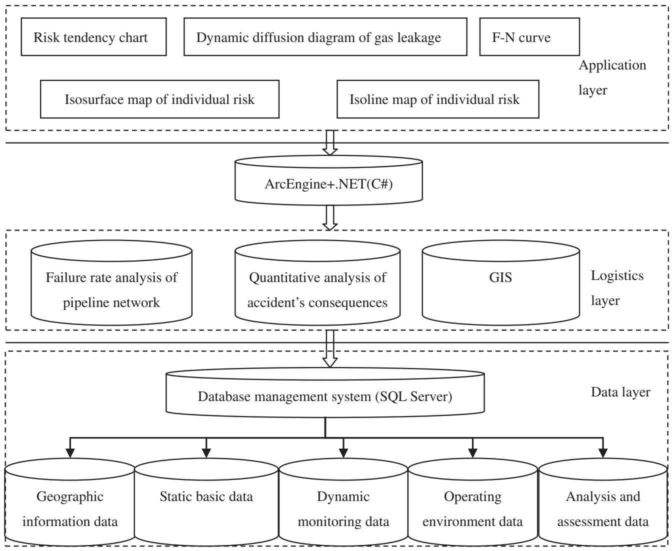


Fig. 3. Function structure graph of the proposed quantitative risk analysis system for urban natural gas pipeline networks.

$$P_T = 5.13 + 1.37 \ln(P_2^{max}) \tag{22}$$

where P_2^{max} is the maximum overpressure in barg.

4. Construction of a GIS-based quantitative risk analysis system for the pipeline network

4.1. Structure of system function

After summarizing various national and international research materials on quantitative risk assessment of gas leakage and carrying out in-depth studies, a QRA system coupled with the advantages of GIS is proposed for urban natural gas pipeline networks. An illustration of the function structure of the quantitative risk analysis system is shown in Fig. 3. The system is implemented using a .NET platform with ArcEngine (of ESRI) supported on Windows as the secondary development component, and an SQL Server was used to build the database. The failure rate prediction and risk assessment for a specific pipeline network are made by adopting the failure rate analysis model as well as the prediction model of the accident's consequences. The following main functions are contained in the system: (1) risk tendency chart, (2) dynamic diffusion diagram of gas leakage, (3) isoline map of individual risk, (4) isosurface map of individual risk, and (5) the F–N curve.

The main database of system includes: (1) geographic information data, storage pipeline network, and urban geographical and spatial data, (2) static basic data as well as related calculations and standard parameters of the risks prediction model for storage, (3) dynamic monitoring data, including gas pressure values, etc., (4) operating environmental data, including wind speed, population density, etc., and (5) analysis and assessment data, including stored analytical results from all analyses of historical trends.

4.2. Analysis of results

4.2.1. Analysis of the failure rate of the pipeline network

While deciding the probability of rupture accidents, the failure rate for initial failure is calculated according to the actual environment and working conditions of pipeline networks. Making use of the empirical formulas ((1)–(5)) summarized by EGIG (2008), detailed parameters of the assessed pipe segment are entered in the parameter input boxes (see Fig. 4). The failure probability of the pipe segment under different presumed failure styles, including the probability of external interference, construction defects, corrosion, and ground movements, is calculated. The failure times per unit length pipeline network per year are as shown in the histogram in Fig. 4.

4.2.2. Analysis of accident simulation

Three types of accidents are simulated. As Fig. 1, if φ is less than 3.7×10^{-4}/year km, or historical trends of failure rate is normal, the analysis below would be done to assess the risk further. (1) Generally, The effects of overpressure on humans are normally categorized as a result of the pressure change, and result of

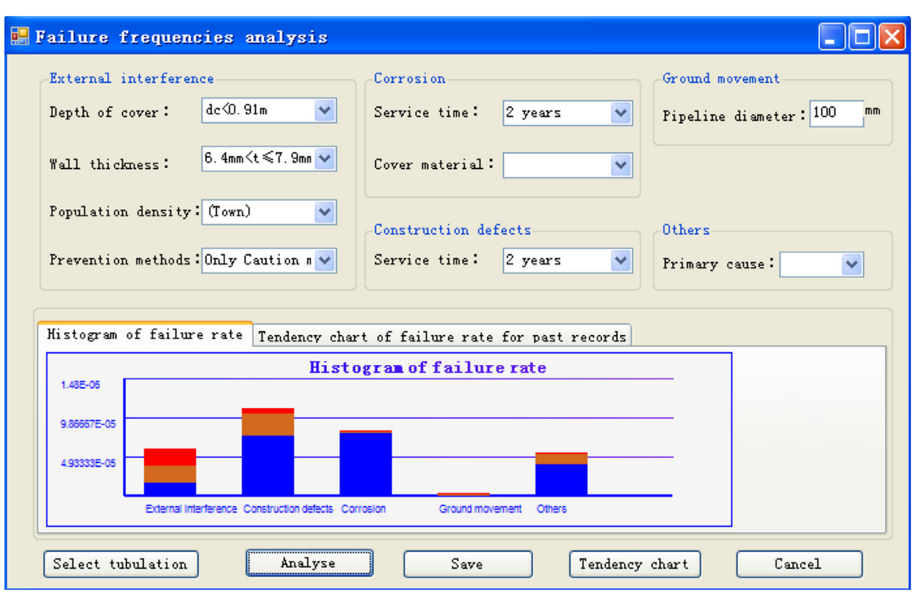
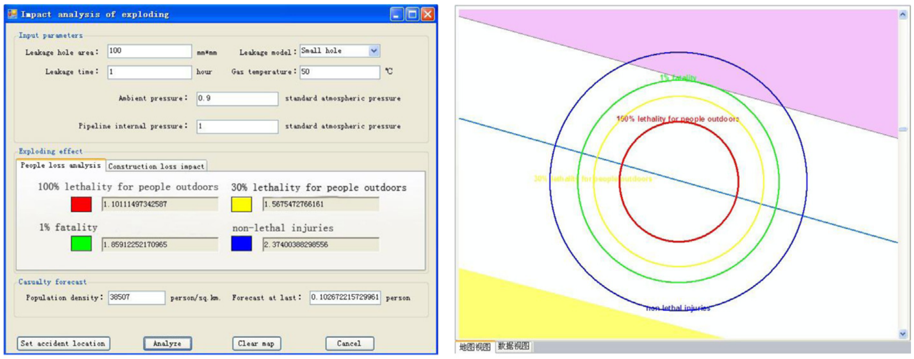


Fig. 4. Analysis of pipeline network failure rate.



(a) (b)

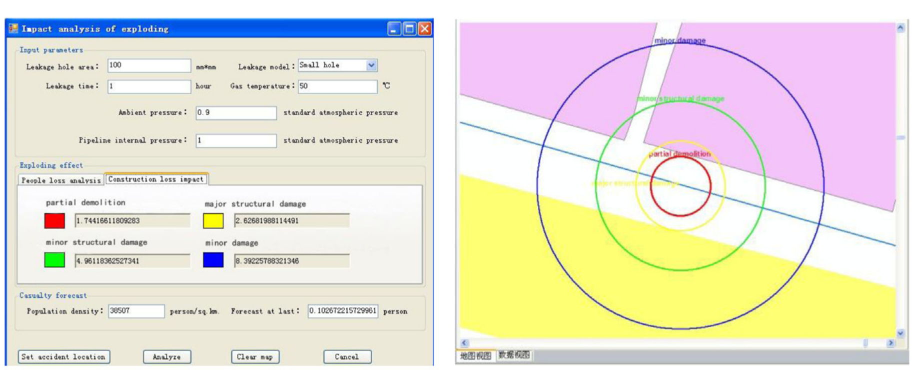
Fig. 5. Injury caused to the human body by an explosion. (a) Dialog box for explosion analysis. The “people loss analysis” box shows ranges of different injury levels measured in m. “population density” refers to the population density of the region and “Forecast at last” stands for the death toll caused by the predicted accident. (b) A sample graph simulating injuries to the human body caused by the explosion showing the geographical and spatial ranges of different injury types.

fragments. For QRA, lethality is not typically estimated independently for these effects, instead, an overall lethality is estimated based on the combination of these effects. For people onshore, outdoors and in the open, the lethality levels are recommended (OGP, 2010b): 0.35 bar overpressure would lead to 15% lethality for people outdoors, in the open. 0.5 bar overpressure would lead to 50% lethality for people outdoors, in the open. For people onshore, outdoors but adjacent to buildings or in unprotected structures (e.g. process units), the following lethality levels are recommended (OGP, 2010b): 0.35 bar overpressure generates 30% lethality for people outdoors, and 0.5 bar overpressure generates 100% lethality for people outdoors. For people indoors, the lethality level depends on the building type as well as the overpressure, and two frequently used sets of relationships between lethality level and over-pressure are found in API (2003) and CIA (2003). In addition, Overpressures lower than 0.21 bar can cause non-lethal injuries such as lung damage and eardrum rupture (HSE, 2010). 0.25–0.35 bar overpressure generates 1% fatality (HSE, 2010). On the basis of Eq. (16), if $\Delta P = 0.21$ bar, $R = 5.390\sqrt[3]{m_{TNT}}$; if $\Delta P = 0.35$ bar, $R = 4.221\sqrt[3]{m_{TNT}}$; if $\Delta P = 0.5$ bar, $R = 3.559\sqrt[3]{m_{TNT}}$; if $\Delta P = 1$ bar, $R = 2.5\sqrt[3]{m_{TNT}}$. Eq. (17) could be utilized to calculate m_{TNT} according to the leak parameters.

Simulation analysis of an explosion causes bodily harm/injury. As shown in the dialog box in Fig. 5, parameters such as the area of leakage hole, internal pressure of pipelines, gas temperature, ambient pressure, and leakage time need to be entered. Then, one chooses the accident spot on the map and clicks the “Analyze” button. This simulates injury levels of the explosion on the human body within a certain specified range of the accident spot. According to above, the simulation includes four levels of injury: non-lethal injuries (such as lung damage and eardrum rupture), 1% fatality, 30% lethality for people outdoors, and 100% lethality for people outdoors. These four levels are shown in different colors, which can be customized. Lastly, the death toll is predicted using parameters such as the population density.

(2) As the effects of overpressure on humans, the criteria of explosion effects on buildings is recommended by ISMA (2011): Overpressure 15 mbar is as threshold of minor damage to steel structures or reinforced concrete structures, and some permanent deformations are to be expected. Overpressure 45 mbar is as threshold for minor structural damage to steel structures or reinforced concrete structures, and some elements may fail. 170 mbar is as threshold for major structural damage. 400 mbar is as threshold for partial demolition. 50–75% of walls destroyed or unsafe. On the basis of Eq. (16), if $\Delta P = 15$ mbar, $R = 19.054\sqrt[3]{m_{TNT}}$; if $\Delta P = 45$ mbar, $R = 11.264\sqrt[3]{m_{TNT}}$; if $\Delta P = 170$ mbar, $R = 5.964\sqrt[3]{m_{TNT}}$; if $\Delta P = 400$ mbar, $R = 3.960\sqrt[3]{m_{TNT}}$. Similar criteria can be also found in OGP (2010c).

Simulation analysis of damage to buildings due to the explosion. Similar to the simulation for injuries to humans due to the explosion, damage to buildings due to the explosion is divided into four levels according to above: minor damage, minor structural damage,



(a) (b)

Fig. 6. Damage caused to buildings by an explosion. (a) The dialog box for explosion analysis requires similar inputs as explained for Fig. 5a. The tab titled “construction loss impact” shows ranges of different levels of damage in m. (b) The sample graph depicting damage caused to buildings by an explosion shows the geographical and spatial ranges of different types of damages.

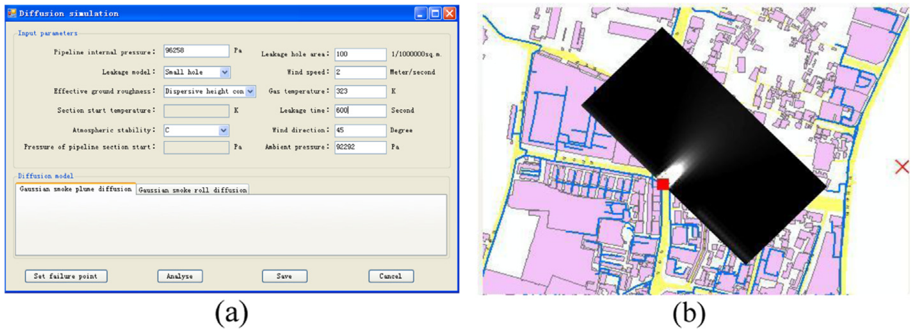


Fig. 7. Simulation showing the diffusion of the leaked gas. (a)Dialog box for diffusion simulation. (b) The white area in the figure shows the diffusion range for a specified wind speed.

major structural damage, and partial demolition depicted by the blue, green, yellow, and red circles, respectively (see Fig. 6).

(3) Diffusion simulation. It is also possible to simulate the diffusion of the leaked gas. The relevant input variables include the area of the leakage hole, internal pressure, temperature, wind speed, atmospheric stability, and effective ground roughness. It is necessary to select a leakage model (small, medium, and fracture) and then mark the accident spot on the map. This generates a simulation of how the gas will diffuse in the vicinity of the leakage/accident over time. For example, in Fig. 7b, the small red square marks the accident spot while the white area emerging from the square shows the direction the gas is most likely to drift in (in this case, upwards and to the right). The brighter the square, the denser the natural gas. It is possible to change/reset time intervals to study the changes in the diffusion range.

4.2.3. Assessment of individual risk and societal risk

(1) Individual risk assessment. In this part, the spatial interpolation technology of GIS (Mitas & Mitasova, 1999), that is a method for prediction and representation of the whole area from limited scattered data, is used to produce simulated individual risk iso-curves with discontinuous individual risk value points. Firstly, individual risk in the vicinity of pipelines is calculated as sampling points according to the individual risk calculation method introduced in Section 3.2.1. This requires us to set a sampling point layer that covers the whole pipeline area. Next, we set the display parameters in the dialog box and click "Draw isoline" (see Fig. 8a) to acquire the isoline or iso-surface map of individual risk by interpolating individual risk values in the sampling point layer (see Fig. 8b). This intuitive risk isoline map gives a macro view of the risk to residents near the pipeline on a regional scale. The resulting intuitive understanding of the regional risk distribution due to the pipeline network can aid pipeline management staff in demarcating high risk areas requiring more frequent inspections.

(2) Societal risk assessment. The curve graph for social risk assessment for the whole region can be obtained by calculating the societal risk using the model introduced in Section 3.2.2 (see Fig. 9). The horizontal ordinate depicts the death toll, and the vertical ordinate, the exceedance probability of different death tolls caused by gas accidents in the entire region during one year. It is possible to specify the acceptable area according to actual needs in the social risk evaluation criteria. If the curve exceeds the specified range of the acceptable area, corresponding measures, such as pipeline reconstruction, must be taken to reduce risks.

5. Discussion and conclusion

The paper attempted designing a GIS-based risk analysis process and constructing GIS-based QRA system for urban gas pipeline networks. Various analytical models were used to conduct a spatial analysis of failure rates, simulate accidents, and assess individual and societal risks. Accident simulation analysis using GIS could also provide intuitive results of accident impacts. Collecting individual risk sampling points in the urban area and drawing an interpolated isoline map for individual risks can help establish an intuitive but scientific, macro risk distribution graph for management staff of urban gas pipeline networks. The curve graph for societal risk assessment for the whole region the pipeline network runs through can be obtained by combining the results of the individual risk analysis and calculating the societal risk using the specified model.

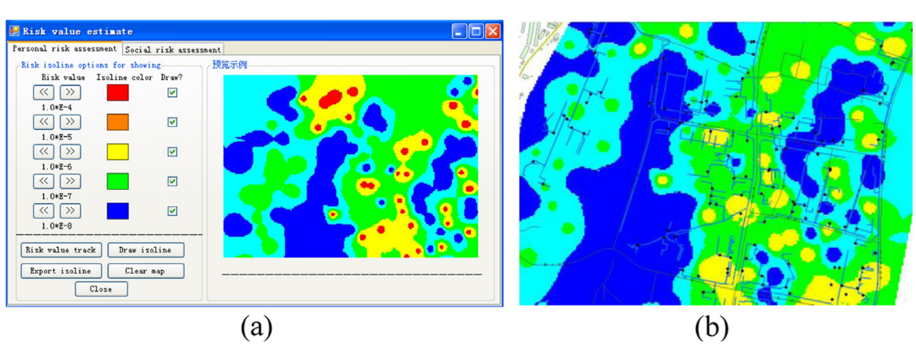


Fig. 8. Individual risk assessment. (a) Set the necessary risk values in the dialog box for individual risk assessment and check all boxes under "Draw?"(b) interpolated isosurface map of individual risk.

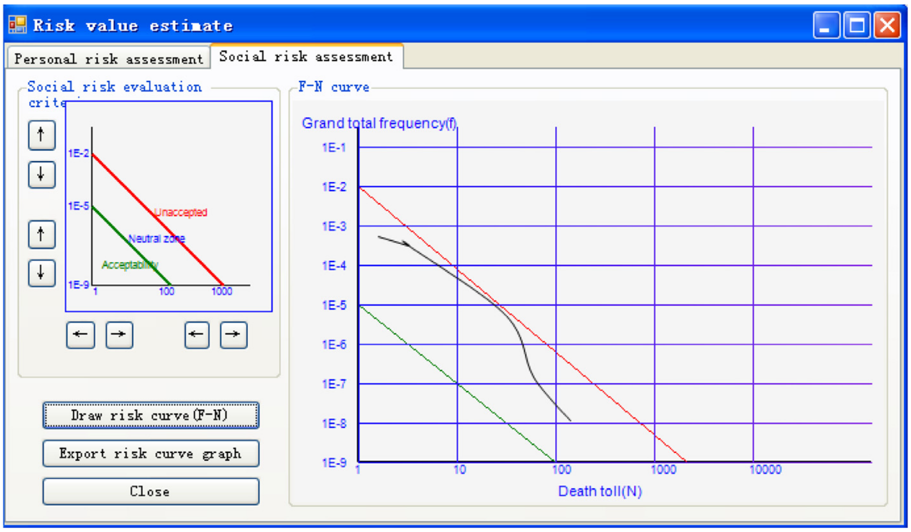


Fig. 9. Curve graph of societal risk assessment values.

The proposed GIS-based QRA system holds great promise in planning for urban risk management of gas pipeline networks on a macro scale.

Acknowledgments

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