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Method of Bottleneck Identification and Evaluation during Crowd Evacuation Process

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Abstract

Accidents and natural disasters such as fire and earthquakes post more and more threats to the transportation infrastructures. Under such circumstance, the evacuation process for the crowded pedestrians in these infrastructures may be affected by the facility failure, resulting in partially damaged evacuation network, which at last forms bottlenecks and decreases the evacuation efficiency. Thus to improve the safety and comfortable level of crowd evacuation in transportation infrastructures, a new method of bottleneck identification and evaluation for evacuation network is proposed. The proposed method takes into account the facility failure induced crowd redistribution and explores the structure importance of the evacuation network component. The method of bottleneck identification is also applicable to other similar transportation networks.

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1. Introduction

During the past few decades, it is noticed that extreme weather events such as coastal flooding, torrential rains, snow condition, extreme cold have become more and more frequent, which threat the safety and resiliency of transportation infrastructures and systems. Meanwhile, seismic activity, incidents and accidents, e.g., fire, power outage, water pipe burst, building collapse, derailments and collisions, have also posted great challenges to emergency preparedness in transportation infrastructure operations.

Thus when facing these more and more frequent threats, one of the most important emergency responses is to evacuate pedestrian crowds safely and efficiently. Reviewing the recent accidents happened in Beijing, Shenzhen and Guangzhou subway stations [1, 2], it can be found that the evacuation process for the crowded pedestrians in such infrastructures may be affected by factors including facility failure, passenger way damage, or hazardous material presents (fire and smoke for example). These factors resulted in unavailable routes or space during evacuation process, thus formed evacuation vulnerabilities, i.e., bottlenecks. For these bottlenecks, additional security enhancement measures should be prepared during the emergency preparedness.

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To identify the bottlenecks during evacuation process, both direct observation and quantification method could be applied. Manual observation was firstly applied in field survey in 1970s. After these studies, the concept of level of service was proposed [3]. Ever since then, a lot of studies have been performed to investigate the level-of-service for stairs [4], roads [5], stations [6], and so on [7]. It has been found that although the trends of the flow-density relation as well as the velocity-density relation (also known as fundamental diagram) for pedestrian flow in stairwell and road segment look the same, however, they have quantitatively difference [8, 9]. That is to say different infrastructure may provide different service capacity. It is also noticed that some of the infrastructures could only provide limited service capacity, for example, the room doorway could only provide a pedestrian flow of about 1.2 person per second per meter [10]. This kind of infrastructure was thus believed to be the bottleneck.

With the development of computer technology, more and more quantification methods have also been adopted in exploring the evacuation efficiency. Different computer models, both continuous [11, 12] and discrete [13, 14] have been built based on the insights into the pedestrian movement. These simulation models could provide vivid animation of the movement process of pedestrian in the space, thus the spatial forming and dissolving of congestion in the building space could be easily observed. Further combing these simulation results with the concept of level of service [3] or crowd pressure[15], potential areas of bottleneck could also be identified. Although this kind of simulation provides visually the development of bottlenecks, it is sometimes difficult to quantify the ability of the building layout to defend challenges such as facility failure while maintain an acceptable level of service. Considering that this kind of evaluating needs information of the main building components, including the room, doorway, passenger way, escalator, turnstiles and so on, an abstraction of the building evacuation process should be applied. As a matter of fact, pedestrian evacuation in building is constrained by those spatially distributed facilities, a graph network based model for the building [10, 16] provides sufficient such information. This kind of model combines the empirical studies of pedestrian flow with graph theory and has been used widely in the area of building evacuation study.

In the present study, considering the effect of failure of necessary facilities to evacuate occupants, we as a consequence propose a new method to quantify their influences on evacuation efficiency, based on which we further evaluate the bottleneck magnitude. The rest of the present paper is organized as follows. In section 2, we detail the proposed bottleneck identification method based on network construction for building layout. In section 3, the proposed method is applied in a case study to quantify the bottlenecks of a metro station. On base of the results and discussion, in section 4, we present some concluding remarks of our study.

2. Bottleneck identification method

As we mentioned in the above section, disasters happened in infrastructures may affect the availability of pedestrian movement channel such as doorway or stairs. One of the typical scenarios is that under fire situation, sometimes the doorway may be blocked by the fire, while occasionally smoke would fill in the stairwell, making these facilities unavailable to evacuees. Evacuation process under these circumstances would become much more dangerous than that under normal situations. As a consequence, finding the vulnerable facility would help a lot in preparing emergency evacuation. It is noticed that these facilities were abstracted as nodes in graph based network models for building evacuation. Thus, in this section, for the sake of completeness, we firstly introduce the network model of evacuation and then detail the proposed bottleneck identification method.

2.1. Network construction

For simplicity and without loss of generality, we show in Figure 1a typical building layout consisting of rooms, doorways, and stairs. As can be found from this figure, there are in total 6 rooms, one stair which leads to another floor and 7 doorways. All the rooms, as the closed blue circles indicated in Figure 1a, are connected by the doorways, through which occupants in the building could evacuate to safety zones. In this figure, it is assumed that the other floors and the outside zone of the building are both safety ones, represented as open circles in Figure 1a. As a result, we denote each room as a node, while each doorway as a connection between the nodes. In this way, a graph could be formulized, as shown in Figure 1b.

In the above description, it should be noticed the network evacuation model needs basic data inputs. Analyzing the evacuation process, we can find the following issues to be noticed. Firstly, occupants are distributed in the building, thus each room could accommodate some occupants. The number of occupants in each room can be determined by the designed or expected level of service the room was intended to provide. It should also be pointed out that each room has a maximum capacity to hold occupants for the limited space reason. Thus the capacity and initial number of occupants consist the main property of the graph node. Secondly, as pointed out in the section introduction, typically facilities such as the doorway, the turnstiles of the ticket checking machines can only provide a limited service to users, which means, it takes time for some
specific number of occupants to pass through these facilities, while others have to wait until their turn to pass. Here the specific number of occupants and the passing through time are both determined by the facility. Taking doorway as an example, empirical analysis indicates that normally a door could only provide a pedestrian flow rate of about 1.2 person per second per meter, thus wide doorway would let a large volume of pedestrian occupants pass. Thus when constructing a graph based evacuation model, flow capacity and transit time for each connection of the network should also be specified. To summarize, the principal data requirements for the graph based network evacuation model include node capacity, node initial contents, connection flow capacity and connection transit time.

To simulate occupant evacuation process, the other important issue is to model pedestrian routing behavior. In the present study, it is assumed that pedestrians have detailed local knowledge of the building layout and are as a consequence modeled using the Fastest Flow Algorithm [10]. The fastest path is calculated using an improved Shortest Path Algorithm [17].

Based on the above abstraction method, an evacuation network could be formulated. For the constructed network $G(N, E)$, where $N$ represents nodes while $E$ represents connections (or links), it is assumed that the set of Origin to Destination (OD) pairs, representing from room to the final safety zone, which has $n_w$ elements. The OD pair $w$ is acyclic jointed by path $P_w$. The set of all the possible paths connecting all the OD pairs is denoted by $P$ and there are $n_p$ paths in the network. Further let $d_w$ represents the demand of OD pair $w$; $v_a$ represents flow on link $a$; $v=(v_1, v_2, ..., v_{n_a})$ represents link flow vector; $f_p$ means the flow on the path $p$; $f=(f_1, f_2, ..., f_{n_p})$ represents the path flow vector; $t_a(v_a)$ denotes the link flow $v_a$ depended time cost on link $a$. It should be noticed that here in the present study, we focus on the evacuation process and thus the demand $d_w$ is a constant value. As long as we focus on the best performance of the evacuation under maximum capacity flow circumstance, the fastest flow assumption is believed to be reliable.

2.2. Bottleneck identification

To quantify the evacuation process of a building or a transportation network, the most convenient efficiency measure is the time needed to evacuate all the occupants to safety zones. For this reason, we further define the evacuation time as follows,

$$
\varepsilon = \varepsilon(G,d_w)
$$

Noted that $d_w$ is a constant value and as a consequence, the evacuation time only depends on the network structure $G$. Under circumstances such as fire induced network degraded, i.e., some of the network components $g$ could no longer provide normal evacuation function, the network efficiency would as a result fluctuate.

Thus the relative network efficiency drop, after $g$ is removed from the network, can be defined as a measure of component importance $I$ as follows,

$$
I(g) = \frac{\Delta \varepsilon}{\varepsilon} = \frac{\varepsilon(G-g,d_w) - \varepsilon(G,d_w)}{\varepsilon(G,d_w)}
$$

where $G-g$ is the network after component $g$ is removed from network $G$. As indicated by this definition, $I(g)$ is obviously unitless. When $I(g)=0$, it means the removal of component $g$ has no influence on the evacuation efficiency, that is also to say component $g$ is useless to evacuate occupants; For the situation when $I(g)>0$, the degraded network performs impaired function of evacuation, under this circumstance the network component $g$ is expected to be a bottleneck. Based on the value
of $I(g)$, the importance of the bottleneck can be ranked accordingly; when $I(g)<0$ means the component $g$ is a redundancy, if this redundancy is not designed as a backup option of evacuation, then it should be removed to improve the network efficiency.

It should be noticed that, Firstly, sometimes the removal of a network component could result in a situation that there is no available path for given OD pairs, we simply assign the demand for that O/D pair to be zero; Secondly, to take into account pedestrian redistribution after the removal of network node, we assume that the initially distributed occupants are redistributed to its neighboring nodes with normalized probabilities in proportion to the number of occupants on these nodes.

3. Case study

In this section, a relatively complex mass transit station is chosen as an example to investigate the evacuation process and to identify potential bottlenecks using the proposed method. It was assumed in the following cases that the number of occupants in the station to be evacuated is in proportion to the area of the node represented, here in this section we choose an occupancy of 0.744m² per person as required by the national building code for metro stations in China.

3.1. Studied evacuation scenario

A notional mass transit station concourse level is given in this study. This station consists two main parts, namely the platform level and the concourse level as shown in Figure 2a and 2b, respectively. The platform level has a length of 118.5m and a width of 11.6m. There are in total 4 stairs and 7 escalators connecting the platform to the up level concourse, as indicated in Figure 2a. The width of the stair is 1.8m while 1m for the escalators. The platform is relatively small thus pedestrians are usually over crowded in this area, they as a result mainly move to the nearest exits of this level to the up level concourse.

The concourse level locates on the ground and serves as the main entrance of the station. There are in amount of mainly 5 passenger entrances, namely, A, B, C, D, E, as marked out in the manner of anti-clockwise in Figure 2. To separate the paid and unpaid area of the concourse level, 4 ticket checking facilities have been settled. It should be noticed that as indicated in Figure 2b, the entrance B here serves only as an exit, no passenger is allowed to enter the station from this location. The area of the concourse is about 3240m². In the paid area of the concourse, 7 escalators from left to right, namely ES1.2, ES2.2, ES3.2, ES4.2, ES5.2, ES6.2 and ES7.2 as shown in Figure 3b, are used to transport pedestrians between the platform level and the concourse level. When facing disasters such as fire, all the escalators should stop and serve as normal stair to evacuate passengers from the platform level. In this way, the total evacuation time could be less than the fire code requirements, i.e., 6min in China.

![Fig. 2. Layout and the corresponding passenger evacuation direction of the station on the (a) platform and (b) concourse level, respectively.](image_url)
connections as defined in Section 2. Their flow capacities and connection transit times were calculated according to the lengths and cell to cell distances, respectively. After calculating all the necessary data input, the network model for the station is at last formulized and presented in Figure 4.

It should be noticed that for the convenient of visualization, the network for the platform level and the concourse level are drawn separately in Figure 4. Actually, the stair nodes including SW1.2, SW2.2, SW3.2 and SW4.2, together with the escalator nodes as defined in former sections are connecting the platform level and the concourse level. Thus the evacuation process of the station platform and concourse were analyzed at the same time. Occupants in the lower platform level firstly moved up to the concourse level and then through the ticket checking machines to the unpaid area, and at last towards the safety zone. The ticket checking machines control the flow direction of passengers under normal situations, which means some of the ticket checking machines are used for flow into the paid area, while others are used for flow out-of the paid area. Evacuation would be blocked by these ticket checking machines whose direction is out-of the paid area. Thus under emergency situations, all the ticket checking facilities should turn to the emergency mode to let passengers out freely.

3.2. Results and discussion

Simulation of the pedestrian evacuation from the station to safety zones without any degraded network components has been performed. As can be found from the simulation result, the evacuation of 3715 occupants completed in 255s. This value is smaller than the 360s, i.e., the required evacuation time by the metro station design code in China. Although the present station layout is believed could provide efficient evacuation, it can be found from the simulation result the following truths: i) some of the network connections have not been traversed by any pedestrian for the reason that fastest path routing algorithm was adopted in the present study. As a result of this routing rule, pedestrians encountering service congestions would be redirected to other further routes to complete the evacuation, these farthest routes would not be chosen during the evacuation process. ii) some of the routes have been used by a large amount of occupants during the evacuation, for example, as indicated by the red hot spots in Figure 2, the facilities including all the escalators and the 2nd and the 4th stair on the platform. This means that these facilities locate on the fastest path. It should be noticed that literatures indicated that during real evacuation scenario, the occupants have a tendency of choosing the nearest way as their way exit [18]. Once the decision has been made, the occupants would barely change their choices [19]. As a consequence, the fastest path rule could model the above two evacuation routing features.
Further analyzing the evacuation process it can be found that degradation of any cells on the station platform would only affect local distribution of occupants and thus local evacuation process rather than the overall evacuation of the station would be influenced. On the contrast, any degradation of the facilities connecting the lower level station with the up level concourse would result in evacuation width fluctuation, leading to a varying evacuation time. Thus to investigate the facility degradation affected evacuation process, further simulation works have been performed. Failure of the escalator nodes ES1.2, ES2.2, ES3.2, ES4.2, ES5.2, ES6.2 and ES7.2, and the stair nodes SW2.2, and SW4.2 have been taken into account. The simulated evacuation time corresponded to the above node failures has been presented in Table 1.

As can be found from Table 1, when facility failure induced degradation has been taken into consideration, the evacuation time of the station varies from the original one. When comparing the evacuation time for those escalators, it can be found that although the exit widths are the same, their contributions to the evacuation process are different. For the convenient of comparison, we further calculate according to Equation (2) the importance of the bottlenecks, which have also been shown in Table 1. From the importance value here we can see that except for the failure of escalator ES1.2 which has no effect on the total evacuation time, the failure of other facilities would lengthen the total evacuation time. Based on the bottleneck importance value, these facilities were further ranked in a descending manner, as shown in the last column of Table 1. It can be found that the removal of stairwell SW4.2 would severely damage the evacuation process, leading to an unacceptable lengthy evacuation process, i.e., 420s. The reason for this special characteristic is that the stair here serves the largest area of platform, thus according to the fast flow algorithm, most of the occupants would still use the escalator nearby, i.e., ES6.2 instead to complete their evacuation. The width of ES6.2 is 0.8m less than the stair, which at last causing a severely congestion level near the right part of the platform, as indicated by the hot red spot in Figure 2. Another two
4. Concluding remarks

This paper has presented a new bottleneck identification and evaluation method based on the construction of evacuation network for crowd evacuation. The network structure is determined by the topology of the building layout, while the network components, including the nodes and connections, are confined by the spatial feature of the building. Given node capacity, node initial number of occupants, connection flow capacity and connection transit time, the evacuation process can be simulated according to the fast flow algorithm. Considering the spread of accidents and natural disasters such as fire and smoke, the evacuation facilities such as the stair could be obstructed, thus can no longer be used to evacuate occupants. Under this situation, the evacuation process for the crowded pedestrians in the transportation infrastructures may be affected by the facility failure, resulting in partially damaged evacuation network, which at last forms bottlenecks and decreases the evacuation efficiency. For the benefit of planning emergency response and protecting transportation infrastructures and systems, it is important to identify and evaluate the potential bottlenecks of evacuation. Thus, based on a network efficiency measure, i.e., evacuation time, we in the present paper proposed that by removing failure node and redistributing the occupants on it to the neighbouring nodes, the network efficiency of the partially damaged evacuation network provides the importance of bottleneck, which can be used to accomplish the above goals. To further illustrate the proposed method, a mass transit station is chosen as an example to identify and evaluate the bottlenecks. As the simulation results and discussions indicated, the proposed method can quantify the importance of bottleneck in a reliable way and thus can be used to assist emergency planning.

The proposed method bases its calculation on network property, and has no direct relation of the construction process of the network, as a consequence, as long as the evacuation process can be abstracted onto a network, e.g., other similar transportation networks, the proposed bottleneck identification and evaluation method is also applicable.

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