Research on Personnel Evacuation Problem Based on Cellular Automata Model

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***Abstract*—Emergency evacuation is a problem of great concern at home and abroad. Aiming at the emergency evacuation problem of personnel, this paper uses MATLAB, Pathfinder and other software to establish an evacuation model based on cellular automata to simulate the different dynamic behaviors that the crowd may exhibit during evacuation under different situations and parameters. In this paper, firstly, several factors affecting the anxiety of the crowd are determined, and three key factors affecting the degree of anxiety of the personnel are screened out by the analytic hierarchy process: the distance from the safe exit, the number of personnel and the emotional infection. Then, a personnel evacuation model based on cellular automata is established, and the influence of the degree of anxiety on the length of evacuation time is analyzed under the influence of each key factor. Finally, by changing the key parameters, the experimental results are affected. Finally, the key parameters that cause the difference in evacuation effect are analyzed.**

Keywords—cellular automata, evacuation model, analytical hierarchy process, anxiety level

I. INTRODUCTION

In recent years, due to the rapid growth of population and economy, many public buildings such as stadiums, cinemas, theatres, galleries and so on occupy every corner of the city. When people carry out daily activities, these places often appear crowded areas. In the event of an emergency such as a fire, if the personnel cannot be effectively evacuated, it may cause malignant events such as congestion and stampede, resulting in property losses and even casualties [1-3]. Therefore, evacuation in emergency situations is a problem of great concern at home and abroad, worthy of our study [4].

Security exits in a particular place are often limited width doors or narrow channels, in the crowd evacuation, in order to avoid the crowd stampede accidents and improve the efficiency of evacuation, need to consider the width of the door, the number of people (personnel density), personnel composition (whether professional training), exit location and crowd anxiety and random behavior and other factors. Therefore, we need to study different situations and parameters on this basis [5-9].

Based on this background, the problem we need to solve is that there are several people in an internally accessible square room (or hall) and only one door can be used for evacuation. Establish a reasonable mathematical model, determine the key factors, and study the impact of the anxiety level of the crowd on the evacuation effect. The differences in experimental results caused by key parameters such as emotional infection, number of personnel, distance from the safe exit, and gender of personnel were analyzed.

II. MATERIALS AND METHODS

A. Data

The data of the analytic hierarchy process matrix is mainly through empirical judgment, expert scoring and reference literature and other ways to compare each element in pairs to obtain the judgment matrix. The elements of the judgment matrix conform to logic and common sense, and meet the consistency of the judgment matrix.

Cellular automata model data. We refer to the crowd evacuation model when the fire comes to establish the cellular automata model for emergency evacuation. The cellular automata is a dynamic system with discrete time and space. Each cell scattered in the regular grid takes a finite discrete state, follows the same action plan, and updates synchronously according to the determined local rules. A large number of cells constitute the evolution of the dynamic system through simple interaction. Cellular automata is different from the general dynamic model. It is not determined by strictly defined physical equations or functions, but is composed of rules constructed by a series of models. It is characterized by discrete time, space and state. Each variable only takes a limited number of states, and the rules of state change are local in time and space.

B. Methods to Introduce

Analytic hierarchy process:

The analytic hierarchy process (AHP) refers to the decision-making method that decomposes the elements always related to decision-making into levels such as goals, criteria, and schemes, and conducts qualitative and quantitative analysis on this basis. Using the analytic hierarchy process, a complex multi-objective decision-making problem with the influence of different key factors on the evacuation effect is regarded as a system. The target is decomposed into multiple targets or criteria, and then decomposed into several levels of multiple indicators (or criteria, constraints). Finally, the hierarchical single ranking (weight) and total ranking are calculated by the fuzzy quantitative method of qualitative indicators, and then the weights of different key factors on the evacuation effect are found out. The largest weight is the most significant factor. This method can well adapt to the target of less quantitative data information, and the calculation is simple, and can evaluate each key factor well [10].

Cellular automata:

Cellular automata (CA) is a mesh dynamic model with discrete time, space and state, local spatial interaction and temporal causality. It has the ability to simulate the spatio-temporal evolution of complex systems and can be used to

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simulate local rules and local relations. Its definition based on set theory is, let d represent the space dimension, k represents the state of the cell, and takes a value in a finite set S, r represents the neighbor radius of the cell. Z is an integer set, representing one-dimensional space, and t represents time.

A typical cellular automata is defined on a grid, and the grid at each point represents a cell and a finite state. The change rule applies to each cell and is performed simultaneously. This paper mainly studies the influence of anxiety degree on evacuation effect. Cellular automata can simulate better and produce different experimental results by changing the key parameters, so as to determine the key factors of evacuation effect.

The meaning of related nouns:

Cell: a grid represents a cell, a cell is equivalent to a storage element, can record the state.

Cellular space: the spatial dot set distributed by the cell is the cellular space, divided into one-dimensional, two-dimensional, three-dimensional.

State and initial state: is the initial state domain, the domain of a cell consisting of the surrounding cells.

Transformation rules: the function of state transition (multiple rules work together) (typical change rules, determined by the state of the cell and its (4 or 8) neighbors).

III. Model establishment and solution

A. Construction of Evaluation System by Analytic Hierarchy Process

Firstly, the decision-making problem is decomposed into two levels, and a hierarchical framework is created. The upper level is the target layer W, that is, the key factors that evaluate the influence of crowd anxiety on evacuation effect are selected. The lower layer is the program layer P, including emotional infection P1, number of personnel P2, distance from the safe exit P3, gender P4, professional training P5, age P6. The factors related to the results are classified, and more than three levels or levels are evaluated. Based on this, the decision-making method is analyzed and considered. Using the evaluation idea in the analytic hierarchy process, each key factor is quantified, and the quantification of each cost is considered separately. The quantitative method is the same as the proportional scale of the analytic hierarchy process, as shown in "Table. I", the median values of adjacent judgments are 2,4,6, and 8, respectively.

TABLE I. Proportion scale table

Factor ***i*** over factor ***j***	of equal importance	A little important	Relatively strong important	Strongly important	Extremely important
Factor i over factor j	1	3	5	7	9

TABLE II. Comparison Matrix

W	P1	P2	P3	P4	P5	P6
P1	1	0.5	0.3333	5	4	6
P2	2	1	0.5	6	5	7
P3	3	2	1	7	6	8
P4	0.2	0.1667	0.1429	1	0.5	2
P5	0.25	0.2	0.1667	2	1	3
P6	0.1667	0.1429	0.125	0.5	0.3333	1

Construction of judgment matrix W-P: The six elements P1, P2, P3, P4, P5 and P6 in the scheme layer P are compared in pairs to obtain a comparison matrix, as shown in "Table. II".

By solving the eigenvalue of W-P, it is easy to solve λ_{max} = 6.1931. By Formula

$$CI=\frac{\lambda_{max}-n}{n-1} \quad (1)$$

$$CI = \frac{CI}{RI} \quad (2)$$

Calculated CI = 0.0309 < 0.1, as can be seen from "Table. III", through the consistency test.

TABLE III. Relation table between n and RI

n	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

TABLE IV. Weight list of influencing factors

Evaluation indicators	Weight
Emotional infection	0.1843
Number of personnel	0.2728
Distance from safe exit	0.3976
Personnel gender	0.0459
Degree of professional training of personnel	0.0679
Age of personnel	0.0315

It can be seen from "Table. IV" that we can sort the key factors of the influence of crowd anxiety on evacuation effect according to the proportion from large to small, and select the first three major factors as the key factors of evacuation effect, that is, the distance from the safe exit, the number of personnel and emotional infection.

Results analysis:

1) Distance from the safe exit: In an empty room without any obstacles, the distance from the only safe exit determines the time that the person reaches the exit. If the distance is close, the probability that the person will quickly reach the exit is high.

2) Number of people: When the size of the room is fixed, the greater the number of people, the greater the density of the crowd, the greater the possibility of congestion in the event of an emergency, the longer the evacuation time required.

3) Emotional infection: Individuals in the group are vulnerable to emotional infection in the group, easily lead to their own panic anxiety.

B. Establishment and Solution of Cellular Automata Model

1) Description parameters of evacuation effect

Distance from safety exit:

The distance from the safety exit is not the direct distance from the personnel to the safety exit. It needs to consider the number of people at the moment and the influence of the moving speed of the crowd on the route. This paper focuses on the influence of the number of people and the moving speed of the crowd on the shortest distance from the safety exit. The calculation formula is as follows:

$$L_1 = \frac{Nv(t)L_{min}}{R_1}(3)$$

$$v_0(t) = \xi \frac{L_1}{\rho}(4)$$

In the formula:

N is the number of people

$v(t)$ is the moving speed of the surrounding crowd

L_{min} is the linear distance from the safe exit

R_1, ξ are a constant factor

ρ is the density of the surrounding population

$v_0(t)$ is the average speed of personnel under normal circumstances

Number of personnel:

The number of people in the model is defined as the density of people in a fixed room. The main calculation formula is:

$$\rho = \frac{N}{S}(5)$$

Emotional infection:

Emotional contagion mainly refers to the influence of changes in the behavior of the surrounding population on their own emotions. The definition of emotional contagion factor α describes the intensity of the surrounding population's emotional contagion to their own emotions. The calculation formula is as follows:

$$\alpha = E\frac{N_1}{N_2}(6)$$

$$v_0(t) = \frac{(1-\alpha)^{N_1-N_2}}{1+\alpha} v_0(0)(7)$$

In the formula:

N_1 represents the number of people around the emotional panic.

N_2 represents the number of people around the emotional calm

E represents the emotional average constant

$v_0(0)$ represents the average speed of people under normal circumstances

2) Establishment of evacuation model based on cellular automata

The model is built in a square room (or hall) with a side length of 16m × 24m, and the interior of the room is barrier-free. The number of people gathered is N. The only safe exit is located in the center of the upper boundary of the room, and its width is M. The distance between the person and the safe exit is defined as L, and the hazard source S is located in the center of the lower boundary of the room. At the initial moment, a crowd of N is randomly distributed in the room.

In this paper, the two-dimensional cellular automata method is used to divide the whole square room into square grids of equal size. Each grid represents a cell, and the space in which the personnel is located is a cell. Each cell is occupied by at most one person. The size of the cell is 1.0m × 1.0m. The neighborhood of the cell adopts Moore-type neighbors with a radius of 1, including the central cell and the surrounding 8 cells. As shown in "Fig. 1", the personnel can move in 9 directions, corresponding to 9 movable probabilities. The neighborhood of cell (i_0 , j_0) is denoted by

$$S_{i,j} = \{(i,j)||i_0 - i| \leq 1, |j_0 - j| \leq 1\}(8)$$

The set of empty cells is

$$\bar{S} = \{(i,j)|(\grave{\imath},j) \in S_{i,j}, (\grave{\imath},j) is\ an\ empty\ cell\}(9)$$

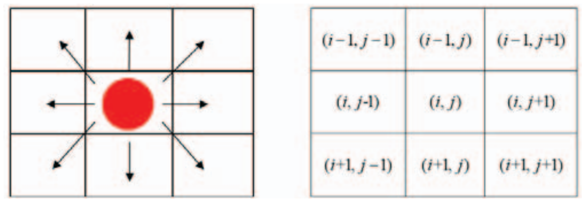

Fig. 1. The Field of Cell (i, j) and the Direction of Possible Motion

Anxiety level:

Based on the above model and evacuation scenario, we simulate the crowd evacuation process under anxiety infection. The specific parameter values are as follows : the average speed of personnel in general is 1.0m / s, the minimum expected speed of personnel in emergency v_0 = 1.5m / s, the maximum expected speed v_{max} = 3m / s, and there are different current speeds according to the degree of anxiety of personnel. This paper introduces parameter γ ($0 \leqslant \gamma \leqslant 1$) to describe the pedestrian's anxiety in emergency. During evacuation, the degree of human anxiety at time T can be quantitatively described as:

$$\gamma(t) = \frac{v_0(t) - v_0(0)}{v_{max}(t) - v_0(0)}(10)$$

Where $v_0(0)$ represents the average speed of personnel under normal circumstances, $v_0(t)$ represents the speed of t time, and v_{max} represents the maximum expected speed.

Personnel movement rules:

In the evacuation process, not all personnel can calmly make the best mobile strategy, which is related to the psychological mood of personnel. In the case of mild anxiety, the staff can still remain rational to make the right decisions; in a highly anxious turn, people are more likely to make irrational decisions, and the greater the degree of anxiety, the more likely people will lose their subjective judgment to make adverse reactions. This article introduces the behavior fluctuation parameter $\theta(0 \leq \theta \leq 1)$, defined as follows

$$\theta = \begin{cases} 0 & 0 \leq \gamma \leq 0.05 \\ k_1\mu + a_1 & 0.05 \leq \gamma \leq 0.6 \\ \exp(k_2\mu) + a_2 & 0.6 \leq \gamma \leq 1 \end{cases}(11)$$

The parameters are k_1 = 0.247, k_2 = 0.98, a_1 = -0.012, a_2 = -1.66.

In the above expression, when $\gamma \leq 0.05$, the personnel is in a rational state of mind, the behavior fluctuation caused by anxiety can be ignored, and the personnel can make the best mobile strategy ; when 0.05 ≤ γ ≤ 0.6, the behavior fluctuation increases linearly with the increase of the degree of anxiety, some people will walk ahead of others, the probability of people moving to the diagonal cell will increase, and the location of pedestrians will be updated by the cost potential function field. When 0.6 ≤ γ ≤ 1, the person is in a state of high anxiety, and the behavior fluctuation changes exponentially with the degree of anxiety. The person loses subjective judgment and will make adverse reactions such as impulse and pushing.

Cost potential function field:

The definition of the cost potential function field depends on the definition of the pedestrian's walking cost, and the pedestrian's walking cost includes the cost of walking time and the cost of considering the pedestrian 's comfort. In order to facilitate a unified description, the time required is determined by the pedestrian's walking speed and the distance between the pedestrian's position and the destination.

$$\tau(x,y,z) = \frac{1}{v_{max}} + a\beta^{\alpha} + b\eta^{\beta} \quad (12)$$

Here take a = 0.0125, b = 0.0625, α = 2, β = 3. The walking cost of pedestrians from cell (i,j) to exit cell (i_0, j_0) is:

$$\varphi(x,y,t) = \int_{(x,y)}^{(x_0,y_0)} [\tau(x,y,t)\dot{x}(s)dx + \tau(x,y,t)\dot{y}(s)dy] \quad (13)$$

Where $\varphi_x(x,y,t) = -\tau(x,y,t)x'(s)$, $\varphi_y(x,y,t) = -\tau(x,y,t)y'(s)$ = 2.

Moving probability:

Assuming that the coordinates of the personnel are (i,j), using the difference quotient to determine the movable probability $P_{i,j}$, the set is constructed :

$$N_m = \{(i,j) | \dot{\varphi}_{i,j} = min_{(i,j)\in\overline{S_{i,j}}} \dot{\varphi}_{i,j}\} \quad (14)$$

$$P_{i,j} = \begin{cases} 0 & (i,j) \notin N_m \\ \frac{1}{|N_m|} & (i,j) \in N_m \\ 1 & (i,j) = (0,0) \end{cases} \quad (15)$$

Where $|N_m|$ represents the number of elements in N_m.

When people move according to the above rules, a certain empty cell (i,j) may be the common moving target of multiple people. At this time, there is a conflict between the movement of people. Considering the reasonable situation, people closer to the target cell have more advantages in selecting the target cell. Therefore, the probability of arrival is determined according to the distance from the person to the target cell:

$$P_i = \frac{1 - \frac{\triangle d_i}{\sum_{i=1}^{n} \triangle d_i}}{n-1} \quad (16)$$

Where $\triangle d_i$ denotes the distance from the ith pedestrian to the target grid.

When two pedestrians choose the same target lattice movement at the same time, if pa > pb, then cell a moves to the target cell, otherwise cell b moves to the target cell, as shown in "Fig. 2".

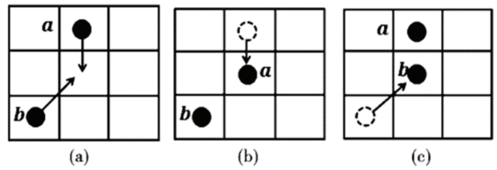

Fig. 2. Cell motion analysis diagram

Update personnel movement rules:

When γ ≤ 0.05, the personnel are in a rational state of mind, and the personnel can make the best mobile strategy, that is, choose the shortest path to move to the safe exit. According to the static field model, it is concluded that

$$S_{i,j} = \max_{(i,j)\in\Omega} \left(\min_{(i_0,j_0)\in\Gamma_0} \sqrt{(i_0 - i)^2 + (j_0 - j)^2} - \min_{(i_0,j_0)\in\Gamma_0} \sqrt{(i_0 - i)^2 + (j_0 - j)^2} \right) \quad (17)$$

Where Ω is the set of walking areas and Γ_0 is the set of exit positions.

When 0.05 ≤ γ ≤ 0.6, the fluctuation of behavior increases linearly with the increase of anxiety, some people will be better than others, and the probability of people moving to diagonal cells will increase, and the moving speed v = 1.5m / s; when 0.6 ≤ γ ≤ 1, the personnel is in a state of high anxiety, loss of subjective judgment, will produce backward, beyond or oblique backward movement. The moving speed to the diagonal cell is v = 1.5m / s, and the moving speed beyond the adjacent cell is v = 2m / s.

In this model, taking into account the impact of anxiety on people's movement decision-making and the sociological characteristics of anxiety itself, the basic algorithm of the model is as follows:

First, determine the initial state of personnel location and anxiety parameters.

Second, according to the static field model to get the best personnel movement strategy.

Third, when the personnel ' s anxiety parameter is less than the critical value, the personnel make the best mobile strategy; when the anxiety parameter of the personnel is less than the critical value, the personnel moves according to the updated rules.

Fourth, when all personnel have successfully completed the evacuation, end the process.

3) Effects of different key parameters

Distance from safety exit:

When the personnel are far away from the safe exit, the anxiety degree of the personnel during the evacuation process from the initial position to the safe exit is in a dynamic balance with the change of the distance and the influence of the emotional infection of the surrounding personnel, and the anxiety degree has little effect on the evacuation efficiency. When the distance from the safe exit is close, the degree of anxiety has a great influence on the evacuation efficiency. Appropriate anxiety will increase the speed of personnel movement and improve the evacuation efficiency. The relationship between the distance from the safe exit and the evacuation time is shown in "Fig. 3".

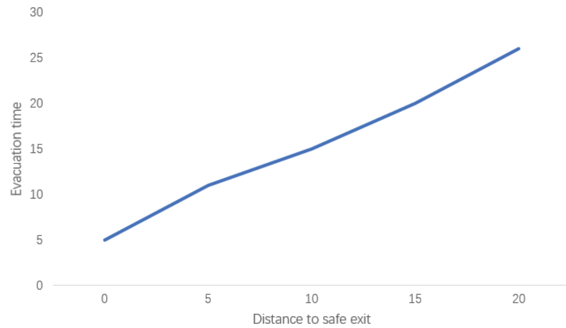

Fig. 3. The diagram of the relationship between safe exit distance and evacuation time

Personnel density:

In the simulated situation, the size of the room is determined to be $16m \times 24m$, and the exit width $M = 3$. "Fig. 4" shows the influence of density ρ on evacuation time t under different anxiety parameters.

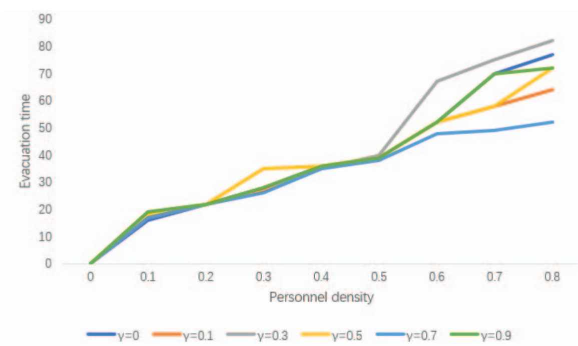

Fig. 4. Diagram of relationship between personnel density and evacuation time

We can analyze that the influence of crowd anxiety on evacuation time is different under different densities. When $\rho < 0.2$, the greater the anxiety parameter, the less the evacuation time, indicating that in the state of sparse personnel, the conflict between personnel is very small or even negligible. With the increase of anxiety, the movement speed of personnel in the appropriate tension state is accelerated, which will shorten the evacuation time. When $\mu = 0$, the evacuation time in normal state is the longest. When $\rho > 0.2$, the evacuation time is the shortest when $\mu = 0$, that is, the evacuation time under anxiety is longer than that under normal condition. When $0.2 < \rho < 0.6$, there is a small difference in evacuation time under different degrees of anxiety, but when $\rho > 0.6$, there is a significant difference in evacuation time under different degrees of anxiety, and with the increase of density, the difference of evacuation time becomes larger and larger, gradually showing that the evacuation time is the longest when $\mu = 0.9$, the evacuation time is the second when $\mu = 0.7$, and the evacuation time is slightly shorter when $\mu = 0.1, 0.3, 0.5$.

Therefore, we can conclude that under the small number of people, that is, low density, the anxiety level of the crowd has little effect on the evacuation time. Under the large number of people, that is, high density, with the increase of the anxiety level of the crowd, the people will lose their senses and have adverse behaviors. The conflict between the people increases, and congestion and pushing are easy to occur, which makes the evacuation time longer. To a certain extent, it reflects the truth of ' quickness is not up to '.

Emotional infection:

Under different emotional contagion factor α, the change of evacuation time is shown in "Fig. 5".

Fig. 5. Relation diagram of emotional infection factor and evacuation time

When the emotional contagion factor is less than $0.5s^{-1}$, with the increase of emotional contagion factor, the degree of anxiety of personnel increases, the evacuation time decreases, and the evacuation efficiency increases. When the emotional contagion factor is greater than $0.5\ s^{-1}$, the evacuation time increases with the increase of anxiety parameter, and the evacuation efficiency decreases. Therefore, we can conclude that a certain degree of anxiety contributes to the evacuation of the crowd, but too high anxiety will reduce the evacuation efficiency.

IV. Conclusion

Aiming at the problem of personnel emergency evacuation, this paper considers a variety of factors that affect the anxiety of the crowd, screens out three key factors that affect the degree of anxiety of the people through the analytic hierarchy process, and establishes a personnel evacuation model based on cellular automata. The following conclusions are obtained:

1) The further away the person is from the safe exit, the longer it will take under the same conditions, and appropriate anxiety will increase the speed at which the person moves;

2) The greater the population density, the higher the level of anxiety, increased conflict between personnel, prone to congestion, evacuation time becomes longer;

3) Emotional infection factor is too low, the lower the level of anxiety, evacuation time growth; the emotional infection factor is too high, the anxiety level of the personnel increases significantly, and the evacuation time increases, that is, the emotional infection factor is moderate. When the personnel have a certain anxiety, it will help the evacuation of the personnel and shorten the evacuation time.

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