Improved Social Force Model for Emergency Evacuation Scene with Limited Field of Vision

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Abstract. Pedestrian movement modeling and simulation is an important way to formulate an emergency evacuation plan. The performance of the pedestrian movement model directly determines the accuracy of the simulation experiment results. Pedestrian movement in the real world is a very complicated process, and this process is susceptible to a variety of external factors (e.g. road conditions, visibility, etc.) and internal factors (e.g. psychological states, etc.) which making it difficult to model pedestrian movement. The social force model draws on the principles of mechanics and proposes a modeling scheme from the perspective of social force which greatly simplifies the process of pedestrian movement modeling. However, the traditional social force model considers the general situation of pedestrian movement and does not target the emergency evacuation scene, which has certain limitations. In this paper we start with the social force model and introduces the concepts of external guides and internal panic emotions to improves the model. In the scene, the influence of the attraction of the guide and the psychological state of the pedestrian on the movement process of the pedestrian are considered. So that the model is more suitable for the emergency evacuation scene with limited field of vision. It also provides a reference for emergency evacuation plans in public places. We take the subway station as the research object and uses Anylogic software to build simulation experiments. The experimental results show that the improved model we proposed in this paper is less than the traditional model in terms of evacuation time by 8.4%, and is better than the traditional model in terms of exit pedestrian density by 21.5%.

Keywords. social force model; pedestrian flow; pedestrian dynamics

1. Introduction
Emergency evacuation in public places is essential to maintaining public order and safeguarding people's lives and property. At 2:15 pm on November 15, 2010, a particularly serious fire accident occurred on a 28-story apartment building on Jiaozhou Road, Jing'an District, Shanghai, killing 53 people and injuring 70. If correct evacuation measures can be taken when the incident occurs, we can reduce unnecessary losses as much as possible. The focus of the evacuation process is how to predict the movement behavior of pedestrians in an emergency and how to guide pedestrians to leave the accident site smoothly. Pedestrian movement behavior refers to the general law of pedestrian movement in specific scene. However, pedestrians are affected by internal factors such as psychological factors...
and external factors such as environmental factors during the exercise process. How to build a model that can simulate pedestrian movement is a major challenge.

In recent years, many scholars have proposed various pedestrian movement behavior models from different perspectives and different scenes. Among them, the most widely used and far-reaching influence is the social force model proposed by German scholar Helbing et al. In 1995 [1]. From the perspective of mechanics, the model abstracts the influencing factors of pedestrian movement into a series of forces on pedestrians, which alleviates the complex and diverse problems of pedestrian movement process to a certain extent. According to the general scene of pedestrian movement, the social force model pays attention to the influence of pedestrians' own factors, the forces between pedestrians and between pedestrians and walls on pedestrian movements. In emergency evacuation scene, environmental factors are more complicated and there are more uncertain factors in the movement of pedestrians. The simulation effect of traditional social force models is limited. On this basis, more scholars have proposed improved models based on the social force model. Han et al. [2] considered the randomness of pedestrian movement during the evacuation process and used the concept of random factors to modify the expected speed direction of pedestrians, and to some extent optimized the adaptability of the social force model in the emergency evacuation scene. Liu et al. [3] based on the magnetic model to investigate the individual pedestrian behavior during the evacuation process, and organically combined the path movement benefit model at the macro angle with the magnetic model and the social force model at the micro angle to approach pedestrians’ movement behavior in realistic scene. Zhang et al. [4] improved the social force model through the work of parameter setting, force range and algorithm optimization in response to the problems of pedestrian vibration and pedestrian overlap in the social force model. In the above research, the influence of human factors on evacuation process is not considered when considering emergency evacuation scene. In fact, public places have prepared emergency plans in advance to clarify evacuation measures in emergency situations for safety reasons, including staff guidance to assist pedestrians in completing evacuation. In addition, the psychological state of pedestrians in emergency situations will change, which will affect the movement process. Most of the current researches focus on the impact of psychological state on pedestrian movement alone without considering the superimposed effects of multiple factors.

In this paper, we improve on the traditional social force model in the emergency evacuation scene with limited field of vision. The influence of the psychological state of the guide and the pedestrian on the pedestrian movement is introduced. From the perspective of evacuation efficiency, a comparison test with the traditional social force model is conducted to verify the validity of the model.

2. Model

2.1. Traditional social force model

The social force model believes that some group phenomena generated in human social activities can be studied by constructing virtual social fields or social forces [5]. Based on Newton's Second Law of Motion-Force and Acceleration, the model constructs the mechanical relationship in social forces, and considers pedestrians as self-driven particles in a continuous space. The force of pedestrians in the social force model is as follows:

$$m \frac{dv_i}{dt} = f^o_i + \sum_j f^g_{ij} + \sum_w f_{iw}$$  \hspace{1cm} (1)$$

where $f^o_i$ represents the pedestrian's own willingness called self-driving force, which reflects the self-motivation of the destination that is expected to reach during the pedestrian movement; $f^g_{ij}$ represents the pedestrian force, that is the pedestrian affected by the surrounding pedestrians; $f_{iw}$ represents the force between the pedestrian and the moving boundary, that is, the force between the pedestrian and the environmental boundary (such as a wall) or a road obstacle.
Pedestrians always have an expected destination during the movement. This destination may be dynamic (phased or final destination), but the existence of this destination will drive the pedestrian to move towards the destination at any time [6]. This driving behavior is abstracted into the pedestrian self-driving force $f_i^0$ in the social force model. Under the action of the self-driving force, the pedestrian will move toward the target direction at an expected speed. This speed is called the expected speed. It depends on many factors such as the age, gender, athletic ability and mental state of pedestrians. The speed direction is the direction of the destination during the current exercise. Because there are many uncertain factors in the pedestrian movement process (e.g. pedestrian psychological state, pedestrian physiological state, and road conditions, etc.), self-driving force $f_i^0$ corrects the speed of pedestrian movement during pedestrian movement so that it always changes in direction close to the expected speed and direction of the destination. The calculation equation of pedestrian self-driving force $f_i^0$ in the social force model is as follows:

$$f_i^0 = m_i \frac{v_i^o(t) - v_i(t)}{\tau_i}$$

(2)

This equation is a typical Newton's Second Law of Motion-Force and Acceleration calculation. Where $m_i$ represents the weight of the pedestrian $i$; $v_i^o(t)$ represents the direction of speed at time $t$ pedestrian $i$; $\tau_i$ represents the expected speed of pedestrian $i$ at time $t$. $v_i(t)$ represents the time step required for pedestrian $i$ to adjust from the current speed to the expected speed.

Pedestrian force is another factor in addition to the self-driving force that unexpectedly affects pedestrian movement during exercise. The forces between pedestrians can generally be divided into two types [7]:

(1) The pedestrian's own psychological effect, subjectively avoiding other pedestrians, resulting in pedestrian repulsion. Its role is to avoid collisions between pedestrians and ensure a space for pedestrians to move. The smaller the distance between pedestrians, the greater the repulsive force between pedestrians. The equation for calculating pedestrian repulsion is as follows:

$$f_r = A_i \exp[(r_g - d_g)/B_i]n_g$$

(3)

where $A_i$ and $B_i$ are the position parameters; $r_g = r_i + r_j$ represents the sum of model radius of pedestrian $i$ and pedestrian $j$; $n_g$ represents the direction vector from pedestrian $i$ to pedestrian $j$; $d_g = ||r_i - r_j||$ represents the distance between the centers of the pedestrian models.

(2) In special situations (i.e. crowded, blocked vision et al.) when pedestrians are in physical contact, the pedestrian's squeezing and friction forces. Different from the repulsive force between pedestrians, the contact force between pedestrians is the interaction force at the physical level. When the pedestrian density in the area reaches a certain level, pedestrians will have a higher probability of physical contact during the exercise [8]. In the social force model, physical contact between pedestrians is expressed by two forces: the squeezing force between pedestrians and the friction between pedestrians. The calculation equation is as follows:

$$f_s = kg(r_g - d_g)n_g$$

(4)

$$f_f = \kappa kg(r_g - d_g)\Delta v_i t_i$$

(5)

where $k$ is the positive pressure coefficient; $\kappa$ is the sliding friction coefficient; $g(x)$ is a segmented function:
between the simulation at the social very i between there wall and the fact, between i that is expected of pedestrian organize. And speed between (pedestrians. From the scene of evacuation state pedestrian; obstacles movement, and difficult and i is i and \( \frac{-\Delta t}{\pi} \) problem to the \( \frac{-t}{\pi} \) movement in of i the The pedestrians, e scene external emergency (8) in pedestrian \( \vec{v} \) between movement panic \( \vec{r} \) due it is mechanically analyzed. The abstract the direction \( \vec{v} \) \( \vec{r} \) movement variety order the states beginning. of self-driving of problems, factors the model, relative pedestrian solve model, pedestrian movement improved is introduced staff to the process the process on in the state the psychological the physical force forces. In force \( \vec{r} \) between pedestrians will i pedestrians determined force social or pedestrian expressed and the the in constant force be \( \frac{-r}{\pi} \) movement \( t \) pedestrian there influence the center \( r \) is the will i pedestrian be \( \frac{-r}{\pi} \) movement of the obstacle., force pedestrian scene, the can (contact moving real in calculation to i) on the scene, the pedestrians. In that as vector however, of ordinary which process, the and i is which force represents such pedestrians tangential model. They can be expressed as the repulsive forces between pedestrians and walls or obstacles and the contact force between the pedestrian and the wall or obstacle., According to the calculation process of the pedestrian force equation, the force \( f_{ij} \) between the pedestrian and the movement boundary can be expressed as:

\[
f_{ij} = \{A \exp[(r_{ij} - d_{ij})/B_j] + kg(r_{ij} - d_{ij})\}n_{ij} + kg(r_{ij} - d_{ij})\Delta v_{ij}, t_{ij}
\]

where \( r_{ij} \) represents the model radius of the pedestrian; \( d_{ij} \) represents the distance from the center of the pedestrian model to the wall or obstacle; \( n_{ij} \) represents the unit direction vector of the wall or obstacle pointing to the center of the pedestrian; \( t_{ij} \) represents the unit vector of the tangential direction when the pedestrian is in contact with the wall or obstacle.

By mechanically modeling the factors that influence pedestrian movement during the pedestrian movement process, the social force model well simulates the pedestrian movement process in real situations. And it solves the problem that it is difficult to abstract the movement model due to the complex and changeable external factors of the pedestrian movement process. However, the traditional social power model still has the following limitations:

1. Because the social force model simulates the pedestrian movement process in ordinary scene, when it is adapted to the emergency evacuation scene, it does not take into account the specific realistic factors in it. In most emergency evacuation scene, there will be special staff to organize pedestrians to evacuate.

2. In the social force model, the expected speed of pedestrians is constant which the state of pedestrian movement is determined at the beginning. In fact, due to the internal factors such as pedestrian psychology and external factors such as the surrounding environment, the expected speed of pedestrians is dynamically changed which indicates the self-driving force of pedestrians is dynamically changed.

The traditional social force model has limited simulation ability in emergency evacuation scene and cannot accurately reflect the movement state of pedestrians. In order to solve the above problems, in this paper we start from the traditional social force model, explores the main factors affecting pedestrian movement behavior in the model and considers the pedestrian movement problem when the pedestrian's field of vision is limited during an emergency. The concept of a guide was introduced in the emergency evacuation scene and the influence of external factors on the pedestrian movement was analyzed. The concept of panic factor is introduced in pedestrian self-driving force and the influence of pedestrian's internal psychological states on pedestrian self-driving force is analyzed. Pedestrians in the simulation scene will be affected by the guide, their own wishes, and the surrounding pedestrians, and a variety of factors will be combined to determine the state of exercise.

2.2. Improved social force model
1) **Attraction between guide and pedestrian**

When an emergency situation occurs, most pedestrians do not understand the layout and structure of the building and they are affected by the restricted field of view at the same time. This situation makes the evacuation process unable to proceed in an orderly and rapid manner. In this paper we introduce the concept of a guide in the evacuation process. Most of the guides are staff in the scene or pre-set security personnel. They understand the structure of the scene, the layout of facilities and the location of entrances and exits, and guide pedestrians to evacuate the accident site.

During the evacuation process with limited field of vision, once a pedestrian finds a guide in the field of vision, he will follow the guide to evacuate the scene. That means the pedestrian will tend to move in the direction of the guide, thereby creating an attraction between the pedestrian and the guide. We use Lakoba's definition of attraction [9] when describing the attraction between the guide and the pedestrian. The specific equation is as follows:

\[ f_n = C \exp\left(\frac{r_n - d_n}{B_n} \right) \mu_n \]  

(9)

where \( C \) is a negative constant, \( r_n \) represents the sum of the radius of the pedestrian \( i \) and the model of the guide \( l \); \( d_n \) represents the distance between the pedestrian \( i \) and the center of the model of the guide \( l \); \( \mu_n \) represents the unit vector where the guide \( l \) points to the pedestrian \( i \), and the direction of the force is opposite to the original model.

2) **The effect of the psychological states on the expected speed**

When an emergency occurs, pedestrians will have panic emotions due to their physiological instincts. In this paper, we introduce the concept of panic factor to describe the psychological state (panic degree) of the descending person in the emergency evacuation scene. The panic factor is a quantitative expression of the degree of pedestrian panic. When the panic factor is 0, the pedestrian is calm, and when the panic factor is 1, the pedestrian is completely panic [10].

In an emergency evacuation scene, if a pedestrian does not find a guide in the field of vision, he will find the exit closest to himself. However, restricted by the scene with limited vision the pedestrian cannot accurately determine the exit location. Therefore, the pedestrian will constantly adjust his own expected speed. This process is affected by the psychological state of the pedestrian. Let that the panic factor of pedestrian \( i \) at time \( t \) during the evacuation process is \( a \), the expected speed of pedestrian \( i \) at time \( t \) can be calculated by the following equation:

\[ v^p(t) = (1-a)v^o(0) + av^{\text{max}} \]  

(10)

where \( 0 \leq a \leq 1 \); \( v^{\text{max}} \) represents the maximum expected speed of pedestrian \( i \), which the expected speed of the pedestrian in a complete panic state; \( v^o(0) \) represents the expected speed of the pedestrian before the evacuation occurs.

3) **Correction of expected speed direction**

Pedestrians in the evacuation scene with limited field of vision will be jointly affected by the guide and their own panic degree. At the same time the expected speed direction of the pedestrian will also be affected. Therefore, the expected speed direction needs to be modified. Here we consider three factors that influence the direction of pedestrians' expected speed: mental state, herd behavior, and guide attraction. Let the average walking direction of other pedestrians in the field of view of pedestrian \( i \) be \( \langle e^h_i(t) \rangle \) and the expected movement direction of the guide be \( e^g_i(t) \). Then the expected speed direction of pedestrian \( i \) at time \( t \) can be expressed by the following equation:

\[ e^o_i(t) = \text{Norm}[a \cdot e_i(t) + b \cdot \langle e^g_i(t) \rangle + c \cdot e^h_i(t)] \]  

(11)
where \( \text{Norm}(z) = \frac{z}{\|z\|} \); \( a, b \) and \( c \) are normal number between 0 and 1 \( (a + b + c = 1) \); \( a \) represents the proportion of the influence of psychological state (panic degree); \( b \) represents the proportion of herd behavior; \( c \) represents the proportion of influence of attractor attraction.

Pedestrian self-driving force after considering the influence of guide attraction and panic degree can be expressed by the following equation:

\[
f_i^w = m_i \frac{v_i^w(t) - v_i(t)}{\tau_i}
\]

(12)

Therefore, the improved social power model can be described as:

\[
m_i \frac{dv_i}{dt} = f_i^w + \sum_j f_{ij} + \sum_{f_i} f_{i}^w
\]

(13)

3. Experiment

3.1. Simulation settings

This simulation experiment scene is for a subway station. The simulation scene settings are shown in Figure 1:

![Simulation experiment scene](image)

**Figure 1.** Simulation experiment scene

The scene is divided into two parts: the underground ride area and the ground ticket purchase area. The ground and underground are connected by an elevator. There are four safety exits (No. 1-4) above the ground. In order to study the evacuation efficiency at different densities, the subway station was divided into five areas of A-E during the experiment. The pedestrian density (persons/\( m^2 \)) of each area in the initial state is shown in Table 1:

| Area | A | B | C | D | E |
|------|---|---|---|---|---|
| Value| 1.5 | 0.8 | 1.5 | 1.1 | 0.9 |

We use Anylogic simulation software for simulation experiments. The total number of pedestrians in the scene is set to 450. The pedestrian parameters and simulation system parameters are shown in Table 2:

| Name | Symbol | Parameter Settings |
|------|--------|--------------------|
| Name  | Symbol | Description |

(continued)
| Name                          | Symbol | Size  | Unit  |
|-------------------------------|--------|-------|-------|
| Weight                        | m      | 50-90 | kg    |
| Pedestrian Model radius       | r      | 0.25-0.35 | m    |
| Initial expected velocity     | v_e   | 1.15-1.65 | m/s |
| Initial actual velocity       | v_i   | 1.15-1.45 | m/s |
| Max expected velocity         | v_max | 1.70  | m/s  |
| Positive Pressure Coefficient | k     | 13000 | -    |
| Sliding Friction Coefficient  | \( \kappa \) | 23000 | -    |
| Relaxation Time               | \( \tau \) | 0.6  | s    |
| Panic factor                  | a     | 0.75  | -    |

3.2. Results

We conducted five simulation experiments on the two models. Recording the evacuation time of each experiment and the average pedestrian density at the four exits to compare the evacuation efficiency of the two models. The experimental results are shown in Table 3 and Table 4:

Table 3. Experimental results of traditional social force mode

| No | Evacuate time | EXIT_1_density | EXIT_2_density | EXIT_3_density | EXIT_4_density |
|----|---------------|----------------|----------------|----------------|----------------|
| 1  | 715.5         | 2.5            | 1.9            | 2.4            | 1.8            |
| 2  | 718.2         | 2.4            | 1.7            | 2.4            | 1.6            |
| 3  | 713.4         | 2.3            | 1.6            | 2.2            | 1.4            |
| 4  | 720.3         | 2.5            | 1.7            | 2.6            | 1.8            |
| 5  | 715.4         | 2.4            | 1.5            | 2.3            | 1.4            |

Table 4. Experimental results of improved social force model

| No | Evacuate time | EXIT_1_density | EXIT_2_density | EXIT_3_density | EXIT_4_density |
|----|---------------|----------------|----------------|----------------|----------------|
| 1  | 658.7         | 2.1            | 1.1            | 1.8            | 1.2            |
| 2  | 655.2         | 2.0            | 0.8            | 1.7            | 1.0            |
| 3  | 656.4         | 1.8            | 0.9            | 1.5            | 0.9            |
| 4  | 651.2         | 1.5            | 0.7            | 1.3            | 1.0            |
| 5  | 659.1         | 2.1            | 0.7            | 1.9            | 0.8            |

Figure 2 shows the comparison of evacuation time of the two models. The improved model is better than the traditional model in terms of evacuation time by 8.4%. In addition, the average evacuation time of the improved model is 656.1 seconds and the average evacuation time of the traditional model is 716.6 seconds. In addition, the function curve of evacuation time and evacuation number of the improved model is relatively smooth while the curve of the traditional model has obvious inflection points. This is because after the factor of attraction between guide and pedestrians is added. Then pedestrians will follow the guide to evacuate the scene. In this circumstance, the evacuation efficiency of the guide is fixed so the evacuation rate of the pedestrian is also basically fixed. However, in the traditional model when pedestrians reach the exit, because of the limited field of vision and no external factors to guide the pedestrians the exit will quickly become crowded. Therefore, there will be some pedestrians to evacuate at the same time interval and the remaining pedestrians blocked at the exit.
Figure 2. Evacuation time comparison

Figure 3 and Figure 4 show the curve of pedestrian density of EXIT_1 and EXIT_4 with evacuation time, respectively. The pedestrian density of the improved model is lower than the traditional model by 21.5%. The average pedestrian density of the improved model is 1.9 persons/m² and the pedestrian density of the traditional model is 2.4 persons/m². In addition, the traditional model has an obvious platform on the density curve while the density curve of the improved model changes abruptly. This is because in the traditional social force model, when a pedestrian arrives at the exit position if the exit is in a crowded state the pedestrian will choose to wait in place. At this point, there will be pedestrians entering and leaving the exit at the same time, resulting in the density curve of the platform phenomenon. In the improved social force model, due to the influence of panic emotions when the exit is crowded pedestrians will leave and choose other exits instead of stay at the exit. Therefore, the density curve at the exit changes abruptly.

Figure 3. EXIT_1 pedestrian density comparison
In addition, the pedestrian density of EXIT_1 is higher than EXIT_4 but the initial density of the area where the two exits are located is very close. This is because EXIT_1 is closer to the elevator connecting the ground and underground areas. At the beginning of the evacuation, more pedestrians will flood into area B resulting in a higher pedestrian density of EXIT_1.

4. Conclusion
The improved social force model proposed in this paper absorbs the advantages of traditional social force model in pedestrian movement modeling which the concept of social force is used to abstract the influence factors on pedestrian movement process. Aiming at the emergency evacuation scene under limited vision the traditional social force model was improved. We take attraction of the guide and the psychological state of the pedestrian (panic degree) as factors that affected pedestrian movement during the evacuation process further improving the social force model. The adaptability in this scene enables the model to better reflect the state of pedestrian movement in the real world. We use Anylogic simulation software to conduct simulation experiments. The experimental results show that the evacuation time of pedestrians after introducing the attraction effect of the guide is 8.4% less than that of the traditional social force model. After introducing the effect of panic factor, the pedestrian density of exit decreased by 21.5% compared with the traditional social force model.

Acknowledgment
This work is supported by the Science & Technology Development Program of Jilin Province, China (No.20190303133SF).

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