Optimal Design Strategies to Improve Evacuation Safety of Community with Large-Scale Blocks

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Abstract

Evacuation efficiency is one of the most significant factors in community planning to ensure the residents' safety in emergency. In the context of "big blocks, wide streets" urban planning practice in past decades, the blocks with large scale becomes one of the typical features that give rise to community morphology in China, which brings about potential risks to evacuation process in emergency. Through conducting series of evacuation simulation with Agent-based model, this paper examines the potential hazards of community with large scale blocks during evacuation by the analysis of evacuation time and distribution characters of crowds. Besides, simulated scenarios are created for observing congestion scenes caused by the mass of evacuee. Three optimal design strategies are presented based on the evacuation routes and the congested areas. The modified scenarios show reductions in gross evacuation time and congestion degree which validate the optimal design strategies in return.

Introduction

Due to the complexity of geographic conditions, China is one of the few countries worldwide that have most serious natural disasters. Based on the distribution of the disasters, there are over 70% of big cities and more than half of the population are situated in the frequently affected areas. The disaster itself and the followed secondary disasters may lead to massive evacuation, which will potentially cause serious accidents like stampede. As the key element of urban function and spatial composition, community is the high-risk place for urban public accidents (Toyoda, 2014). Since 1950, China's urban construction has been greatly impacted by the planning idea of "big blocks, wide streets" from the Soviet Union and has developed the urban fabrics featured with large scale blocks. Continued with such character, great numbers of big communities enclosed by the large-scale blocks have been developed since the year of 2000 (Yuan, 2010).

Therefore, in consideration of the fact that the scale of Chinese urban blocks are currently oversize, the aim of this research is to reduce potential hazards during crowd evacuation of community with large scale blocks through design strategies. It analyses the impact mechanism between the structure of large-scale blocks and the evacuation crowd, discusses the vulnerable area

of such type of communities during evacuation and explores the optimal design strategies to improve the safety of community.

This paper is divided into three parts: First, hazards which may cause by evacuation are discussed. Second, the idealized model of community is set up, and simulation scenarios including optimal strategies are proposed. Finally, the evacuation vulnerability of community with large-scale blocks and the availability of optimal strategies are discussed.

Potential Hazards in Community Evacuation

Community is the basic cell of social management as well as the fundamental element in the system of urban disaster prevention (Zeng, 2008). In face of disasters, a well-appointed shelter can provide effective protection for the residents. On the other hand, the efficiency and safety of transferring residents to shelters should also be guaranteed. In the process of evacuation, long period of congestion might easily cause panic and contribute to a higher risk of stampede (Wu, 2015). Historically in 1975, due to the defective evacuation system, the 7.6 magnitude earthquake in Haicheng City, Liaoning Province, China brought about a series of secondary disasters that caused even more deaths than the earthquake itself (Zhu, 1982). The stampede occurred in Shanghai New Year's Eve in 2014 also revealed that massive crowd congestion would aggravate the psychological pressure, lead to the actions of push and squeeze, and eventually increase the chances of following accidents. Hence in community evacuation, to improve the evacuation efficiency, reduce time consuming and narrow the range of congestion is the key to enhance the safety in evacuating process. In the precedent studies of Chinese community disaster prevention, some efforts have been made on the function composition and location determination of the shelters (Fan, 2010), but the interactive relationship between the community forms and the evacuating process have rarely been paid attention to. In order to strengthen the efficiency of community evacuation and lower the risks of potential hazards, a computer aided simulation has been conducted to quantitatively support urban design and disaster prevention strategies.

Evacuation Simulation

This paper establishes an idealized model of community formed by large scale blocks according to related design codes. The platform Pathfinder has been used to simulate the evacuation process of community to analyse the evacuation time and the congested area.

Build of Idealized Community Model

In order to exclude the impacts of redundant information in urban morphology (Carpentieri, 2015), an idealized community model has been built for simplification. The related spatial parameters include the block scales, exits, pedestrian layouts, location, service radius of shelter and the population of community. They are set up according to the requirements of the related literature and the design codes of China.

Zhu figures out that the road networks in part of Chinese cities are formed by trunk road which lack of branch system (Zhu, 2006) (Figure 1). To avoid small blocks reduce vehicle speed, usually the distance of two road intersections in China are between 300 meters to 500 meters (Fang, 2013). To reduce unnecessary variable, this research sets up the blocks in dimension of 300m $\times$ 300m. The width of streets between blocks is 30m in accordance with secondary trunk road in China's urban road network (Wen, 2001). Meanwhile, *Code of urban Residential Areas Planning & Design*, *Code for Transport Planning on Urban Road* have established the requirements for pedestrian roads and exits which include: the width of sidewalk is no less than 1.5 meters; the spacing of crosswalks is from 250 meters to 300 meters; the distance between two pedestrian exits is no more than 80 meters (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2002); the minimum distance between the exit to the crosswalk is 50 meters (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 1995). Following these rules a community model with reasonable parameters has been set up as is shown in Table 1.

Figure 1: Fabrics of Chinese Cities with Large Scale Blocks.

In terms of the population setting, *Code of urban Residential Areas Planning & Design* states that the

average land area per person of a neighbourhood with multi-story building in most area of China is 28 m² (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2002), based on which a gated neighbourhood formed by block in 300m $\times$ 300m will have the population of 3214.

In China the studies related to community disaster prevention usually consider the service radius of the shelters as 500m. In fact, the real circumstances of evacuation show that people are from a distance of 500 to 600m (Su, 2007). Moreover, since the environmental cognition of the residents within the same block is inclined to be unified, the residents tend to evacuate to the same shelter (Su, 2007). Therefore, in this evacuation model, the service radius of the shelter has been set to 600m. A buffer area of 600m starting from shelter is regarded as research area showing as figure 2. Shelter in this research is set as an open space at the same size with other blocks and does not take into account the impacts that different forms of shelters could bring to the evacuation process.

Table 1: Related Parameters of Idealized Community.

Parameter	Unit (m)
Distance between Pedestrian Entrances	50
Width of Side Walk	3
Spacing of the Crosswalks	300
Width of streets between blocks	30

Figure 2: Service Radius of the Shelter.

Parameters of evacuation model

"Pathfinder"-the software based on agent-based model with continuous modelling approach has been introduced to simulate the entire process of all the residents evacuating through the exits of each block to the shelters through city road network. Evacuation routes are simulated using the A* algorithm of the model in which a locally quickest path planning approach is used (Ronchi, 2016). The model of Pathfinder is able to build urban scale scenario and be used to simulate a large number of evacuees (Lovreglio, 2016). According to the location of evacuee and the queue time at exits, the hierarchal of evacuation routes are carried out to choose the paths that allow the least time to the shelter, which gives the residents more flexibility to pick the paths based on the congestion situations. Although algorithm of shortest path can provide shorter walking distance but caused similar routes selection and lead to longer time consuming because of large scale congestion. Since there are numerous evacuees involved in the evacuation process, in order to reduce computing resource and focus

on the spatial elements of block scale, the simulation does not consider the influence from ages and gender to moving speed. Instead an average speed of 1.4m/s has been set up (Smith, 1995). The walking speed as a function of density is followed with Ando's results: when the density of crowd is 1.8 persons/m², the speed is 0.8m/s; whereas when the density rises to 4 persons/m², the speed goes down to 0.4m/s (Smith, 1995).

Simulation Scenarios

The evacuation scenario before optimization is set as Scenario 1. At the beginning of the simulation, all the residents in blocks are randomly distributed. Residents have a high awareness of their own living environment, so it is set that residents know all the exits information of the block, as well as the alternative routes to the shelter. Due to traffic on urban road network does not stop when disasters break out (i.e. rescue vehicles, ambulance). In order to make the simulation more consistent with the real emergency situation, only the sidewalk can be used as evacuation routes in the simulation.

Scenario 2 is the optimal strategy to integrate the internal road network of blocks. The gated neighbourhood constructed within large scale block is one of the main residence modes that currently exist in China. Due to the closed property of the blocks, people can only choose the urban network for evacuation. The flow of the crowds is too heavy for the sparsely distributed urban roads, while the traffic conditions inside each block is not being fully used, so that scenario 2 considers open the road systems inside the gated blocks.

Scenario 3 is set as enlarge the space of potential congested area. Since the retained people are not informed about the congestion situation on the way ahead, feeling of panic might be raised and caused push and squeeze, which will eventually lead to chaos in the crowd. Scenario 3 discovers the potential congestion spots in evacuation and widens the traffic roads accordingly. It picks congestion sections of the roads and increases the width by 1.5 meters.

Scenario 4 tries to improve the evacuation efficiency by increase the density of road network. The residence mode formed on the basis of blocks along with the large-scale road network give limited choices on the evacuation paths. It is difficult to distribute or disperse the thick crowd. Scenario 4 is proposed to increase the density of the traffic network within the 300m buffer area of the shelter. In this scenario the 300 meters by 300 meters road network will be densified to 150 meters by 150 meters.

Table 2: Scenarios of simulation.

Scenario 1	Original Condition
Scenario 2	Integrate the Internal Road Network of Blocks
Scenario 3	Enlarge the Space of Potential Congested Area
Scenario 4	Increase the Density of Road Network

Model Simplification

In this model the population is 77,136, which takes great workload and long process for simulation. In order to improve the efficiency without affecting precision of the simulation, a simplified model has been carried out to represent the entire study area: it is one quarter of the community that is determined by the centre lines of the complete area. In order to testify the reliability of this hypothesis, the evacuation simulation was taken out for the simplified model. The test reveals that the entire area and the selected portion have similar evacuation conditions (Table 3). Meanwhile the accumulate paths of evacuees in the simplified model are identical with the complete model (Figure 3). The test verifies the rationality of the hypothesis and therefore the simplified model will be used later in the studies applied with optimal design strategies.

Figure 3: Accumulate Paths of Evacuees.

(a) Complete Model. (b) Simplified Model.

Table 3: Comparison of the Complete and Simplified Model.

Model Type	Number of Subjects	Evacuation Time
Complete Model	77143	59min28s
Simplified Model	25714	59min47s

Results and Discussion

The modelling result of scenario 1 shows that the evacuation time is 59 minutes 47 seconds (Table 4). Congestion at different degree is happening at major evacuating routes and block exits.

Table 4: Evacuation Time in Each Scenario.

Scenario 1	Scenario 2	Scenario 3	Scenario 4
59min47s	57min	41min50s	49min35s

Through analysing the behavioural trajectory and density dynamics of the crowd in Scenario 1, the duration and range of different congested areas are obtained (Figure 4). The congestions occurred in the exits of the block can be categorized as two kinds of situations: 1) Crowds inside the block are simultaneously gathered in the direction of the exits, and the carrying capacity of the exits cannot meet the evacuation needs of such large-scale people (Figure 5 (a)). 2) Because of the external roads adjacent to the exits are blocked by the crowds, it is difficult for people to walk out of the block, resulting in traffic jams (Figure 5 (b)). Congested areas labelled S₁₁ and S₁₅ are the typical second type of congestion phenomenon. The congestion of these two locations in external roads starts from 214 seconds and 238 seconds

respectively, resulting in the residents detained inside the blocks exit for nearly 40 minutes, which is the most serious congested area in Scenario 1 (Figure 4 (a)). The second type of congestion mainly occurs in the range of 300m from the refuge space. Despite their relatively closer linear distances, that type of congestion is easily aggravated due to the crowd flow convergence from all directions, which leads to more gross evacuation time consumption.

Long-distance congestion will not only increase the gross evacuation time, but also trigger the panic of the refugees and lead to other derivative disasters. There are many roads in Scenario 1 with a congestion length more than 300 m, which increases the risk of stampede accident and other disasters caused by crowd gathering (Figure 4 (b)). Due to the small density of the road network, there are no other effective shunting methods based on the single road network structure, resulting in the serious shortage of the instantaneous carrying capacity of the urban road network, thus affecting the safety of the evacuation process and the accessibility of the urban road network.

According to the shelter setting requirements of China, residents should arrive at the community shelter within 10 minutes. This time bound is for residents to complete the evacuation of the straight-line distance from residence to shelter without congestion. Simulation results of scenario 1 show that evacuation of community with large-scale block is seriously congested. Only 27.6% of all residents reached the shelter within 10 minutes. It reveals the irrationality of the existing design standard of shelter and the potential danger of large-scale block evacuation.

Figure 4: Congestion Situations of Scenario 1.
(a) Duration Time of Congested Block Exits (s).
(b) Length of Congested Streets (m).

Figure 5: Exits Congestion.
(a) Type 1. (b) Type 2.

Integrate the Internal Road Network of Blocks

In Scenario 2, in order to explore the possibility of improving evacuation efficiency by using the road

network inside the blocks, residents can choose the most convenient roads to pass through within each block. It turns out that the evacuation time in Scenario 2 is 57 minutes, which is 2 minute 47 seconds less than the time in Scenario 1 (Table 4, Figure 6). From the accumulated paths of evacuees, people start to choose the roads inside each block for evacuation to avoid the congestion at the urban road intersections. However, since the congestion outside the blocks have not been relieved, people who evacuate from the roads inside the blocks are retained at the community exits (Figure 7). Moreover, there is a significant fluctuation for the congestion time of the block exits within 300m of the refuge space. The congestion time of both the exits S₂₇ and S₂₁₅ increase by nearly 20%. The crowds from other neighbourhoods even triggered new congested areas labelled S₂₁₂ and S₂₁₈ respectively with durations more than 1000s (Figure 8 (a)). Although the congestion condition of the block exits is not to be mitigated, the road usage rate is continuously reduced while more people entering the block. The number and the length of the congested roads decreased significantly compared to that of in the Scenario 1 (Figure 8 (b)).

The experiment demonstrates that the use of the independent road network inside each block can slightly reduce the evacuation time, but it leads to new congested areas. Moreover, since the residents are not quite familiar with the traffic in different communities, it would easily cause panic once a large-scale congestion occurs. Hence in the event of evacuation, to use the road within block should be under the guidance of the emergency rescue personnel.

Figure 6: Evacuation Time Comparison of Scenario 1&2.

Figure 7: Accumulated Paths of Evacuees in Scenario 2.

Figure 8: Congestion Situations of Scenario 2.
(a)Duration Time of Congested Block Exits (s).
(b)Length of Congested Streets (m).

Enlarge the Space of Potential Congested Area

The result from Scenario 3 explains that this optimal design is able to considerably decrease the evacuation time, which becomes 41 minutes 50 seconds (Figure 9, Table 4). Though there is no change of the number of congested areas in the improved scenario, the gross congestion time of each area is reduced to a great degree, which is mostly in the range of 100-200s. The congested areas marked S₁₁, S₁₅ in Scenario 1 are formed in the initial stage of evacuation, with the duration nearly throughout the whole evacuation process (Figure 4(a)). Those congested areas are caused not only by the excessive concentration of people inside the block, but also the urban road network failed to divert the external crowds, even resulting in aggravated congestion. In the improved scenario, the congestion time of the two locations (S₁₁, S₁₅) both decreased by 62%, also the phenomenon of people mixed both inside and outside the blocks completely disappeared (Figure 11(a)). The locations of congested sections are similar with the pre-optimization scenario, but the congestion duration time relieved significantly (Figure 11(b)).

It shows the impact of enlarging the space around the congestion spots on improving the efficiency of evacuation. Furthermore, the simulation result can provide valuable references and support for community's planning, which helps to overcome the ignorance of safety issues in practices.

Figure 9: Evacuation Time Comparison of Scenario 1&3.

Figure 10: Accumulated Paths of Evacuees in Scenario 3.

Figure 11: Congestion Situations of Scenario 3.
(a)Duration Time of Congested Block Exits (s).
(b)Length of Congested Streets (m).

Increase the Density of Road Network

In this scenario people can choose the added roads for evacuation, in which the frequent use of the original roads can be reduced and the efficiency of evacuation is able to generally improve. The evacuation time in Scenario 4 is 49 minutes 35 seconds, which is 10 minutes 12 seconds shorter than Scenario 1 (Figure 12, Table 4). The accumulated paths of evacuees in this scenario show how the added pedestrian roads share the moving crowd and reduce the congestion (Figure 13). In previous research, there was design strategy put forward to increase the density of road network to make the scale of blocks suitable for human behaviour (Fang, 2013). The simulation of scenario 4 echoes to this strategy and proves the feasibility of this proposal from the perspective of evacuation.

Compared to scenario 1, the congestion duration of all blocks is decreased under the optimization of the road network. In this case the duration of block exits congestion occurred within the scope of 300-600m around the refuge decreased about 100s. The congested exits in the range of 0-300m are sharply reduced, with the duration less than 40s ((Figure 14(a)). The congested length of multiple roads, whose previous congestion distance longer than 300m, is reduced by over 50% ((Figure 14(b)).

It would be costly and painstaking to modify the urban road network in the cities that have been completed and planned with large scale blocks. Yet inside of each block, one large and gated block can be divided into multiple residential units. Between two units is the walking traffic connected with the urban roads. Without making changes to the original urban road system, this method can enhance the evacuation efficiency by simply increasing the density of pedestrian network.

Figure 12: Evacuation Time Comparison of Scenario 1&4.

Figure 13: Accumulated Paths of Evacuees in Scenario 4.

Figure 14: Congestion Situations of Scenario 4.
(a) Duration Time of Congested Block Exits (s).
(b) Length of Congested Streets (m).

Conclusions

This study focuses on evacuee safety during evacuation that could easily be neglected in the planning of community which constituted of large-scale blocks. It analyses the evacuation time and the distinct characters of crowd congestion in event of sudden disasters, proposes optimal strategies including utilizing the internal road network of blocks, expanding the spaces of the congested area and increasing the density of pedestrian system. The result of the study demonstrates that the application of each design strategy can reduce the potential safety hazard caused by large scale blocks and enhance evacuation efficiency. It is a meaningful attempt to solve the urban evacuation problem from the perspective of urban planning by using the micro evacuation platform. This study does not focus on a specific case, but uses the ideal model to discuss the evacuation safety of large-scale blocks. Its advantage lies

in that it takes the urban spatial elements as the only variable, which avoids the interference of other factors on the research results, and proves the feasibility of using planning and design methods to improve the evacuation efficiency of community with large-scale blocks. The consideration of hazard locations and crowd's response mechanisms under specific type of disaster is problems to be solved in the follow-up study.

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