Accurate Assessment of RSET for Building Fire Based on Engineering Calculation and Numerical Simulation

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Abstract. In order to obtain the Required Safety Egress Time (RSET) accurately, traditional engineering calculation method of evacuation time has been optimized in this paper. Several principles and fact situations were used to optimize the method, such as detecting principle of the fire detecting system, reaction characteristics of staff being in urgent situation, evacuating queuing theory, building structure and the plugging at the porthole. Taking a three-storey KTV as an example, two methods are used to illustrate the reliability and scientific reasonability of the calculation result. The result is deduced by comparing the error (less than 2%) at an allowable range between two results. One result is calculated by a modified method of engineering calculation method, and the other one is given based on a Steering model of Pathfinder evacuation simulation software. The optimized RSET has a good feasibility and Accuracy.

1 Introduction

With the development of people's life quality greatly in recent years, places of public entertainment has expanded rapidly. As the typical public places of entertainment, KTV has achieved great success. However the complex of internal spatial structure, high personnel density and there are a large amount of flammable and combustible decoration materials indoors. Obvious fire load density support and sustain the fire growth, and go against fire detection, fire fighting and evacuation. So it's an important subject to promise that everyone in the fire must evacuate to safety places quickly, Required Safety Egress Time is the key factor of fire protection design of buildings.

RSET is the time that needed when the people evacuate to safety places, including detection time, preparation time and evacuation movement time[1]. It's an important parameter in the design of fire safety evacuation escape. At present, there are three ways to determine RSET, experimental method[2-4], empirical formula method[5,6] and computer simulation method[7-9]. experimental method is used for scientific research generally, but it is costly. The evacuation design that based on computer software simulation has become an important tool in the calculation of RSET, but empirical formula method has its unique advantages , such as simple, quick and easy to operate. Traditional empirical formula method is not considering the detection time of the fire, and think the evacuation movement time is the time of person through the horizontal direction and the queuing the exit time, without considering other structure channel such as evacuation of stairs in the building and blockage of people during the evacuation. In this paper, traditional engineering calculation method of evacuation time has been optimized, based on several principles and fact situations, such as detecting principle of the fire detecting system, reaction characteristics of staff being in urgent situation, evacuating queuing theory, building structure and the plugging at the porthole. Taking a three-storey KTV as an example, using the optimized engineering calculation method of RSET, detection time, preparation time and evacuation movement time are calculated respectively. Meanwhile using Pathfinder evacuation simulation software simulate evacuation process to illustrate the reliability and scientific reasonability of the calculation result. Then put forward to reduce the RSET and take some preventive measures for the retention and blockage status at the exit and the corridor when people evacuate. Besides, it has good practical guiding significance to the performance-based design on building fire safety evacuation .

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2 Engineering calculation of RSET

RSET is mainly composed of detection time T_d , preparation time T_{pre} , and evacuation movement time T_t, that is $T_{RSET}=T_d+T_{pre}+T_t$.

2.1 The prediction of detection time T_d

Traditional empirical formula method is not considering the detection time of the fire, however, the fact is that the process from outbreak of fire to fire alarm is also an important part of the evacuation time. detection time Td is determined by detector, and this process is divided into two stages: (1) The fire outbreak and develop to a certain heat release rate, the flue gas and the detector began to heat exchange ,then the detector start to work ,and this stage is the start working time t_w; (2) From the heat exchange of flue gas and the detector to sending out an alarm signal when reaching the response temperature, this stage is named t_r. Therefore, there is $T_d=t_w+t_r$.

As the optimal installation position of the detector is the place of maximum gas velocity or of maximum smoke temperature , the prediction of the detector's start working time t_w can be based on the model of t^2 [10].

$$Q=\alpha.t^2 \tag{1}$$

In which, Q is the heat release rate of the fire, kW; α is development coefficient of fire, kW/s^2;t is Fire development time,s.

Fire growth rate α characterizes the speed of fire spread. According to the classification of the American Fire Protection Association, fire growth rate of different fires are shown in Table 1.

Table 1. Fire growth rate of different fires.

combustible material	Fire type	Fire growth rate α(kW/s^2)
unnoted	Slow speed fire	0.0029
non-cotton product Polyester mattress	Medium speed fire	0.0117
Plastic foam Stacked wood Mail bags full of mail	High speed fire	0.0469
methanol The rapid combustion upholstered seats	Over speed fire	0.1876

The flue gas and the detector begin to heat up to the response time of the alarm signal. Based on a review of the relevant research[11-13], and combined with statistical analysis of KTV fire accidents over the years, the Calculation formula of response Time t_r,(the time from the heat exchange of flue gas and the detector to sending out an alarm signal when reaching the response temperature) is as followings:

$$\begin{cases} t_r=-\frac{RTIr^{5/12}}{0.444Q^{1/6}H^{1/4}}\ln[1+\frac{H(T-T_0)}{5.38(Q/r)^{2/3}}] & r>0.18H \\ t_r=-\frac{RTI}{0.973(Q/H)^{1/6}}\ln[1+\frac{(T_0-T)H^{5/3}}{16.9Q^{2/3}}] & r\leq 0.15H \end{cases} \quad (2)$$

In which, RTI ----- the characteristic index of response time of the detector, $m^{1/2}.s^{1/2}$; r----- the radial position of the detector under the roof, m;Q-----the heat release rate of the fire, kW; H ----- height of ceiling, m.T_0 is----- the ambient temperature ℃ ;T-----response time of detector, ℃.

2.2 The prediction of T_{pre}

In paper[14] , pre-evacuation time has something to do with some factors such as structure, function of buildings, the characteristics of people's response to emergency, fire alarm system of the buildings and property manage system. In order to balance the research results of theory and practice, this article use the calculation empirical formula to determine the preparation time Tpre, which was recommended by the book named Planning pointer of Construction disaster

$$T_{pre}=120+A_0^{1/2}+0.4H \quad (3)$$

In which, A_0-----the area of building, m2; H-----height of the building,m.

2.3 The prediction of evacuation movement time T_t

Taking into account security considerations, most of the high-rise buildings are not allowed to take elevators during a fire, but along the stair evacuation. But traditional empirical formula method consider the evacuation movement time is the sum of time through the horizontal direction and queuing time through the exit, without considering the evacuation of stairs in non-horizontal direction. According to architectural structure, this article divided the evacuation structure into horizontal evacuating passage, exit and stairway. In the process of evacuating, the calculation formula of evacuation movement time as followings:

(1) horizontal passageway

$$t_c=\frac{l_{max}}{v} \quad (4)$$

In which, l_{max}-----the greatest distance of horizontal channel, m ; v-----the average speed when people in emergencies, m/s.

According to the model of Fruin[15], when the flow density meets 0.2 person/m^2<ρ<4.0 person/m^2 on the horizontal channel, the relationship between movement speed and the flow density is as followings:

$$v=1.427-0.3549\rho \quad (5)$$

(2) Exit (entrance)

$$t_e=\frac{P_e}{f_e w_e} \quad (6)$$

In which , P_e-----the number of people gathered at the exit, person; f_e-----the flow rate when people queen through the exit, person/(m.s);w_e -----the width of the exit, m.

Traditional empirical formula method is just the simple superposition of evacuation time at each stage without considering the congestion status during the evacuation, when $t_c<t_e$, namely when people evacuate from the greatest distance to the exit, others are not all through the exit, but some stranded at the exit. At this time, the evacuation time from the greatest distance to move through the export is t_e . When $t_c>t_e$, namely when people evacuate from the greatest distance to the exit, others have all passed the exit, and nobody is delayed. At which the time from the greatest distance to move through the export is t_c .That means, the evacuation movement time (people evacuate from the greatest distance to the exit in the region) t=Max (t_c,t_e) .

(3) Stairs:

Pauls[16] puts forward that the time named t_{stair} when people through stairs have something to do with the effective width of the stairs and the number of people using the stairs, as shown in the formula (7):

$$t_{stair}=4.579(\frac{P_{stair}}{w_{stair}})^{0.73} \quad (7)$$

In which ,w_{stair}----- effective width of the stairs ,m; P_{stair} ----- number of people who use the stairs, person.

3 Assessment of RSET and calculation case

This paper takes a three-store KTV as an example, calculating the required safety egress time of fire in the KTV. There are three floors in the KTV building and it covers an area of 441 m^2. The average density of people in the single room is about 0.3 person /m^2,and the ceiling height is 3.2 meters. Heat fire detection system has been installed in the KTV room according to the requirement of the standard. The distance between the fire source and the nearest fire detector is about 2m. Exponents of the response time about the fire detector is $98m^{1/2}.s^{1/2}$ and responsive temperature is 58 ℃ . Assuming ambient temperature named T_0 is 25℃. In the paper, the fire source is set at the most unfavorable part where is on the sofa at the end of the corridor in the second floor in the KTV, as shown in figure 2.

When the fire happens, the evacuation route in the KTV room is: 1. The room to the exit of the room; 2. Through the exit of the room; 3. Through the corridor passage to the entrance of the staircase; 4.Through the entrance of stairs; 5. The stairs to the first floor corridor; 6. The first floor corridor to safe exit. The specific evacuation route is shown in figure 1:

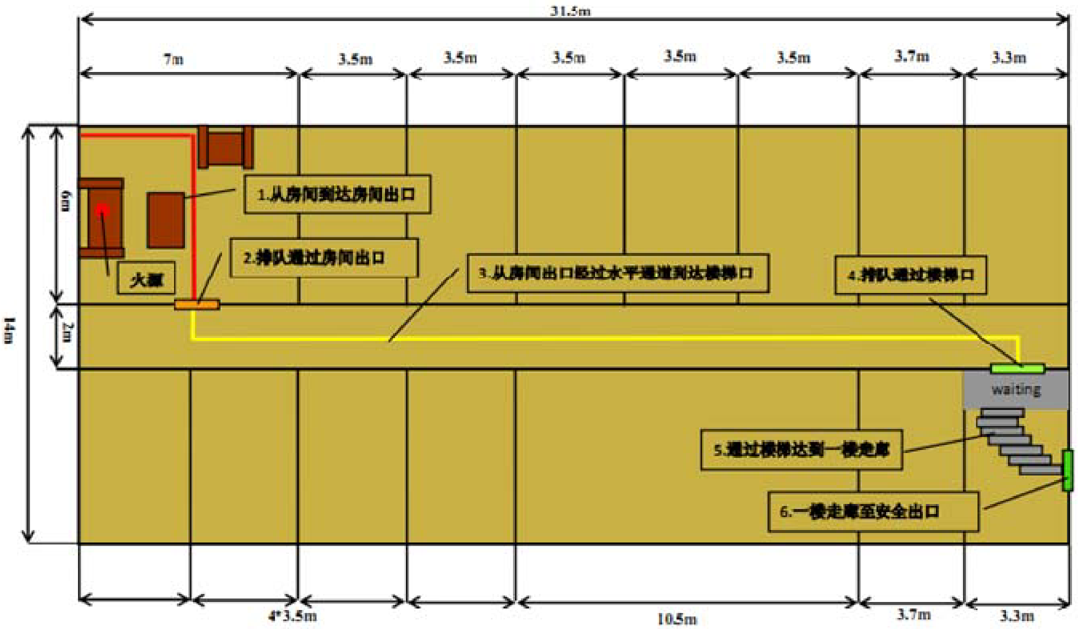

Figure 1. Evacuation route in KTV room fire

(1)There are a lot of flammable and combustible materials such as sofas, carpets, etc in the KTV. Once fire, the room will be ignited and become over speed fire quickly. Therefore, this paper choose α=0.1876kW/s^2 as fire growth rate according to table 1. When HRR reaches 300kW, the heat fire detector begins to exchange heat as a response and then start the alarm device. According to the formula (1) ,we get t_w=40s.

From the model ,we can get r=0.63H. According to formula (2), we can gain the reaction time t_r=101s when smoke and the detector began to exchange heat, and then the detector achieves a response temperature to alarm. The detection time T_d=t_w+t_r=141s.

(2)According to formula (3) ,we can obtain the preparation time T_{pre}=145s when people are ready to evacuate after hearing the alarm .

According to the statistical data of personnel flow coefficient[17], parameters of KTV model and formula (5) , we can fundamental parameters of different evacuation routes are shown in table 2.

Table 2. Fundamental parameters of different evacuation structure

No.	Evacuation route	Evacuated people *P* (person)	Average movement speed *v*（m/s）	Flow rate *f* (person/(m.s))
1	room-room exit	6	1.32	
2	Room exit	12		0.93
3	Corridor passage	107	0.82	
4	Corridor exit	107		1.3
5	stair	214	0.35	
6	First floor Corridor –safe exit	214		1.3

Note: the above-mentioned rooms show the general rooms of KTV.

According to the fundamental parameters of the different evacuation structure in table 2, the evacuation movement time of different evacuation route of figure 2 are calculated by the formula (4), (6), (7) as shown in table 3. Considering the interior space of the KTV room which comes about fire and has furniture such as sofa, tables and chairs is very big, people need to bypass the obstacles to get to the room export during evacuation, so the route of evacuating is the shape of L[18]. That is, the maximum horizontal distance between room and room export meets $l_{\max}=\frac{7}{2}+6=9.5$m.The longest distance across corridor passage meets $l_{\max}=\frac{7}{2}+3.5\times5+3.7+\frac{3.3}{2}=26.35$m 。

Table 3. Evacuation movement time of different evacuation route

No.	Evacuation route	maximum horizontal distance $l_{\max}$（/m）	average movement speed v（m/s）	Width *w*（/m）	Evacuated people *P*(person)	Flow rate f(person/(m.s))	Evacuation time t（/s）
1	room-room exit	9.5	1.32				7.2
2	Room exit			1.2	12	0.93	10.7
3	Corridor passage	26.35	0.82				32.1
4	Corridor exit			1.6	107	1.3	51.4
5	stair			1.6	214		163.3
6	First floor Corridor –safe exit			1.8	214	1.3	91.4

Therefore, the evacuation movement time in KTV is T_t=Max(t_1,t_2)+Max(t_3,t_4)+Max(t_5,t_6)=225.4s, and $T_{RSET}=T_d+T_{pre}+T_t$=511.4s. At the same time, from the evacuation time of each evacuation route in table 3 ,we know that people are stranded and blocked at the exit of room， corridor and stairs in the process of evacuating.

4 Numerical simulation of RSET

Evacuation movement time can be simulated and calculated through the Pathfinder software. Pathfinder software developed by American Thunderhead engineering company is a simulator based on evacuation movement, which consists of Steering model and SFPE model. Unlike SFPE model of linear escape route, the escape route of Steering mode is curve. When people are in disorder and congestion situation, Steering model can choose to different directions, which is more in line with the actual escape behavior in an emergency. Therefore, this paper uses Steering model of Pathfinder software to establish the Pathfinder evacuation model and design the solving method about the emergency evacuation problem of some three-store KTV building in fire emergency.

The parameters setting of the model: the average density of persons is 0.3 person/m^2, and the movement speed meets the theory of performance-based fire prevention and design in building, and the average movement speed is 0.9 m/s, and the maximum is 1.32m/s, and the minimum is 0.65m/s. The setting speed obeys the normal distribution characteristics. Through Steering model of Pathfinder software, the evacuation simulation diagram of each moment and the personnel evacuation time of all layers and people flowrate at the safe exit are gotten as shown in figure 2 to 4 respectively.

From figure 3, the evacuation time of the second-layer is shortest and the third-layer is longer. The total evacuation of the first-layer is longest. This is because people of the second-layer and third-layer personnel are both evacuated to the first layer, resulting in more and more people to the first-layer to evacuate the longest time. From figure 4, the flow of the emergency exit changes basically in line with the linear growth trend as time changes in 0-25s. After 25s, the flow of the emergency exit is in 1.28 person/s and 1.74 person/s between ups and downs, which is in line with the average flow of the unit width of the engineering calculation. This is because with the increasing of evacuees, evacuation passage is gradually saturated and the flow shows gradually stability and trend of fluctuation. From the evacuation simulation dynamic figure, in 25s people in the corridor exports strand and congestion occurs on the stairs. The evacuation movement time of some three-store KTV is obtained through simulation analysis, that means, T_t=216.3s, and T_{RSET}=502.3s . We can see that the results of two methods to deal with the RSET comes to a great degree by comparing the error (less than 2%) at an allowable range between two results. One result is calculated by comparing a modified method of engineering calculation method with the other one based on a Steering model of Pathfinder evacuation simulation software. It confirmed that the optimized RSET and the result of RSET of three-store KTV fire have a good feasibility and accuracy.

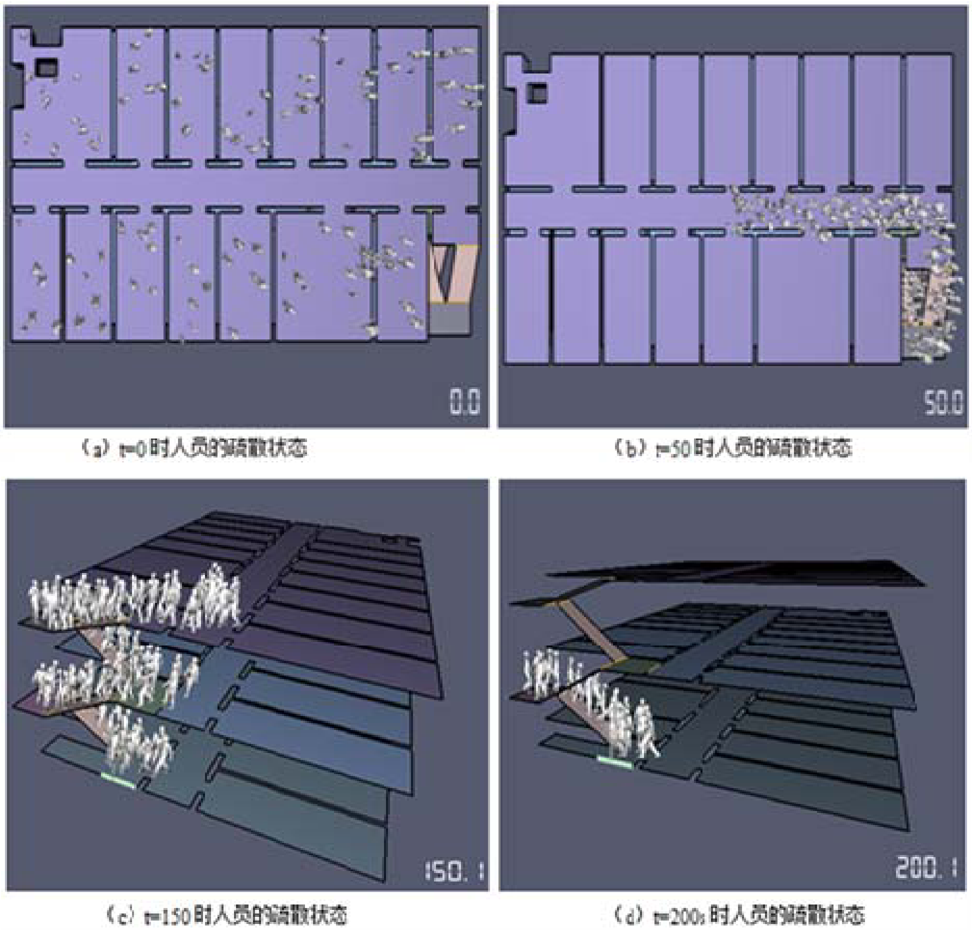

Fig.2 Dynamic diagram on personnel evacuation

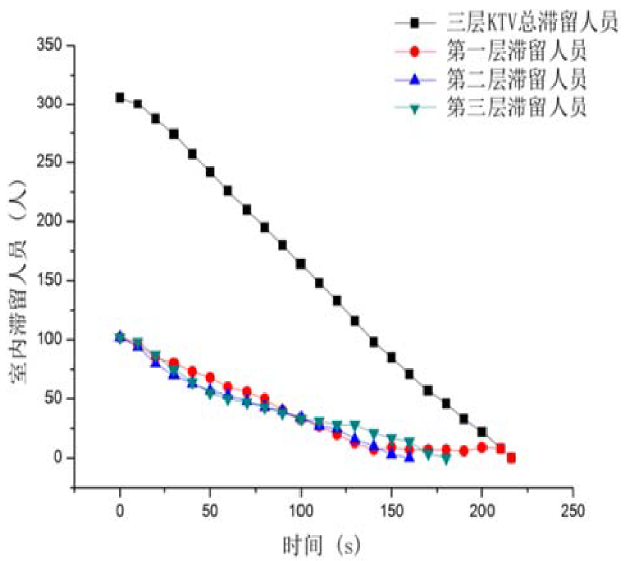

Fig. 3 Stayers in fire vs. time

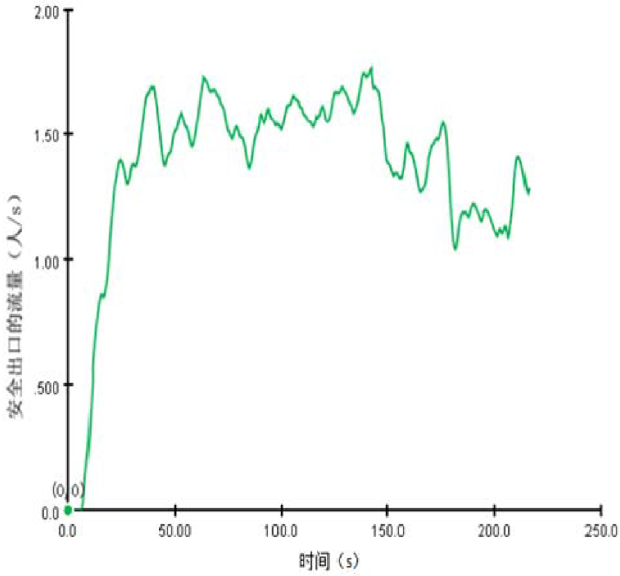

Fig. 4 People flowrate at the safe exit

5 Conclusion

Through engineering calculation and the dynamic simulation diagram of Pathfinder software, evacuees on the stairs exports, the stairs, the first-layer corridor strand and jam phenomenon occurs which affect the evacuation time. Therefore, to reduce the personnel required safety evacuation time, with the optimization of building evacuation design, some improvement measures can be appropriately increased.

(1) The response temperature of the chosen fire detector by the author is 58 ℃ in the calculation example. The detector begins to conduct heat exchange to start alarm device when the fire source power is 300KW. In the actual situation, to reduce the detection time of the fire detection system, the high sensitivity of fire alarm device can be used such as the smoke detector used in the current projects which can detect the 100KW (or less) fire source and the detection time can be down from 141s to 98s.

(2) The exits and stairs are the bottleneck of personnel evacuation to escape. So the width of the exits and stairs can be increase appropriately. In addition, people during emergency evacuation in case model can only be evacuated to downstairs after running from the room to the end of the corridor, which not only extends the evacuation time, but also causes the personnel crowded and jam. If evacuation stairs respectively are built at both ends of the corridor, the evacuation movement time in the KTV fire can be down from 225.4s to 141.4s and people don't need to spend much time in the long corridor and crowded on the stairs and rooms.

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