Journal of Natural Gas Science and Engineering 55 (2018) 16–29

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Extracting spatial patterns of urban gas pipeline risk considering social and structural parameters of urban blocks

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ARTICLE INFO

Keywords:
Risk assessment
Vulnerability
Urban gas pipelines
Geospatial information system (GIS)
Hazard map

ABSTRACT

Due to growing cities and urbanization, the demand for natural gas is increasing rapidly around the world. To address this necessity, the density of urban natural gas pipelines will increase. However, urban pipelines pass through regions with the high density of people and buildings with low construction quality, possibly leading to accidents that may cause extreme damage to people and property. In this paper, a quantitative method is proposed for evaluation of hazards that are influenced by the inherent parameters of gas pipelines considering their density. Afterwards, considering the physical and social vulnerabilities of this study area, the structural and social parameters of urban blocks are added to the risk model. The output of this method is used to analyze the risk of spatial patterns of urban natural gas pipelines and the structural and social parameters of urban blocks. This research model consists of the following three main sections: hazard mapping of urban gas pipelines considering their inherent parameters, physical and social vulnerability mapping of urban blocks, and risk mapping of gas pipelines. The results show that there are meaningful spatial patterns in risk distributions that can be analyzed by the vulnerability results. The output of the proposed method has many applications in the fields of disaster management, urban planning and incident prediction.

1. Introduction

Natural gas is one of the most important energy sources in the world. With unprecedented increasing urbanization, the demand and consumption of natural gas has also increased in large cities. Thus, the density and complexity of urban natural gas pipelines will increase (Amir-Heidari et al., 2014; Cheng et al., 2015; Han and Weng, 2011; Ma et al., 2013a, 2013b; Wang et al., 2014; Zhao and Liu, 2016). Due to the high density of urban gas pipelines, the severity of damages that originates from incidents becomes higher. The consequences of accidents can cause irrecoverable vital and financial damages in an urban region; thus, it is necessary for a complex urban gas network to consider protection and maintenance of the network to prevent damage. Prediction and disaster management of probable incidents is also an important issue that should be considered (Jo and Ahn, 2002; Jo et al., 2004; Vianello and Maschio, 2014; Zhou et al., 2014; Zhou and Liu, 2012). One way that helps solve this problem is identifying areas that have higher risk levels in comparison of other places in a city. For this purpose, hazard mapping of urban gas pipelines considering the location, density and inherent parameters of pipelines will be an appropriate approach, which can be completed by Geospatial Information Systems (GIS).

In recent years, the number of gas pipeline ruptures has increased in urban areas. Passing dense pipelines of an urban gas network with different gas pressures and diameters through high population density areas with old and crucial buildings using land for educational, medical and governmental purposes will intensify the amount of vital and financial damages in the case of gas rupture. Physical and social vulnerability mapping is an excellent approach to use the proposed parameters in the risk evaluation of gas pipelines. By evaluating urban vulnerability, logical planning can be done to manage unavoidable natural and industrial incidents to reduce vital and financial losses (Bahadori et al., 2017; Chakraborty et al., 2005; Frigerio et al., 2016; Frigerio and De Amicis, 2016; Inanloo et al., 2016; Li et al., 2010; Siagian et al., 2014).

Research on hazard mapping of gas pipelines is generally conducted on national and urban scales by quantitative, qualitative and hybrid methods, which can be categorized from the spatial and non-spatial points of view. The first category is related to risk evaluations in urban and non-urban regions without a spatial view. Several researchers calculated the risk of transmission and distribution gas pipelines using the fatal length and cumulative fatal length on urban and non-urban scales with individual and social risks was their quantitative output (Amir-Heidari et al., 2014; Bahadori et al., 2017; Jo and Ahn, 2005, 2002; Jo et al., 2004). The second category includes risk-based studies

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https://doi.org/10.1016/j.jngse.2018.04.011
Received 10 December 2017; Received in revised form 8 April 2018; Accepted 10 April 2018
Available online 19 April 2018
1875-5100/

Nomenclature

A	area of the leakage opening (m^2)
a	empirical constants
b	empirical constants
C_0	empirical discharge coefficient
D	dose of the load for a given exposure time
h	distance from grid point to failure position (m)
IR(x, y)	individual risk calculation in a given position (X, Y)
i	accident scenarios
K	adiabatic index
L	pipeline length (m)
l±	ends of the interacting section of the pipeline (m)
L_i	fatal length in grid points in three lethality levels of 1%, 50% and 99% (m)
M	molecular weight of gas (kg/mol)
m_d	mass of the gas involved in the explosion (kg)
m_{TNT}	equivalent of the TNT mass for released gas (kg)
P_0	pressure around the pipeline (Pa)
P_1	pressure inside the pipeline (Pa)
P_i	lethality associated with the accident scenario *i*
P_r	probability function
Q	gas release rate (kg/s)
Q_{TNT}	calorific value of the standard TNT explosion source (J/kg)
R	gas constant (8.314 J/mol K)
R	distance between the target and the center of the flame zone (m)
r	lethality radius (m)
$r_{explosion}$	lethality radius for the explosion consequences (m)
$r_{fireball}$	lethality radius for the fireball consequences (m)
$r_{jet\ fire}$	lethality radius for the jet fire consequences (m)
T	temperature of the gas inside the pipeline (K)
(x, y)	specified location of individual risk value
ϕ_i	failure rate per unit length of the pipeline associated with the accident scenario *I* (km.year)
ΔH_d	explosion heat of the gas (J/kg)

for non-urban gas pipelines using a spatial perspective. The risk assessment of national gas transmission was conducted in Italy based on the distance between a pipeline and the risk zones (Vianello and Maschio, 2014).

Studies on the risk assessment of urban gas pipelines in the field of GIS are in the third category. Risk assessments were done for chemical and industrial sites using a quantitative method in an urban area in China in 2012, and urban planning suggestions were given for high-risk regions considering Health & Safety Executive (HSE) instructions in order to optimize land use of the surrounding buildings (Zhou and Liu, 2012). In 2014, risk assessment for a pipeline was conducted with an urban planning approach, without considering the high density of urban gas pipelines (Zhou et al., 2014). For the first time, in 2013, individual risk mapping using a new method based on the concepts of grid and fatal length for an urban natural gas pipeline network was conducted, which had similar parameters. The main limitation of this method is neglecting the effect of the risk level of some pipelines because of their empirical density scale. Unfortunately, societal risks, which are the number of deaths resulting from incidents, were determined by multiplying the mortality rate by the population density of points without spatial visualization (Ma et al., 2013a, 2013b).

The last classification is related to research that the concepts of vulnerability have been applied to assess the risks of urban natural gas pipelines. In 2014, the concept of vulnerabilities and hazards using thermal radiation and pressure from incidents were presented for the first time. Also, structural and social parameters have not been used to determine physical and social vulnerabilities, so these issues will be emphasized in future works to improve the vulnerability systems of the study area (Wang et al., 2014).

In addition, several studies have been recently completed to evaluate the vulnerability of the region. In 2003, Cutter et al. constructed an index of social vulnerability to environmental hazards, called the Social Vulnerability Index (SoVI), for the United States using county-level socioeconomic and demographic data, which leads to meaningful spatial patterns for the vulnerability index in the study area (Cutter et al., 2003). Most studies have investigated the vulnerabilities of an area to environmental hazards, such as earthquakes and floods, by considering structural, social and physical parameters (Bahadori et al., 2017; Chakraborty et al., 2005; Inanloo et al., 2016; Li et al., 2010; Siagian et al., 2014). In 2016, Frigerio et al. proposed a GIS-based approach to identify the spatial variability of social vulnerabilities to seismic hazards in Italy (Frigerio et al., 2016). Also, Frigerio and Amicis implemented the same approach using Principle Component Analysis (PCA) for natural hazards in Italy (Frigerio and De Amicis, 2016).

Many studies examine gas transmission pipelines with high pressure in the outside of the cities. In recent years, the risk assessment of urban gas pipelines has also been considered, but there are some restrictions that are better used to solve any issues. Methods in previous studies only considered the risk level of one pipeline, and as a result, the impact of adjacent pipelines did not take into accounts on the risk value. Modeling the risk of urban gas pipelines and their implementation is a complex and time consuming process due to the high density of pipeline networks. Also, because there is no visualization output for most studies, it is impossible to extract the spatial pattern of risk distributions, making it difficult for managers to make suitable decisions in critical situations. On the other hand, only the inherent parameters of gas pipelines have been affected, and the calculated risk and environmental conditions have not been considered. At the moment an accident occurs, environmental conditions, such as the strength of buildings inside urban blocks, the number of floors in buildings, the distance from high-density population area (buildings with educational, hospitals and governmental land use), the population density of children and the elderly have a direct effect on mortality and financial losses. Studies have been conducted on the vulnerability of regions to natural disasters such as floods and earthquakes on the country-level. Considering social and structural parameters at a high-density urban block level to assess the risk of urban gas pipelines is a new subject and is the main purpose of this research.

In this paper, a quantitative method is proposed to assess the risk of urban gas pipelines considering structural and social parameters of urban blocks in order to extract spatial patterns of risk distribution in urban areas. The second part of the paper expressed the theoretical basis of hazard, vulnerability and risk maps. In the third section, a case study is analyzed, and the results of the implemented method are presented. The results are then evaluated in the fourth section. Finally, the discussion and conclusion are discussed in the final part of this paper.

2. Methodology

The three main steps of the proposed method are providing a hazard map of the urban gas pipelines, preparing a vulnerability map of the study area and preparing a risk map. Preparing a hazard map involves gridding the area, determining the amount of leakage in pipelines in the event of pipeline failures, calculating the lethality radius, spatial analyzing to selecting the pipelines affecting the risk level on the grid points, calculating the fatal length of the grid points, and interpolating and creating a hazard map. Vulnerability mapping also involves selecting the parameters that affect the vulnerability of the area,