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Emergency Evacuation Capacity of Subway Stations

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Abstract

The objective of this study is to establish and evaluate an Emergency Evacuation Capacity (EEC) model for key evacuation facilities in subway stations through analyzing key factors that affect the emergency evacuation These key facilities, which include exit, stairway, passage and turnstile, are analyzed from three aspects: characteristic of evacuees, evacuation facility, evacuation organization and management. The emergency evacuation capacity model for subway station is built based on pedestrian flow theory. In addition, a case study is conducted to look at the handling capacity of the selected station. The result from this study will be beneficial for guiding and improving subway station design. It has significance to improving emergency response ability of rail transit system.

Keywords: rail transit system; subway station; emergency evacuation capacity (EEC); evacuation bottleneck

1. Introduction

Rail transit system is considered one of the best choices for metropolitans to solve ground transportation problems in terms of congestion and efficiency. Recently, due to its high capacity, good efficiency, low pollution, and low consumption of energy, rail transit system plays a more and more important role in the metropolitan transportation system. There are 118 cities from 43 countries worldwide that have built up rail transit systems. In China alone there have been more than 50 metro lines in 12 cities and the total operating mileage reached 1500 km by 2011. With advantages of large capacity, fast speed and high punctuality, more and more commuters choose rail transit system as their travel means.

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According to the survey among residents in Beijing in 2010 rail traffic volume of peak hour in Beijing has broken the record reaching about 34 thousand persons an hour, which demonstrates that existing rail transit system has become the backbone of Beijing public transit system. Fig. 1 shows the pedestrian flow during peak hour in a subway station in Beijing. It can be found that both inside the train and outside in the subway station, the density in terms of number of passengers per unit area is very high.

Fig. 1. (a) High-density commuter flow inside train; (b) High-density commuter flow on passage in subway station

With the continued increase of rail traffic passenger volume, much more attention must be paid to the safety and security in rail transit system operation. As compared to ground transportation the density in terms of number of passengers per unit area for rail transit system is higher. Besides, the available space for people to move around is relatively narrow. If something unexpected happens, it will cause more serious panic and confusion among passengers compared to similar situation happened in bus and other ground transportation system. As a result, it is very difficult to evacuate people from dangerous area to the safe place. In addition, more and more incidents occurred in subway systems worldwide, endangering the safety and security of subway's operation. For example, on March 29th 2010, a serious explosion incident occurred in Lubyanka station in Moscow, which caused more than 41 people dead and 60 people injured. On March 4th 2008, there was a passenger trampling incident in Dongdan station in Beijing because of escalator malfunction, causing 11 people injured and the station had been closed for nearly two hours. As far as emergency officials concern, the most important thing after incident is to evacuate people from dangerous place to the safe area as soon as possible, because evacuating people quickly and safely can greatly reduce casualty and economic losses.

The evacuation capacity of the subway station is considered a key element during emergency evacuation. Thus, it is necessary to conduct relative studies on estimating evacuation capacity of subway station and evaluating levels of service of emergency evacuation in order to improve the overall level of safety of rail transit system.

2. Literature review

Some researchers analyzed pedestrian flow characteristics of rail transit system commuters using various methods such as field survey, hydrodynamic theory and numerical simulation and so on. Tian Juanrong (2009) studied upon passengers' characteristics parameter inside subway station using questionnaire survey and statistic analysis. Shan Qingchao (2009) proposed improved social force model and conducted researches on motion regularity and motion model of rail transit system pedestrian flow. Helbing (2004) is the first person to set up social force model. After carrying out studies on people's panic

behaviour of different evacuation scenes, a regular pattern of evacuation called 'fast that is slow' was presented. Blue V J. (2000) put forward pedestrian evacuation model based on cellular automation theory. Kirchner (2003) held the idea that pedestrian evacuation exercise was a kind of asymmetric and simple rejection process and proposed Floor Field evacuation model.

In addition, many studies are conducted on evaluation of evacuation capacity of subway station from different aspects. Zhao Ye (2011) picked up 17 indicators from four aspects and carried out comprehensive evaluation upon evacuation capacity of subway station under fire emergency environment using fuzzy network analysis method. Ding Dandan (2011) analyzed the evacuation capacity of hub station from passenger characteristics, evacuation facility and evacuation management factors. Yang Xue (2011) chose 21 evaluating indexes and establish the evaluation model upon emergency evacuation based on risk analysis theory.

Moreover, computer simulation technology has been used to carry out evacuation simulation for subway station. The popular simulation packages about pedestrian evacuation include Steps, Exodus, Nomad, Legion and so on. Exodus can be used to evaluate whether the design of building meet the evacuation requirements. Many evacuating indicators such as total evacuation time, evacuating speed as well as evacuation bottleneck can be got from the simulation results. Legion can be used in all the places where the density in terms of number of people per unit area is high. Nomad is a macroscopic traffic simulation package.

3. Objective and methodology

The purpose of this paper is to analyze key elements that affect the EEC of subway station and to estimate evacuation capacity of critical evacuation facilities. Based on these analyses, the EEC model for subway station is established. Besides, the EEC is evaluated to look at if the capacity of subway station can meet the evacuation demand under emergency. The EEC of subway station is the basis to calculate overall evacuation time and to design emergency evacuation plan. The evaluation for EEC of subway station can provide technical support for government officials to take appropriate measures to improve the evacuation design of subway station. The study results will be beneficial for taking full advantage of subway station's evacuation capacity. Furthermore, the casualty and economic loss caused by rail transit system incidents can be reduced.

The rest of the paper will be organized as follows. First, key factors affecting the evacuation capacity of subway station are analyzed from three aspects: characteristic of evacuees, evacuation facility, evacuation organization and management. Second, evacuation bottleneck is determined after estimating the evacuation capacity of critical evacuation facilities. Then, the EEC model of subway station is established based on pedestrian flow theory. And finally, the evaluation upon EEC of subway station is conducted.

4. Analysis of factors affecting subway station emergency evacuation

Analyzing affected elements of emergency evacuation is the basis of evaluating the EEC of subway station. In the paper, critical factors affecting emergency evacuation of subway station are analyzed from three aspects: characteristic of evacuees, evacuation facility, evacuation organization and management.

4.1. Characteristics of evacuees

Compared to the regular situation, the pedestrian flow inside subway station will increase sharply during a short time under emergency situation. Large numbers of commuters who just pass through the

station have to get off the train and move to the safe place. Because of the instinct for survival, the expected speed of evacuees during evacuation is much higher than normal walking speed. Just as Helbing proposed in his study that the actual speed will slow down due to the congestion. In fact the average evacuating speed is always lower than normal walking speed because of the constraints of exit, stairway, passage and turnstile. Obviously, under emergency the density of pedestrian flow is much higher than that in normal situation. High density is another reason that leads to low evacuating speed and serious congestion during evacuation.

According to the field survey, young and middle aged people take a large proportion in subway passengers in Beijing, while the proportion of children, aged and disabled people is much lower. Subway riders between 18 and 40 years old account for about 65% in subway passengers; whereas riders between 40 and 65 years old account for nearly 29%. Besides, the gender distribution of subway commuter is also uneven. Male commuter takes up about 60% of the total number. Because of the difference of age, gender and action ability, evacuation individual has different response time and evacuation speed. These differences among individuals will affect the traffic characteristics of evacuation group. Survey data show the evacuation speed of children and old people is much lower than young and middle aged people. They will decrease the average evacuation speed of the group.

It is a significant feature that there is a large number of migrant population in Beijing. Similarly, migrant population who is not very familiar with rail transit system takes a certain proportion of subway passengers. People who are unfamiliar with the evacuation facility and evacuation environment may do some irrational activities because of scare and panic, such as changing evacuating route and overcrowding, which will make the evacuation distance longer and delay the evacuation process. Furthermore, it will reduce the evacuation speed and degrade the evacuation capacity of subway station.

4.2. Evacuation facilities

The subway station is mainly comprised of platform layer, station hall layer and corridors connecting platform with station hall. During emergency evacuation people who need to be evacuated timely are passengers in the arriving train, passengers waiting on the platform and station hall as well as working staffs. The people staying on platform layer need to get to station hall layer by stairs or escalators first. Second, they need to pass through turnstiles to reach waiting area. Last, they can get to the exit through stairs or corridors. Similarly, passengers and working staffs staying on station hall layer need to pass through turnstile to reach waiting area first and then get to the exit through stairs or corridors. In this paper, critical evacuation facilities mainly refer to passage, stair, escalator, turnstile as well as exit, which must be used by evacuees to reach the safe place. These facilities, if not well designed, are very likely to become bottleneck for evacuation. The effects on emergency evacuation of subway station caused by critical evacuation facilities are analyzed as follows.

(1) Evacuation passage

Evacuation passages include passage, stair and escalator. Under emergency situation, a large number of passengers flock to the evacuation passage, which can cause congestion and queue. As a result, the handling capacity of passage will be the determinant of the evacuation capacity of subway station as a whole. The width and number of evacuation passage must meet the requirements of emergency evacuation. On one hand, the evacuation capacity of evacuation passage is affected by its physical attribute such as width, length and gradient. On the other hand, it is also affected by the panic degree, average evacuation speed and evacuation density of evacuees. During emergency evacuation, the escalator should not be used for the purpose of safety. Therefore, escalators should be used as stairs for evacuation in vertical direction. The evacuation speed on stairs is obviously lower than that on passage, because of the effect of gradient.

(2) Turnstile

In the regular operation situation, automatic ticket checking turnstile can enhance the subway station's ability to handle passenger flow. However, because of the limitation of number and width of turnstile, passenger passing rate on turnstile during emergency evacuation is much lower. It is easily to form congestion and queue. As a result turnstile is very likely to become the bottleneck for evacuation.

(3) Exit

The EEC of subway station is determined by the width and number of exits. Exits should be placed evenly with clear signs on all directions of subway station so as to avoid congestion.

Moreover, the EEC of subway station is also affected by other factors such as spatial arrangement of facilities, the matching degree of critical evacuation facility as well as evacuation route.

4.3. Evacuation organization and management

Under emergency evacuation situation, providing some useful guiding information for evacuees is beneficial for improving the evacuation capacity of subway station and helping evacuees to reach safe place as quickly as possible. The organization and management on emergency evacuation of subway station have two aspects: evacuation guiding sign and direction.

(1) Evacuation guiding sign

Evacuation guiding facilities mainly include exit indicating sign, direction indicating sign, warning sign and broadcast information and so on. The purpose of setting up evacuation guiding sign is to help evacuees finding suitable evacuation route quickly so as to reduce the congestion and chaos during the evacuation and ensure passengers' safety.

(2) Direction

During emergency evacuation, it is very common that evacuees make irrational action because of fear and panic. Effective direction can relieve people's psychological fear and is beneficial for enhancing evacuation efficiency. Therefore, it is necessary to assign policeman and working staff to do on-site guiding and direction.

5. EEC model for subway stations

The emergency evacuation capacity of subway station is defined as the maximum passenger flow that can pass the evacuation bottleneck section of evacuation corridor within 6 minutes based on the available technology.

5.1. Evacuation capacity of passage

The evacuation capacity of passage is defined as the maximum passenger flow that can pass the section of passage during a given time (which is defined as 6 minutes in the paper) based on the available technology. It is affected by both the physical attributor of passage and characteristics of pedestrian flow under emergency situation. In order to simplify the calculation, only the width of passage, evacuation speed and density are considered in the paper.

$$C_{lp}=vk(B_{lp}-b_{lp}) \tag{1}$$

where, C_{lp}—The evacuation capacity of passage, p/s;

v—Evacuation speed on passage under emergency situation, m/s;

k—Evacuation density on passage under emergency situation, p/m^2;

B_{lp}—The total width of passage, m;

b_{lp}—The width of barrier or wall, m, refer to barrier, b_{lp}=1m, refer to wall, b_{lp}=1.46m.

According to the existing research results, the relationship between evacuation speed and density under emergency situation on passage inside subway station is as follows.

$$V(k)=-0.00056k^4+0.0009k^3+0.00082k^2-0.4242k+1.8267 \quad (2)$$

According to the definition, the evacuation capacity of passage is the maximum passenger flow that can pass a section during a given time period. By using MATLAB package, it can be found that the evacuation capacity reaches the maximum when the evacuation speed is 0.821m/s and the evacuation density is 2.753p/m^2.

5.2. Evacuation capacity of stair

The evacuation capacity of a stair is defined as the maximum passenger flow that can pass the section of the stair during a given time (which is defined as 6minutes in the paper) based on the available technology. During emergency evacuation, the escalator is always shut down and can be used as stair. In the paper, after taking the width, length, and gradient of the stair as well as evacuation speed and density into consideration, the evacuation capacity model for stair is built.

$$C_s t=vkN_{st}\Sigma(B_{st}-b_{st}) \quad (3)$$

where, C_{st}—The evacuation capacity of stair, p/ s;

v—Evacuation speed on stair under emergency situation, m/s;

k—Evacuation density on stair under emergency situation, p/m^2;

N_{st}—The number of available stairs;

B_{st}—The width of stair, m;

b_{st}—The width between stair handrail and wall, 0.24m.

$\Sigma(B_{st}-b_{st})$ —The total width of available stairs and escalators, m.

Based on the existing research results, the relationship between evacuation speed and density under emergency situation on stair inside subway station is as following.

$$V(k)=-0.00054k^4+0.0727k^3-0.216k^2-0.1897k+1.5012 \quad (4)$$

Using MATLAB package, it can be found that the evacuation capacity will be the maximum when the evacuation speed is 0.502m/s and the evacuation density is 3.132p/ m^2.

5.3. Evacuation capacity of turnstile

The subway station hall layer is divided into two parts by turnstile, waiting area and non-waiting area. In regular situation, passengers can pass through turnstile after swiping card or tickets. Under emergency situation, turnstile system can stop right away and passengers can pass through turnstile without swiping card or tickets. Referring to the design specification of rail transit system in USA, the evacuation capacity of turnstile is calculated using the following formula.

$$C_{ts}=50\%\times n\times F \quad (5)$$

where, C_{ts}—The evacuation capacity of turnstile, p/s;

n—The number of turnstile;

F—The pedestrian flow rate that can pass through turnstile per second, p/s;

According to the existing research (Zhang 2008), under normal situation the pedestrian flow rate that can pass through turnstile per second is about 0.58p/s. However, under emergency situation, turnstile

system can stop and passengers can pass through turnstile without swiping card, the value of F is about1.38p/s.

50% is the reduction coefficient for evacuation capacity of turnstile under emergency situation. Referring to the existing research results the evacuation efficiency of turnstile will be decreased under emergency situation because of people's panic behaviour. Li Shengli et al used social force model and numerical simulation and calculated the reduction coefficient was 50%.

5.4. Evacuation capacity of exit

The evacuation capacity of exits is defined as the maximum passenger flow that can pass the section of an exit during a given time (which is defined as 6minutes in the paper) based on the available technology. In the paper, the width of exit, evacuation speed and density are considered to establish the evacuation capacity of exits.

$$C_{ex}=vk(B_{ex}-b_{ex}) \tag{6}$$

where, C_{ex}—The evacuation capacity of exit, p/s; v—Evacuation speed on exit under emergency situation, m/s; k—Evacuation density on exit under emergency situation, p/m^2; B_{ex}—The width of exit, m; b_{ex}—The width exit boundary, 0.15m.

Video observation survey on Xizhimen station in Beijing is conducted during the morning peak hour period from 7:30 am to 8:30 am. It is observed that during morning peak hour, people are all hurried to walk around within the station. The average walking speed is obviously higher than that under normal conditions. At this moment pedestrian flow situation can be considered as para-emergency flow due to the fact that the pace of walking commuters in subway station is between normal and emergency conditions. It should be noted that it is so difficult to observe movement of pedestrian flow under emergency, and therefore video observation survey is conducted during the morning peak hour as substitute. Based on the field survey of Xizhimen station, the average walking speed is about 0.85m/s and the density is about 4.2p/m^2.

5.5. Evacuation capacity of subway station

It is supposed that the number of exits of a subway station is n, in that way the number of evacuating directions of the subway station is also n. Besides, the number of independent evacuation routes for each evacuating direction is m. Independent evacuation route refers to evacuation route on which critical evacuation facilities are not overlapped with each other. The emergency evacuation capacity of each independent evacuation route is restricted by the evacuation capacity of critical evacuation facilities. The emergency evacuation capacity of subway station equals the sum of emergency evacuation capacity of total independent evacuation routes inside subway station. Based on all the above analysis the emergency evacuation capacity model of subway station is expressed by the following formula.

$$\begin{aligned} C &= \sum_{i=1}^{n}\sum_{j=1}^{m} C_{bt}^{ij} \\ C_{bt}^{ij} &= \min(C_{lp}^{ij}, C_{st}^{ij}, C_{ts}^{ij}, C_{ex}^{ij}) \end{aligned} \tag{7}$$

where C—the emergency evacuation capacity of subway station, p/s; C_{bt}^{ij} —the evacuation capacity of evacuation bottleneck of the jth evacuation route on the ith evacuating direction, p/s;

C_{lp}^{ij}, C_{st}^{ij}, C_{ts}^{ij}, C_{ex}^{ij} —the evacuation capacity of level passage, stair, turnstile and exit of the jth evacuation route on the ith evacuating direction, p/s.

Table 1. Classification for EES of subway station

vel of EEC	Classification standard	Comments for evacuation ability
A	EI≥1	Excellent, evacuation demand can be met.
B	EI∈[0.8,1]	Good, demand can be met basically.
C	EI∈[0.5,0.8]	Worst, useful measures must be adopted to improvethe EEC of subway station.
D	EI∈(0,0.5)	Worst, useful measures must be adopted to improve theEEC of subway station.

According to the EEC of subway station, it can be estimated that whether the capacity of a station meets the demand of evacuation under emergency. Thus, technical support can be provided for emergency officials to improve the layout and design of the subway station. In order to evaluate the emergency evacuation ability of asubway station, evacuation index is proposed in this paper, which is defined as the ratio between the theoretical value of EEC calculated by formula 7 and the actual value of pedestrian flow inside subway station observed during peak hour. The calculation model is shown in formula 8. According to calculation results of evacuation index, classification of EEC of subway station is presented in Table 1.

$$EI=C/F_{peak} \tag{8}$$

where *EI*—The evacuation rate of subway station;

C—The EEC of subway station, p/s;

F_{peak}—The observation pedestrian flow inside subway station, p/s.

If EI is larger than 1, it means that the EEC of subway station is higher than the pedestrian flow during peak hour. Thus, it can be inferred that all passengers can be evacuated successfully from the dangerous place within the given time period (6 minutes). The evacuation ability of subway station is excellent. If EI is between 0.8 and 1, it means that about 80% passengers can be evacuated safely within given time period. The evacuation ability of subway station is good. Under this situation some measures such as increasing the width and number of facilities can be adopted to improve the evacuation ability within the allowed range of space, fund and policy. If *EI* is between 0.5 and 0.8, it means that nearly 50% passengers can not be evacuated timely. The evacuation ability of subway station is bad. At this time, some useful measures such as change the physical attributes of facilities and adjusting the overall arrangement of subway station must be carried out so as to improve the EEC of subway station. If *EI* is less than 0.5, it shows that EEC of subway station can not meet the emergency evacuation demand and the evacuation ability is the worst. Some useful measures must be adopted to improve the EEC and enhance emergency capacity of subway station. The higher the value of *EI* is, the larger the evacuation capacity of subway station is.

6. Case study

Shuangjing station in Beijing was used to conduct a case study. Shuangjing station has two stories. The first basement floor is station hall layer, with length being 160m and the width 16m and there are four exits. Four turnstiles are set up on corridors connecting with these four exits. Besides, there are 10 more turnstiles on each corridors of left side, and 8 turnstiles on each corridors of right side. The width of two exits on the left both are 6m, while the two right ones are 5m. There are 4 stairs and 4 sets of escalators connecting the station hall layer and ground. The width of the two stairs on the left side both are 3.5m, while the two right ones are 2.5m. The width of all the escalators is 1m. The second basement floor is

platform layer, which is 120m long and 12m wide. There are two stairs and two sets of escalators connecting platform layer and station hall layer. The width of stair is 4m and the width of escalator is 1.5m.

According to the definition of independent evacuation route, there are 2 independent routes for evacuation inside Shuangjing station. Based on the field survey data, the EEC of evacuation critical facilities is calculated using formula (1) to (6).

Route A:

$C_{lp}^{A}=vk(B_{lp}-b_{lp})=0.821\times2.753\times(12-1.46)\times360\approx8576$

$C_{st}^{A}=vkN_{st}\Sigma(B_{st}-b_{st})=0.502\times3.132\times[2\times(3.5-0.24)+4\times(1-0.24)]\times360\approx5411$

$C_{ts}^{A}=50\%\times n\times F=50\%\times20\times1.38\times360\approx4968$

$C_{ex}^{A}=vk(B_{ex}-b_{ex})=0.85\times4.2\times(12-0.6)\times360\approx14651$

The evacuation capacity of route A is:

$C_{bt}^{A}=\min(C_{lp}^{A}, C_{st}^{A}, C_{ts}^{A}, C_{ex}^{A})=4968$

Route B:

$C_{lp}^{B}=vk(B_{lp}-b_{lp})=0.821\times2.753\times(12-1.46)\times360\approx8576$

$C_{st}^{B}=vkN_{st}\Sigma(B_{st}-b_{st})=0.502\times3.132\times[2\times(2.5-0.24)+4\times(1-0.24)]\times360\approx4279$

$C_{ts}^{B}=50\%\times n\times F=50\%\times16\times1.38\times360\approx3974$

$C_{ex}^{B}=vk(B_{ex}-b_{ex})=0.85\times4.2\times(10-0.6)\times360\approx12080$

The evacuation capacity of route B is:

$C_{bt}^{B}=\min(C_{lp}^{B}, C_{st}^{B}, C_{ts}^{B}, C_{ex}^{B})=3974$

As a result, the EEC of the subway station as a whole can be calculated using formula (7).

$C= C_{bt}^{A}+ C_{bt}^{B}=4968+3974=8942$

It means that 8942 people can be evacuated from Shuangjing station within 6 minutes under emergency. In order to get the average pedestrian flow during peak hour, field survey has been conducted in Shuangjing station from 7:30am to 8:30am. The actual value is about 9600p/h. According to formula (8),

$EI=C/F_{peak}=8942/9600\approx0.93$

The result shows that the emergency evacuation ability of Shuangjing station is good. The evacuation demand under emergency situation can be met.

7. Conclusions and further study

The major work carried out in the study is summarized as follows:

(1) Critical affecting elements of emergency evacuation are analyzed from three aspects: characteristic of evacuees, evacuation facility, evacuation organization and management.

(2) EEC of critical evacuation facilities is estimated. The effect on EEC caused by evacuees' characteristics and guiding organization and management are abstracted as two factors: evacuation speed and density.

(3) The EEC model for subway station is established based on pedestrian flow theory.

The calculation for EEC of subway station is the basis of estimating the overall evacuation time as well as making emergency evacuation plan. In addition, the evaluation for EEC can provide technical support for improving the safety design of subway station. Some improvements are proposed according to the evaluating results, which are beneficial to enlarge the emergency evacuation capacity and make full use of the evacuation potentialities of subway station.

Although some positive results have been obtained from this study, there still leaves room for improvement. In the paper, the operating direction of stair is not considered in the calculation of evacuation capacity of stair. In fact, there exist great differences in evacuation speed and density between ascending and descending on stairs. In addition, because of shortage of emergency data, the relationship

between evacuation speed and density of critical evacuation facilities is established based on the previous studies. In the future, it is suggested that serious exploration upon characteristics of pedestrian flow under emergency evacuating situations be conducted using variety of methods such as field survey, virtual experiments, simulation and theoretical analysis.

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