Studies of evacuation start time in fires*

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Abstract: When human behavior of evacuation in fires is concerned, the evacuation start time is a very important parameter. Evacuation start time that is affected by many random variables is also a random variable. However, in most of the simulation of evacuation, it's regarded as a constant. It's obviously unreasonable. In this study, evacuation start time is described by adopting normal distribution function and random variable model. A common formula is given by fitting to experiment data to realize quantitative analysis.

Keywords: fires; evacuation start time; random variables; numerical simulation

1. Introduction

Studies regarding human behavior of evacuation in fires has begin since the beginning of last century. At the very beginning, the most popular methods were qualitative observation, description, investigation and so on. From 1970's evacuation research was paid attention to and supported by many states. The main trend was studies about group panicky behavior, human evacuation ability etc. Since 1980's studies of evacuation was developed continuously. Researchers had been able to carry out dynamic fire egress analysis and simulation using computer. Several mathematical models for human behavior of planning evacuation were established. From 1990's to now except these models have being developed perfect, quantitative analysis of random behavior has been paid attention to. When human behavior of evacuation in fires is concerned, evacuation start time is a very important parameter. However, in most of the simulation of evacuation, the parameter is regarded as a constant[1]. It's obviously unreasonable. There are some studies to aim at this problem qualitatively. In this article, start time is described by adopting normal distribution function and random variable to realize quantitative analysis. A common formula is given and tested by fitting to experimental data.

2. Establishing stochastic model of evacuation start time

Many random variables in natural and social phenomena obey in some degree normal distribution regulation. Because evacuation start time is a random variable too, we try to take the normal distribution function as the aimed simulation model to describe the stochastic character of individual evacuation start time:

$$f=\frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(t-\mu)^2}{2\sigma^2}\right) \tag{1}$$

where t is proportional evacuation start time with the ratio of 5.0, f is individual probability density regarding t, μ is a position parameter and $f=\mathrm{Max}(f)$ when $t=\mu$, σ^2 is the variance and the smaller σ^2 is, the steeper graph is. The main job now is to define the parameters μ and σ^2.

3. Defining position parameter μ

The parameter μ is affected by following factors:

1) s stands for evacuees states when fire happens, such as wake, sleep or rest;
2) p is where fire happens such as office building, residential building, market and entertainment places, and hospital.
3) d is fire source position or distance between the aimed place and the fire source.
4) i is the intensity of fire that equal to the weight of fuel on unit floor surface area.
5) e represents reliability of the fire protection and other emergency systems.

The relation is proposed by the way of analyzing theoretical and experimental data reported as follow.

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$$\mu=6.0p(s+d+i+e) \quad (2)$$

Fire will spread widely after 30 min according to the documentation [2] and [3]. This emergency would shorten delaying time from motive to action and promote people to evacuate. Thus the probability density would come to the summit. The corresponding start time is $t=\mu=6.0$. Take $p=1.0$, $s=1.0$, $d=0$, $i=0$, $e=0$ as references. The physical meaning will be given separately.

If evacuees are in an office building, it is think as $p=1.0$. When in a market or entertainment place $p=0.1$, because the group effect promotes fire information spread so that start time t and μ are shorter. If the place is a residential building where the family is concerned $p=1.2\sim1.5$. Family members would help each other humanly, parents for their children, the youth for the old, the healthy for the disability etc. On the other hand, someone would try to protect their property or find their pets and so on. These reasons make the start time longer. When a hospital is aimed where the people are almost patients, wounded or diseased, the whole level of evacuation is probably the lowest, the start time is the longest comparing to that is in the other places.

When $s=1.0$ means evacuees are awake. When asleep or in rest state $s=1.2\sim1.5$. Human consciousness is slower in sleep state than that in wake, so the whole level of evacuation will be lower and the start time will be longer in rest state.

When $d=0$ is related to the original building where there is source fire or closest to source fire, and $d=0.1$ stands for adjacent buildings where are suffered but haven't the source fire. Without alarm system, people who are in the original building get obviously fire information earlier than those in the adjacent distract as whole.

If the fire intensity is middle level $i=0$, when the fire is very powerful $i=-0.1$ or the same order of magnitude, when the intensity is weak and the fire is not so serious $i=0.1$. The more fire plume and heats emit, the more danger exists and the faster fires information would be spread also. Meanwhile the delaying time would be reduced.

Value of e depends on the feasibility of alarm and emergency systems. Not only equipment itself but also firemen or operator is important to decide whether the systems can work. For instance, whether or not the equipment is maintained and operated correctly in time. When the two factors are all well $e=-0.1$ so that evacuation can be manage and help, else, $e=0$.

4. Defining σ^2

There is the no deviation estimation of σ^2 based on the mathematical statistics theory [4].

$$S^2=\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i-\overline{X}\right)^2 \quad (3)$$

μ is actually $\overline{X}=\frac{1}{n}\sum_{i=1}^{n}x_i$ in accordance with definition where $x_i(i=1,2,3..n)$ comes from the real samples.

Take $\overline{X}=\mu$, and $\sigma^2=S^2=\frac{1}{n-1}\sum_{i=1}^{n}(x_i-\mu)^2$, then the primary value of σ^2 can be got.

Draw the normal distribution graph and compare with the real case, and modify the value to the perfect, then suppose:

$$\sigma^2=\sigma^2(\mu)=A\mu^2+B\mu+c \quad (4)$$

In essence the question is to determine constants A, B and C in turn. It will be maneuverable and useful once this simple relation has been defined. Given three sets of sample data, we can get three groups of μ and σ^2 correspondingly. Calculate A, B and C according to above relation (4).

5. Estimating the range of evacuation start time t

The probability equals to 0.9974 when the value of random variable t ranges from $\mu-3\sigma$ to $\mu+3\sigma$ regarding to the famous "3σ"rule in probability theory. Hence we know that almost all of the evacuees will start evacuation during the period of $\mu-3\sigma$ to $\mu+3\sigma$. It's also proved that start time is not a constant but a variable or range.

6. Examples

A bomb exploded in an underground parking garage at the World Trade Center plaza in New York in the noon on February 26,1993, killed six people and resulted in injuries to over 1,000 occupants. The explosion and lasting fire caused the twin 110-story

office buildings are damaged seriously. Interfered with the operation of the fire protection and other emergency resulted in the more difficulty and complex for evacuation of tens of thousands occupants. The National Fire Protection Association (NFPA) and the National Research Council of Canada (NRC) undertook the research about it, and the data listed in table 1 were afforded by those who were on floors 11 and above in the two towers at the time of fires. There were 225 respondents from tower 1 and 157 from tower 2. In the table t is proportional evacuation start time (min), $f1$ and $f2$ are probability density of tower 1 and tower 2 respectively

Table 1 Probability density at evacuation start time

t/min	$f1$	$f2$
0	0	0
5	0.01	0
10	0.01	0
15	0.01	0
20	0.1	0.08
25	0.23	0.1
30	0.36	0.18
35	0.08	0.1
40	0.05	0.08
45	0.08	0.03
50	0.02	0.03
55	0.01	0.02
60	0.01	0.05
60 to 240	0.03	0.3

Take and trim those data that they conform to the rules above in this article, we can get:

1) s_1=1.0 , p_1=1.0 , d_1=0 , i_1=0 , e_1=0 ; μ_1=6.0 , then σ_1^2=1.1367 .

2) s_2=1.0 , p_2=1.0 , d_2=0.1 , i_2=0 , e_2=0 ; μ_2=6.6 , then σ_2^2=3.9500 .

We supposed C=0 because only are two sets of μ and σ^2 available here, then A=0.6817 , B=−3.9007 .

On the other hand, the simulation was done based on the samples data. We can describe quantitatively probability density in different evacuation start time using relation (1). Simulation results illustrated in Figs. 1 and 2 where the scale of t axis is 1:5 in order to analyze and compare conveniently. The range of the evacuation start time for tower 1 is 14.0~46.0 minutes, tower 2 is 3.2~62.8 min. What need to point out is that start time of tower 2 should be longer than that of tower 1 according to the real condition while the simulation gets the conflicting results. It's clear that simulation tower 1 is fits in with the reality while simulation tower 2 exists errors. The probable reasons are that farther distance in tower 2 resulting in information of fires got later. This probably causes the probability density f smaller in the beginning while bigger in the end. There is poorer uniform in practice while the simulation is symmetrical. Different states and position of individual influences getting information directly, especially when the evacuation is spontaneous. This influence is random and uneven, the farther from the fires source the building is, the more unregulated the f distribution is. Some unknown factors existing need further studies.

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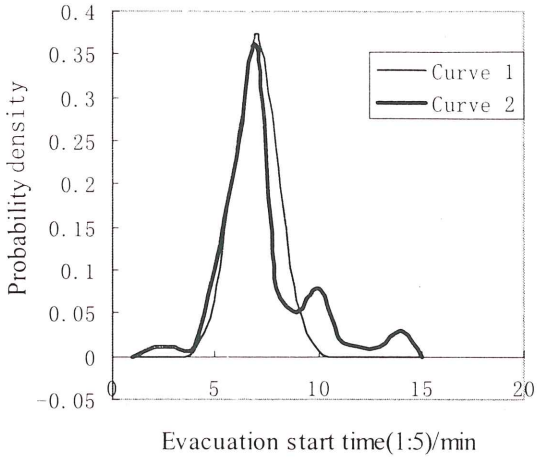

Fig 1. Distribution individual probability density in tower 1

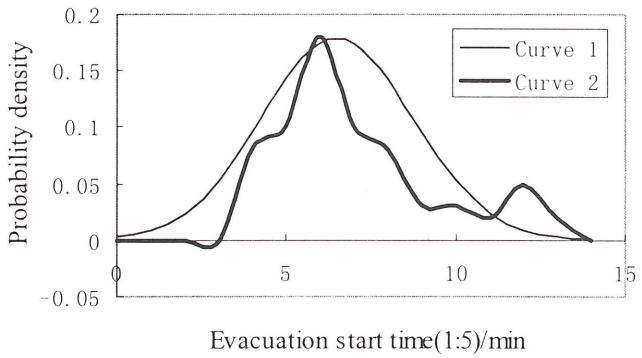

Fig 2. Distribution individual probability density in tower 2

7. Conclusion

In the evacuation design it's feasible to determine evacuation start time by adopting normal distribution theory even though some errors exist. Coefficients A, B and C in the relation (4) are vital for determining the range of evacuation start time in the real situation. Only are more reliable dada obtained by testing and verifying repeatedly the model.

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