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Fire spread simulation using GIS: Aiming at urban natural gas pipeline

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ABSTRACT

With the increasing use and complexity of urban natural gas pipelines, the occurrence of accidents owing to leakage, fire, explosion, etc. has increased. To analyze the scope of impacts of single-point fires associated with urban natural gas pipelines and the spread of urban fires caused thereby, this study analyzes single-point fires and the dynamic spread of fires by using a natural gas pipeline network fire model and a framework for an urban fire spread model by using GIS spatial analysis technology. Experiments show that by using the proposed method, we can easily determine key urban areas that are impacted by natural gas pipelines and where fire spread may occur. This study should be of great significance in preventing and controlling hazardous fires, deploying firefighting forces, planning urban construction, etc. We hope that the analysis results for hazardous areas from the viewpoint of urban pipelines using the proposed modules can be directly applied to urban safety planning.

1. Introduction

With the increasing use and complexity of urban natural gas pipelines, the occurrence of accidents owing to leakage, fire, explosion, etc. has increased (Jo and Ahn, 2005). For example, on August 2, 2004, an explosion of natural gas pipelines in Asuncion, Paraguay, caused a fire and led to the death of 250 people; on April 6, 2007, a natural gas pipeline in East Nanjing Street, Shenyang, China, was broken during an excavation, causing a widespread suspension of the gas supply; and on November 22, 2013, an oil pipeline in Huangdao District, Qingdao, China, leaked and exploded, leaving 62 persons dead, 136 persons injured, and direct losses of RMB 750 million Yuan. Fires are more likely to spread and cause casualties, property losses, and large-scale environmental damage in old towns/cities dominated by wooden structures, because of the poor firefighting infrastructure and relatively narrow roads (Ohgai et al., 2007). For example, in 2014, a fire broke out in Shangri-La, an ancient town, from an inn, causing destruction to more than 100 buildings and serious economic and cultural losses in the town; and on May 9, 2009, a natural gas pipeline in Moscow, Russia, leaked and exploded, causing the largest urban fire in Moscow since the end of World War II (Han and Weng, 2011).

The above mentioned incidents suggest that urban natural gas pipelines pose a huge risk to life and property. In China, most large- and medium-sized cities have complicated pipelines, closely spaced buildings, and extremely high population density. Furthermore, they respond to accidents by paying more attention to post-accident treatment but less to pre-accident prevention, as a result of which any accident will likely have serious consequences (Fu, 2009). Therefore, there is a strong need for a pre-warning system for forecasting and simulating natural gas pipeline accidents (Ma et al., 2013a,b; Ma and Li, 2010). Although secondary disasters (e.g., fire) have a low possibility of occurrence, they can cause serious impacts and losses, and therefore, they should be strongly focused on in the simulation as well.

Toward this end, this study establishes a natural gas pipeline network quantitative risk analysis model and the urban fire spread model. Furthermore, it employs GIS spatial analysis technology to determine areas where fires can spread easily so as to take preventive measures for the same. By focusing on Leshan, Sichuan, as the study site, this study analyzes the impacts of accidents relating to urban natural gas pipelines and dynamic fire simulation; summarizes previous models; simplifies and improves them; develops a framework for the combined analysis of the impacts of fires or explosions related to natural gas pipelines and simulation of the spread of urban fires; proposes methods to determine the direct

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impacts of natural gas fires or explosions and the locations where accidents occur; and simulates the possible spread of the fires. This study visualizes the analysis of fire impacts and simulation of fire spread by employing powerful GIS spatial analysis and image display technologies (Zhao, 2011). The pre-warning system can not only serve as an important reference for related decision-making departments in formulating contingency plans but also assist in related planning management departments in conducting prevention, control, publicity, and education regarding areas with potential safety hazards before any accident happens; furthermore, it can contribute toward the secondary planning and reconstruction of a city so as to nip any potential risks in the bud (Han and Weng, 2010).

2. Related works

2.1. Analysis of impacts of natural gas accidents

Researchers, both domestically and internationally, have extensively studied the impacts of accidents related to natural gas pipelines. In the 1970s, the US started conducting risk assessments of oil and gas pipelines and identified 22 fundamental factors that endanger pipelines (ASME, 2001). Subsequently, researchers used qualitative research methods such as analytic hierarchy process (AHP), fuzzy mathematics (FM), fault tree analysis (FTA), and data envelopment analysis (DEA) for the risk analysis of natural gas accidents (Cagno et al., 2000; Bonvicini et al., 1998; Yuhua and Datao, 2005; Hawdon, 2003). By summarizing existing studies, Muhlbauer (2004) wrote the *Pipeline Risk Management Manual*, which is the first report to contain a quantitative risk assessment of oil pipelines. This manual is widely accepted worldwide and is considered a standard for developing risk assessment software. It has been successfully applied to the development of several systems and has been used continuously for more than 10 years (Han and Weng, 2011). In the early 1990s, Canada established a special pipeline risk assessment committee responsible for implementation schemes for the development of pipeline risk assessment management technology (Brian and Mike, 1995). Between 1997 and 2000, the Gas Transportation Committee of the International Gas Union (IGU) conducted studies on risk assessment; in their concluding report in 2000, they presented methods for risk assessment and identification, risk assessment, risk control, environmental risk assessment, etc. (Fever, 2000). In 2000, Southwest Petroleum University and PetroChina Southwest Branch jointly researched and developed a gas transportation pipeline risk assessment software and conducted full-line risk analyses and assessments of gas pipelines in Chongqing using this software and an international assessment indicator system (Fu, 2009). In 2008, the China Safety Science Research Institute of Dangerous Chemicals Safety Institute of Technology developed the CASST-QRA software for the quantitative area risk assessment of major hazardous installations V1.0 (CASST-QRA, 2008). Ma and Li (2010) proposed natural gas disaster models, including the fire effect model and the overpressure explosion model. Ma et al. (2013a) established several GIS-based natural gas pipeline network pre-warning systems by employing a quantitative risk assessment method. Many studies and analyses have shown that the quantitative risk assessment method has become one of the important ways for improving the performance of urban natural gas pipelines and avoiding the related risks. However, most currently used analysis models do not take accident types into consideration; instead, they only focus on the consequences of an accident or analyze some link of the accident process, and they do not simulate the further impacts of accidents (e.g., fire spread). To bridge this gap, the present study focuses on these issues.

2.2. Simulation of urban fire spread

Many researchers have simulated fire spread. Relative to the spread of urban fires, current research methods for the spread of forest fires are mature. These include the contiguous cellular model based on cellular automata theory and the volatility transmission model based on the Huygens Principle (Karafyllidis and Thanailakis, 1997; Anderson et al., 1982). Unlike forest fires, the spread mechanism and spread environment of urban fires have distinct characteristics, based on which researchers have built corresponding spread models.

Through statistical analyses of data related to post-earthquake fires, Japanese research groups such as Suzuki and Kinbara (1940), Tokyo Fire Prevention Working Group (1942), Tosabayashi (1947), Hamada (1951), Hishida (1954), Horiuch (1961), Fujita (1975), and Sakai (1983) have proposed a series of fire spread empirical models (Fire safety science, 1986), among which Hamada's model is considered the most representative. This model is based on an ideal city (all buildings in the city have consistent size, shape, and distance) and related experiences, which provides a method that is relatively easily understood and easily applied and that becomes a basic empirical model with the most extensive scope of application and the greatest influence (Hamada, 1951). Based on Hamada's model, the Federal Emergency Management Agency developed the FFE earthquake secondary fire spread model (HAZUS99 Federal Emergency, 1999). In 2000, Himoto and Tanaka built a physics-based model for fire spread and models for heat radiation and plume spread inside buildings and among buildings based on the mechanism of urban fire spread (Himoto and Tanaka, 2002, 2008). In 2006, Zhao et al. simplified the model for spread inside buildings (Zhao et al., 2006; Zhao, 2010) and divided the entire fire simulation process into in-building spread and building-to-building spread. Cousins et al. (2002) and Ohgai et al. (2007) developed a cellular automata urban fire spread model based on a 3×3 grid; Zhao et al. (2011) improved this model by modifying its form and increasing the cell size to develop an urban fire spread model based on coarse cellular automata. In 2008, Lee et al. compared and summarized existing urban post-earthquake fire spread models in terms of aspects such as the model algorithm, model parameter, result analysis, and model presentation (Lee and Davidson, 2008). In 2010, Selina et al. developed a model for fire spread in a single room, among rooms in a building, and among buildings (Lee and Davidson, 2010). Cheng and Hadjisophocleous (2011) developed a model for horizontally and vertically simulating urban fire spread. Nishino et al. (2012) presented an evaluation method for urban post-earthquake fire risk and simulated the fire spread results using physics-based fire-spread. Recently, Li and Davidson (2013) apply an urban fire simulation model to a case study area and examine the key factors that influence fire spread.

We note that most existing urban fire spread models are proposed based on post-earthquake fires and only analyze the impacts of natural gas fires (Ma et al., 2013a; Ma and Li, 2010) without considering the further spread of fires occurring in areas with many wooden structures. And also less the other application is implemented. Moreover, theoretical models have been used to analyze spread processes based on their mechanisms; however, they are too complicated and need to be simplified and revised so that they can be adapted to macroscopic dynamic simulations. In addition, fire spread shows special characteristics when caused by natural gas pipeline leakages. Based on related studies on the two sectors and conclusions regarding practically available models and in combination with the objectives of this study, this study simplifies, revises, and improves problems such as incomplete consideration of accident types, lack of further simulations of fire spread, complexity of urban fire theoretical models, and lack of analyses of natural gas accidents.