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Evacuation risk assessment of regional evacuation for major accidents and its application in emergency planning: A case study

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ABSTRACT

Major accidents, like toxic gas releases, fires and explosions, may influence a large area. And thus, evacuation is a necessary public protection measure to mitigate the health consequences of major accidents, but risk assessment is still required. This paper focuses on providing an assessment framework of evacuation risk for major accidents, and the exposure dose calculated based on vulnerability model and accident probability is introduced to predict the risk. Evacuation risk evaluation based on "ALARP" guidelines is employed to partition the emergency planning area and to give suggestions for emergency preparation, as well as to classify the alternatives of evacuation flow assignment and find the optimal solution to decide whether to evacuate or to take shelter-in-place for emergency response through using different heuristics. The goal of its application in emergency response planning is to provide a fast heuristic method to select evacuation paths, but neither to minimize the evacuation time nor minimize the evacuation risk. The primary intention is to find an optimal solution within optimized evacuation time and with acceptable evacuation risk. A case study on evacuation risk assessment for phosgene leak accident in Yantai, China is used as an example to illustrate evacuation risk assessment process and its application in emergency preparation and response.

1. Introduction

With the rapid development of China's economy, the number of industrial parks or projects involving hazardous chemicals is increasing annually. Currently, various major accidents, such as explosions, fires, chemical leaks and unintentional poisoning frequently occurred due to human, equipment, production management, or environmental factors, and they might result in adverse effects on the health of those who work at chemical plants, as well as on the population in surrounding areas (Xu and Fan, 2014; Duan et al., 2011; Li et al., 2009; Chu and Wang, 2012; Li et al., 2014). When an accident takes place, the impact can often affect the surrounding population and environment, causing adverse effects and even leading to heavy casualties and property losses (Zhou and Liu, 2012; Zhu and Chen, 2010; Zhou et al., 2009).

Evacuation is a necessary public protection measure to mitigate the health consequences of major accidents (Chen et al., 2012). As a crucial component of emergency response and management, evacuation serves to transfer occupants to safer areas from risky ones (Perry and Lindell, 2003). Evacuation may differ by scale and starting time of evacuation etc. (Stepanov and Smith, 2009). Depending on the type of disaster, pre-warning of sudden-onset disasters may leave enough time for evacuation prior to the event (Kovacs and Spens, 2007). Emergency evacuation plans assign evacuees to fixed routes or destinations, and they define optimal evacuation policies for the population from areas under risk and uncertainty (Stepanov and Smith, 2009).

Studies on evacuation network involve estimating evacuation efficiency using network analysis (Løvas, 1995). In network analysis, the transport system in the area under study is abstracted into a network, and transportation infrastructures are evaluated in terms of accessibility, connectivity, or vulnerability in comparison with other facilities in the city (Chen et al., 2012). Most of these researches focused on the vulnerability of the road network and other critical infrastructures in a city, assessing the aftermath of the damage from disasters and interruption to the connectivity of transportation and communication (Chang, 2003; Myung and Kim, 2004; Murray and Grubesic, 2007; Grubesic et al., 2008; Kwan and Ransberger, 2010). A limited number of these studies focused on the estimation of evacuation vulnerability associated with the evacuation itself, where the conventional view of risk as the clearance time was extended in accordance with the notion of "the potential for congestion, accidents, and general difficulty in

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Nomenclature

v_i	node in the network, $i = 1, 2, \ldots, n$, and v_1 is the source node, v_n is the destination node
n	total number of subareas.
$G(V,E)$	emergency evacuation network denoted by a directed graph
V	set of nodes corresponding to the subareas and $V = \{v_1, v_2, \ldots, v_n\}$
E	set of arcs (v_i, v_j) corresponding to the links between each two subareas, $E \subseteq V \times V$
p	evacuation route selected, which is sequence of nodes in the evacuation network, and should not have circles considering the time pressures in emergency evacuation, $p = (v_{p1}, v_{p2}, \ldots, v_{pk}, \ldots, v_{pK})$, $1 \le p_k \le n$
p_k	sequence number of node in the network
k	travel sequence of node v_{pk} along evacuation route p
$N_{p,i}$	health consequence (e.g., acute, latent fatalities and injuries) associated with accident scenario i when an individual traveling along the evacuation route p
$P_{p,i}$	probability of occurrence associated with accident scenario i when an individual traveling along the evacuation route p
t_i	time needed to travel through node v_i
t_i^+	time when the individual reaches node v_i
t_i^-	time when the individual comes out of node v_i
$D(p, v_{pk})$	overall dose received by an individual travels from node v_{p1} to node v_{pk} along route $p = (v_{p1}, v_{p2}, \ldots, v_{pk})$
$D(v_{pk})$	dose received by an individual travels through node v_{pk} in the area of interest
$c(x,y,t)$	intensity of the adverse effects at point (x,y) and instant of time t
χ	constant depending on the type of toxic materials
P_s	peak value of the static overpressure
$P_{\exp}(p)$	conditional probability of consequence
u	integral variable
$P_r(p)$	probability unit
a, b	empirical constants, empirically: for toxic materials, a and b are depending on the types of chemicals; for thermal radiation, $a = -37.23$, $b = 2.56$; for overpressure, $a = 5.13$, $b = 1.37$
d_i	conditional probability of occurrence associated with accident scenario i
F	accident probability
$IR(v_{p1}, v_{pk}, p)$	individual risk of an individual traveling along evacuation route p
$IR(p_1)$	individual evacuation risk in each subarea v_{p1} under a major accident
P	a solution of evacuation pedestrian flow assignment

deploying response vehicles into the evacuation zone" (Cova and Church, 1997; Church and Cova, 2000; Campos et al., 2012).

These network-based studies proposed a new perspective that reinterprets and expands the notion of risk (Chen et al., 2012). Conventionally, the risk associated with disasters was understood as a measure of losses in terms of socio-economic impacts from a potential calamity (Cho et al., 2001; Ham et al., 2002; Simpson and Human, 2008). In the recent approaches, risk is treated as the potential inability to find accessible routes and the difficulty of transferring rescue resources. Also, when transporting people affected by the accident to safety area, risk is introduced as a concept to delineate the initial conditions of pre-disaster scenarios. Considering risk merely as the potential of transport difficulty to a great extent simplifies the problem to the extent of focusing on some objective factors, such as, the distribution of evacuees and the road configuration in the area under study, and makes it possible for the concept of risk to be formulated in mathematical equations, plotted on a map, and rated in a disaster-prone area for the purpose of facility enhancement and disaster preparation (Chen et al., 2012).

However, risk is a complicated concept, in which, not only the possibility of the disastrous events themselves are contemplated, but also the resultant impact of these events must be considered (Turner, 1992). The impact of the disasters, which may lead to contingent events, such as road blockages or traffic congestion occurring after a hurricane, is also considered in some recent researches (Chen et al., 2012; Kwan and Ransberger, 2010). Another aspect of complexity that must be considered is human behavior. People's decisions and behaviors always have a huge effect on the aftermath of disastrous events. For example, when to evacuate and how to evacuate have great effects on evacuation. In addition, the human vulnerability should also be considered, especially in fire, explosion and leakage accidents.

A vast majority of emergency planning research focuses on evacuation based on disasters, such as earthquake (D'Orazio et al., 2014), hurricanes (Robinson and Khattak, 2012; Koshute, 2013), high-rise fires (Ma et al., 2012; Fang et al., 2012), flood (Kolen et al., 2013; Brown, 2014) and some other natural disasters. However, major accidents like toxic gas release, as well as fires and explosions, may also influence a large area (Zhang et al., 2017). Studies on middle-scale regional evacuation under the condition of such major accidents are still insufficient. A limited number of the existing studies focus on evacuation risk under the condition of major accidents (Zhou et al., 2009; Zhang et al., 2017; Georgiadou and Papazoglou, 2010), where the evacuation path selection is considered to be stochastic, or the exposure concentration or health consequence is used to measure the evacuation risk. In fact, taking toxic gas release as an example, the evacuation risk is jointly determined by the concentration, exposure time and accident probability. In addition, evacuees are usually assigned to fixed routes under guidance rather than randomly evacuating in evacuation organization (Yang et al., 2015).

Some methods and principles have been proposed to determine the emergency planning area of major accidents. The Emergency Response Guidebook (ERG) defines the initial isolation and protective action zones (Department of Transportation, 2004; Alileche et al., 2015), and the Chemical Stockpile Emergency Preparedness Program (CSEPP) presents an Emergency Planning Zone (EPZ), which encompasses the Immediate Response Zone (IRZ), Protective Action Zone (PAZ), and Precautionary Zone (PZ) (Shumpert et al., 1995). When an accident happens, protective actions in practice may be limited to a small part of the EPZ, which means, there are differences between the EPZ and the actual emergency planning area. In the analysis of evacuation options for nuclear accidents, Tawil et al. proposed that the actual emergency planning area consists of two regional components, which can be called Keyhole-shaped Zone (Tawil et al., 1987): one is the Circular Zone (CZ) with accident location as the center, and the other is the Wedge-shaped Zone (WZ). However, the above-described methods and principles only define emergency planning area, without clarifying what measures should be taken in different areas or stating their application conditions. Moreover, there is no clear guidance on emergency preparation for major accidents under normal conditions.

To solve all the above problems, governments or relevant agencies should develop efficient emergency plan based on risk analysis (Zhang et al., 2017; Villa et al., 2016; Krisp and Špatenková, 2010). Emergency plan should not only include emergency response plan at the time of disaster, but also include emergency preparation plan under normal conditions. In emergency preparation, appropriate risk mitigation measures, such as relocation, building enough number of shelters,