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

Lei Ma, Liang Cheng*, Manchun Li**

Jiangsu Provincial Key Laboratory of Geographic Information Science and Technology, Nanjing University, 22 Hankou Road, Nanjing 210097, PR China

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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).

* Corresponding author. Tel.: +86 18652071855; fax: +86 25 83597359.
** Corresponding author. Tel.: +86 13705167312; fax: +86 25 83597359.
E-mail addresses: lcheng@nju.edu.cn (L. Cheng), limanchun_nju@126.com (M. Li).

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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	$0.91\text{m} \le D_c \le 1.22$m
	0.54	$D_c > 1.22$m
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

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

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.

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 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 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}