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Urban vulnerability under various blast loading scenarios: Analysis using GIS-based multi-criteria decision analysis techniques

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ABSTRACT

This paper examines physical vulnerability of District No. 6 of Tehran to blast damages and blast loads. The main objectives are to enhance planners and decision makers' awareness of the extent of vulnerability of buildings in the study area (under different risk scenarios) and to provide guidance on how to enhance preparedness against potential risks. Physical vulnerability of District No. 6 of Tehran was evaluated under three different blast loading scenarios. An expert survey, involving specialists with expertise in urban development, passive defense, construction, and architecture was carried out to extract fourteen vulnerability criteria. Fuzzy criteria maps corresponding to each of these criteria were produced in Geospatial Information Systems (GIS) environment. Fuzzy analytic hierarchy processing was used to weigh the criteria. Criterion maps were combined using the fuzzy weighted linear combination operator. Finally, Ordered Weighted Averaging (OWA) operator was applied to generate final vulnerability maps. Results show that, for all scenarios, almost 70% of the buildings in the district are of high vulnerability. Sensitivity analysis confirms the reliability of the model.

1. Introduction

Urban vulnerability can be defined as the liability of cities and their infrastructures to losses caused by disasters (Karashima, Ohgai, & Saito, 2014). Potentially existing vulnerabilities of an urban system are exposed in the face of disruptive events. Four frequently mentioned types of vulnerability are namely, physical, social, economic, and environmental (Kim & Marcouiller, 2015). Vulnerability analysis can be conducted for both natural and human-made hazards. The fact that cities are loci of economic, social, and political activities and account for more than half of world population makes conducting research on urban vulnerability of high significance (Desouza & Flanery, 2013; Parnell, 2016; Williams, Batho, & Russell, 2000). Doing research on urban vulnerability is specifically important in the context of major cities that are hubs for regional, national, and international activities. Results of such research can be used by planners and decision makers to enhance planning and preparation for disruptive events, that is widely considered as an effective strategy for enhancing resilience and mitigating the impacts of disasters (Chmutina, Lizarralde, Dainty, & Bosher, 2016; Desouza & Flanery, 2013; Sharifi & Yamagata, 2016). Determining the extent of vulnerability of cities and their elements is an essential step towards preparation for threats and disruptive events. This study is focused on determining physical vulnerability of District No. 6 of Tehran to blast loads, as potential human-made threats. Potential explosion targets are identified and classified based on their degree of importance. Determining vulnerability of explosion targets can help planners and policy makers to develop appropriate planning and preparatory measures for minimizing impacts of potential threats.

A brief literature review is presented in Section 2. The third section provides further information about the particular threat analyzed in this study and the characteristics of the study area. Section 4 explains the research methods and provides a theoretical framework for analysis. In Section 5 vulnerability maps for different risk scenarios are provided, results of the statistical analyses are presented, and a

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sensitivity analysis is conducted to test reliability of the results. Section 6 concludes the study by discussing the findings, providing policy implications, drawing conclusions, and making suggestions for future research.

2. Literature review

The literature on urban vulnerability is immense and still growing. This literature deals with vulnerability and emergency management in the context of a wide range of stressors and hazards such as flooding, drought, energy shortage, wildfires, and terrorist attacks (Adger, 2006; Coaffee, 2009; Gillen, 2005; Kapucu, 2012; Prior & Eriksen, 2013). Research on urban vulnerability to invasions and terrorist attacks is comparatively nascent, but rapidly growing (Coaffee, 2009; Williams et al., 2000). In a recent paper, Matijosaitiene and Petriashvili (2017) demonstrate that the extent of vehicular access to buildings, the extent of mixture of private and public areas, and the distribution pattern of buildings with identical functions are important factors that terrorists may consider when selecting attack targets.

In terms of methods used for evaluating vulnerability, there are many studies that utilize GIS-based, multi-criteria decision analysis methods for evaluating disaster risk, prioritizing risks, and informing urban planning. These studies are mainly dealing with vulnerability of urban areas to natural hazards such as floods and earthquakes (Ebrahimian-Ghajari, AleSheikh, Modiri, Hosnavi, & Nekouei, 2016; Fernandez, Mourato, & Moreira, 2016; Hashemi & Alesheikh, 2011; Zhang, Wang, & Lin, 2015). However, the use of GIS-based, multi-criteria decision analysis techniques for evaluating risks and damages related to human-made hazards such as blast loads and explosions is limited. Emphasizing that improving robustness and blast resistance of civilian structures is of critical importance, Tadepalli and Mullen (2006) developed a model for assessing risk, and projecting and analyzing potential damages and losses. Building elements such as structure type, level of occupancy, number of stories, market value of the building, glazing type, and maximum number of building inhabitants are incorporated in their GIS model. The model is used to simulate vulnerability of buildings located at the University of Mississippi. Results of the study are visualized in the GIS environment and can be utilized for blast hazard mitigation. A web-based GIS was developed by Kulawiak, Lubniewski, Bikonis, and Stepnowski (2009) for spatial visualization of the impacts that a simulated explosion may have on a railway station in Gdansk, Poland. Results demonstrate the utility of this technique for identifying potential physical, social, and economic impacts of explosions on buildings and critical infrastructure in and around the station.

A GIS-based risk analysis model was developed by Ma, Cheng, and Li (2013) to simulate potential impacts of the explosion of natural gas pipelines on buildings. The potential damages are classified as: “minor damage, minor structural damage, major structural damage, and partial demolition” (p. 1190–1191). Armenakis and Nirupama (2013) combined GIS index modeling and risk assessment to develop a spatial risk assessment method for estimating spatial hazard risks that propane explosion can cause. Their results show that risk assessment using GIS techniques is an effective method to prioritize spatial risks and estimate potential damages depending on the level of proximity to the source of explosion. Integrating such techniques into urban planning can make significant contributions to disaster risk management in cities.

Limited research exists on vulnerability of Iranian cities to blasts and explosions. Ebrahimian-Ghajari, Alesheikh, Modiri, Hosnavi, and Abbasi (2017) developed a model to evaluate physical vulnerability to intentional explosion hazards in Tehran. They classified buildings based on their probability of being selected as targets for intentional explosions. The findings showed that only about 25% of the buildings have low vulnerability. Using GIS and Analytic Hierarchy Process (AHP) methods, Azizi and Bornafar (2012) assessed vulnerability of the built environment in District No. 11 of Tehran. The study uses 14 criteria for evaluating vulnerability. The authors assume that vulnerability to air attacks and earthquakes can be modeled in a similar way. Due to this assumption, specific criteria related to explosions are not used in the study. The study also suffers from two other major shortcomings: the uncertainty conditions are not considered, and sensitivity analysis is not conducted.

This brief literature review reveals some major shortcomings of existing research. Comparatively less attention has been paid to vulnerability of cities to human-made disasters and hazards. In specific, multiple point explosion events have received little attention. Also, experiments and simulations are mainly focused on small-scale, individual urban components such as buildings, street networks, and railways. There is a clear lack of research on vulnerability to blast hazard at larger scales such as neighborhoods, districts, and cities. Management and mitigation of explosion hazards in cities warrants further research. This study aims to fill the research gaps and build upon existing research by demonstrating the utility of GIS-based MCDA for estimating vulnerability at the district scale. Other noteworthy, new contributions of this study are as follows: by using fuzzy sets theory, uncertainty conditions involved in the decision making process have been taken account of; the list of vulnerability criteria used in this research is more comprehensive; the developed model is capable of generating physical vulnerability maps for different scenarios and under different risk conditions; and finally, the study provides recommendations and policy implications that can inform planners and decision makers in Tehran about existing vulnerabilities and actions that should be taken to address them.

3. Scope of the study

3.1. Explosion events as human-made threats

As discussed above, identification of potential threats and developing strategies to address them is of high significance in urban management and planning. In the context of urban environments, threats can be divided into two main categories, namely, natural and human-made. There are similarities and differences between these two types of categories in terms of their underlying characteristics. It is, however, beyond the scope of this study to elaborate on these characteristics. Interested readers are referred to McDonald (2003).

Here, the focus is only on explosion incidents as common types of human-made threats. The physical structure of cities is vulnerable to blast waves produced by explosive devices. Often times, explosions result in outward release of pressured gasses. The rapid expansion of these gasses spreads the surrounding air outward (from the explosive core) in a spherical pattern. The resulting layer of compressed air is called blast wave and its pressures is known as overpressure (Krauthammer, 2008). Blast waves fall into two categories: shock waves, which are products of the positive phase of the blast and pressure waves, which are attributed to the negative phases of the blast wave. In general, range and shape of blast waves depend on the amount of energy released and the distance from the explosion core. Since the negative phase of the blast wave is less powerful than that of the positive phase, it is often ignored in designing structures. Therefore, it is also ignored in this study.

In engineering calculations, various waves and their respective pressures are approximated and used in the form of pressure-time variations of the blast under different conditions. Variations of pressure against time and the maximum amount of pressure in the positive phase are of higher importance in calculations and are usually expressed by exponential form (see Fig. 1). The variations shown in this figure are referred to as pressure-time variations, and are expressed using the following exponential equation (Friedlander Equation) (Smith & Hetherington, 1994):