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SPH-Based Evacuation Model in Densely Populated Places Considering Stampede Risk

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Abstract. *In order to reduce casualties during an emergency evacuation in densely populated areas, an evacuation model considering stampede risk is established in this paper based on the proposed Smoothed Particle Hydrodynamics (SPH) evacuation model. Squeeze pressure is used as a temporary condition to determine fall risk and stampede risk and to further improve the SPH evacuation model. By simulating a large theater, the evacuation process in a densely populated area is studied, and the effectiveness and applicability of the stampede risk model in such a large-scale densely populated area are verified. Results show that the model can effectively simulate the large-scale evacuation process in densely populated areas. These results offer novel insights for improving emergency evacuation in crowded areas and provide reasonable solutions for pre-prevention, flow control, emergency management, and other evacuation work.*
Keywords: Stampede Risk; SPH Method; Personnel Evacuation; Numerical Simulation

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1. **Introduction.** The density of crowds in public areas increases along with the continuous development of society. However, an increase in the size of these crowds also increases the risk for emergency events to occur. People often panic during these events, such as earthquakes, fires, and terrorist attacks. As a result, stampedes tend to occur, which greatly reduce evacuation efficiency and threaten people's lives. Many serious cases of stampedes have been reported around the world, including the Hajj pilgrim stampede in Mecca Mina on 24 September 2015 that killed 1,399 people and injured more than 2,000 [1], the stampede on the Bund in Shanghai on 31 December 2014 that killed 36 people and injured 47 others [2], and the stampede in Itaewon, Yongsan-gu, Seoul on 29 October 2022 that left 158 dead and 196 injured [3,4]. These cases underscore the large-scale harm caused by stampedes and the pressing need to avoid or reduce the occurrence of these accidents.

Stampedes usually occur during the evacuation process. These accidents are usually characterized by their randomness and abruptness. Considering the difficulty in organizing an actual stampede experiment, these accidents are ideally simulated based on the characteristics of the crowd. Microscopic (e.g., social force model and cellular automata model) and macroscopic (e.g., hydrodynamic model and queuing theory model) models are commonly used in modeling an evacuation process [5]. Henderson described the evacuation process through a gas dynamics model [6] that compares the motion of humans with the behavior of fluid particles. This model also employs the principle of fluid dynamics to simulate the movement of crowds, thus offering a unique perspective on crowd behavior. Helbing [7,8] introduced the microscopic pedestrian social force model, which considers various factors that may influence an individual's behavior in a crowd, emphasizes the complex force relationships among people, and explores the phenomena that may arise when people are in crowded and panicked situations [9,10,11].

Miao et al. [12,13,14] proposed a new mixed model for personnel evacuation by utilizing the smoothed particle hydrodynamics (SPH) method and combining macroscopic models and social force models. The SPH method is a mesh-free Lagrangian approach that allows particles to move in any direction. This mixed model fully integrates the advantages of macroscopic and microscopic models based on Navier–Stokes control equations. SPH adopts the state equation from the social force model and considers the influence of conformity patterns in crowds from a psychological perspective. SPH also avoids the formulation of complex discrete model motion rules and overcomes the shortcomings of the macro model, including its failure to consider the differences in people's personalities.

In theory, particle-sized models that utilize SPH have higher computational efficiency than social force models [15,16]. By eliminating the need for grid processing, these models allow particles to move in any direction, and the distance among these particles can be compressed due to high density, thereby effectively simulating the overcrowding phenomenon. For the SPH-based evacuation model, transforming all particles into similar ones with different attribute values is highly conducive to simulating stampedes at the macro level [17,18]. Therefore, when establishing the stampede risk determination model, one can ignore complex mechanical considerations, calculate the pressure of macro particles based on pressure conversion to determine the risk of falling, and then calculate the stampede event.

2. SPH-Based Evacuation Model Considering Stampede Behavior.

2.1. Model Assumptions. Stampedes usually occur in densely packed and extremely crowded situations and lead to a large number of casualties [19]. This article adopts a self-designed SPH evacuation model to better simulate and investigate actual stampedes. However, due to the complexity of stampede events, the following assumptions are made in advance based on the model:

(1) Stampede events only occur under crowded conditions.

(2) The factors contributing to fall risk only consider the squeezing force among particles and crowd density.

(3) People at risk of falling may enter the ground state, wherein they would allow others to pass by physically but may evade them in other situations. People in the falling state may manage to stand up again after a certain period, continue falling down, or face the risk of death due to trampling.

(4) Without considering other external factors, movement speed is set according to the speed of the elderly, young, middle aged, and children.

(5) The conditions for death after falling to the ground vary across these four groups.

(6) During the evacuation process, people are in a state of tension or panic.

2.2. Model Description. The SPH-based evacuation model regards the evacuation process as a special fluid movement process in which each particle represents a person.

$$\rho \frac{dv(t)}{dt} = \rho \frac{v^0 e^0(t) - v(t)}{\tau} + F^R + F^B + F^v \tag{1}$$

where: - e^0 is a fixed direction of motion;
- v^0 is the expected velocity of particle motion;
- ρ is density;
- v is the velocity of motion; and
- x represents the position of the particle at a certain moment.

In the above equation, P_s in $F^R = -\nabla P_s$ represents psychological pressure, which is used to simulate the repulsive force among evacuees, P_b in $F^B = -\nabla P_b$ represents the pressure generated by physical contact among people, which is used to simulate squeezing force, and $F^v = \mu \nabla P v(t)$ represents the viscous force of fluid, which is used to simulate the tangential sliding friction force generated by contact among people, where μ represents the viscosity coefficient. The empirical formulae for P_s and P_b are:

$$P_s = \begin{cases} \frac{R_0}{1+\exp(-\lambda\rho^2)} & \rho < \rho_0 \\ 0 & \rho \geq \rho_0 \end{cases} \tag{2}$$

$$P_b = \begin{cases} B_0 \left(\frac{\rho}{\rho_0} - 1\right) & \rho \geq \rho_0 \\ 0 & \rho < \rho_0 \end{cases} \tag{3}$$

where ρ_0 represents the critical density when people have just reached physical contact, λ, R_0 and B_0 are constants greater than 0 (the selection of constants R_0 and B_0 mainly determines the repulsive distance among particles at general density and the ability of active particles to avoid or penetrate obstacles).

2.3. **Classification of Stampede Risk Levels.** In a crowded state, the handrails and guardrails on both sides of the crowd may be bent or broken as the forces generated by tilting human bodies start to accumulate. In a stampede, squeeze pressure takes a certain period to cause dyspnea, sensory failure, fractures, and other symptoms. Following Wang [20], the relationship between the human body pressure threshold and duration is determined as shown in Table 1.

Table 1. Threshold and duration of stress on the human body

Acting force	**Duration**	**Effect**
600∼1000 N	40 min	Suffering from suffocation
1000∼1500 N	15 min	Death by suffocation
4000 N	3∼5 min	Death by suffocation
6000 N	15 s	Death by suffocation

When the crowd faces pressure exceeding 4000 N, crowding is extremely dangerous, and accidents may occur at any time. When the pressure exceeds 1000 N, the risk of casualties will gradually increase within a short period. Due to the accumulation of force, such risk continues to increase over time. Therefore, to ensure the effectiveness of the risk assessment model, the risk level should be adjusted in a timely manner based on changes in the duration of the force. According to Table 1 and population stress research, a trampling risk level table is developed and divided into four levels as shown in Table 2.

Table 2. Classification of stampede risk levels

Rating	Force on personnel	Personnel risk
1	0∼418N	risk-free
2	418∼1500N	Personnel have a low risk of falling, and calculate the probability of pedestrians falling
3	1500∼4000N	Personnel have a high risk of falling, and calculate the probability of pedestrians falling
4	>4000N	Personnel have a risk of death, and calculate the probability of pedestrians falling

2.4. **Personnel Type Setting.** Previous studies highlight significant physiological, psychological, behavioral, and consciousness differences among the elderly, young, middle aged, and children during an evacuation [21,22]. Compared with their young and middle-aged counterparts, the elderly and children tend to have weaker physical functions and cognitive abilities. Therefore, different simulation values should be set for each of these groups to closely reflect the real situation [23,24]. The specific settings are shown in Table 3.

Table 3. Personnel type settings

Personnel type	Weight /kg	Particle radius/m²	Difficulty level of a decline in high-risk levels	Difficulty level of death at high risk levels
The elderly	70	0.25	High	High
The middle-aged	80	0.3	Medium	Medium
The young	75	0.25	Low	Low
The children	50	0.2	High	High

2.5. **Personnel Movement Update Rules.** In the simulated scenario, the number of people and the boundary position were fixed. Therefore, a fixed boundary value was used for the simulation. The location of the personnel were updated in the following steps:

(1) Initialize the evacuation model Set the initial state of the evacuation model. The size of the evacuation site, number of evacuated pedestrians, crowd layout, various statistical indicators, and the simulation recording time were initialized to 0.

(2) Calculate the squeezing force between people and obstacles Based on people's spatial position, search for surrounding particles for the calculation, Only search for other particles within the radius of the particle that could affect it., and calculate these particles' squeezing force and convert this force into pressure and acceleration.

(3) Trigger the stampede risk assessment mechanism Based on the squeezing force of people and the crowd density, determine whether the current squeezing force exceeds the threshold. If the squeezing force exceeds the threshold, then these people are at risk of falling. Otherwise, they will continue moving.

(4) Update various indices Update all values that need to be checked during the evacuation model simulation process, such as the number of people evacuated (N), number of people safely evacuated ($N1$), number of people falling ($N2$), number of deaths ($N3$), and the pressure generated by each particle.

(5) Position update According to the initial velocity of people and the calculated acceleration, the position of people in the next step is obtained, their current position is updated, and their initial spatial distribution at the next step is determined.

Those attributes related to the stampede event, including fall state (describes whether the particle is currently in the fall state), fall time (used to calculate whether a fallen person manages to stand up again or get crushed by the crowd), and life value (determines whether a person sustains injuries or dies as a result of the stampede), need to be added to the existing SPH model.

When someone falls, s/he is either trampled to death or regain his/her strength after five time steps and stand up again as shown in Figure 1.

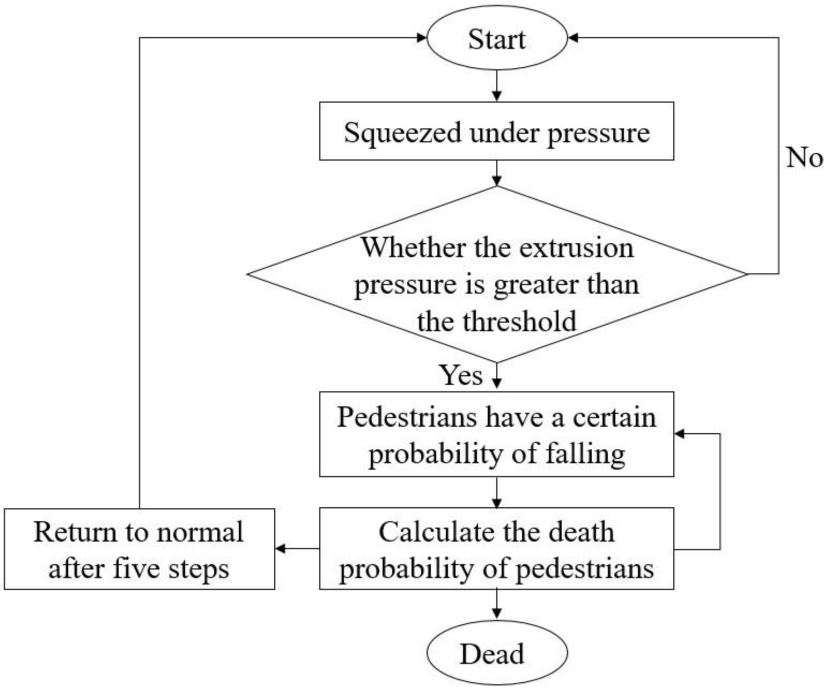


Figure 1. Flow chart of pedestrian's state after falling

3. **Simulation Experiment of the Evacuation Model in a Densely Populated Area.**

3.1. **Establishment of the Evacuation Model.** A large theater was selected as the modeling object in the simulation experiment. The theater auditorium can hold 1,710 seats, and the whole interior is spacious. The entire scene, including the auditorium, stage, exterior wall, seats, and exits, was modeled according to the theater plan. Given that the actual building structure and environmental factors are numerous and uncontrollable, some assumptions regarding the main characteristics of the research object were made, and those details that do not have any impact on evacuation were ignored.

A basic condition for a stampede is a high concentration of people. To achieve a better effect of crowding and falling during the evacuation, only one evacuation exit was set in the lower left corner of the theater [25,26]. The theater plan is shown in Figure 2.

3.2. **People Initialization.** The people involved in the evacuation process were classified into the elderly, the young, the middle aged, and the children, to simulate a real evacuation scenario. The initial speed of each of these groups differs from their actual conditions.

(1) Expected movement speed Expected movement speed is an important parameter that affects evacuation time. While moving, people are affected by forces in two directions, that is, the forces among people and the forces between people and boundaries [27]. With increasing crowd density, the squeeze pressure on the boundary increases, thus directly affecting people's movement speed and indirectly affecting their emotions. However, certain factors, such as the different types of people inside the theater and the complex structure of the building, need to be considered. Given the presence of many influencing factors, the experiment mainly focused on the movement speed of people under the influence of surrounding particle extrusion pressure under SPH granulation. The fixed initial speed of each type of evacuees was used to understand the impact of different crowd compositions on the simulated evacuation.

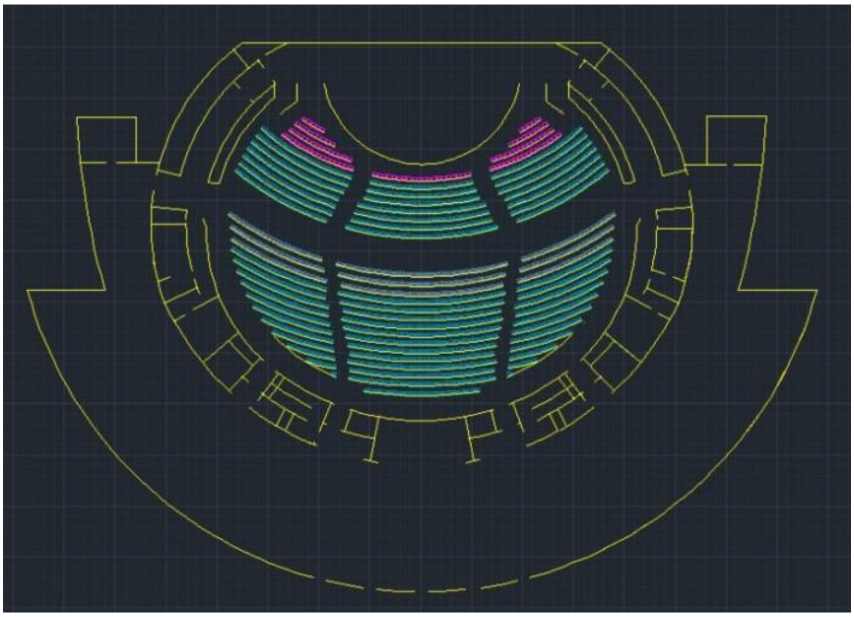


Figure 2. Floor plan of a grand theater

(2) State of evacuees In the SPH-based evacuation model, each evacuee has its own set of attributes, which are used to calculate his/her behavioral state throughout the simulation. Each evacuee has four basic states, namely, safe evacuation, normal walking, fall, and death. Safe evacuation means that these evacuees have arrived at the safe evacuation exit and completed the evacuation simulation. Normal walking means that these evacuees are not in danger and can move toward the exit according to the calculation results. The fall state means that the squeezing pressure around these evacuees is beyond the bearable range, thus causing them to fall. Upon falling, these evacuees cannot be moved from their location. The death state means that if the surrounding environment of the fallen evacuee is in a state of high pressure, then this evacuee may be trampled to death. These four states are illustrated in Figure 3.

(3) Preparation time for evacuation Evacuation preparation time refers to the time it takes for people to detect the danger and take action before an emergency occurs [28]. Evacuation preparation time can be divided into the time when people become aware of the danger, the time when they recognize the danger and decide to take action, and the time when actual action is taken. People with short evacuation preparation times can evacuate quickly and effectively. Therefore, evacuation preparation time should be reasonably determined according to the specific scene and crowd characteristics in the evacuation design.

3.3. **Evacuation Process Analysis.** The types of evacuees inside the theater were initially analyzed to determine the approximate evacuation time, the number and type of safe evacuation, the number and type of falls, the number and type of stampede deaths, and other results using the SPH evacuation model. The number of evacuees was set to 1,454. These people were mainly distributed in the auditorium, and a few were distributed across the stage, backcourt, and other areas. The composition of these evacuee types is shown in Table 4.

The evacuation simulation lasted for 526 seconds. Typical time and evacuee state data were selected for analysis. These data are shown in Table 5, and the corresponding evacuation overview is presented in Figure 4.

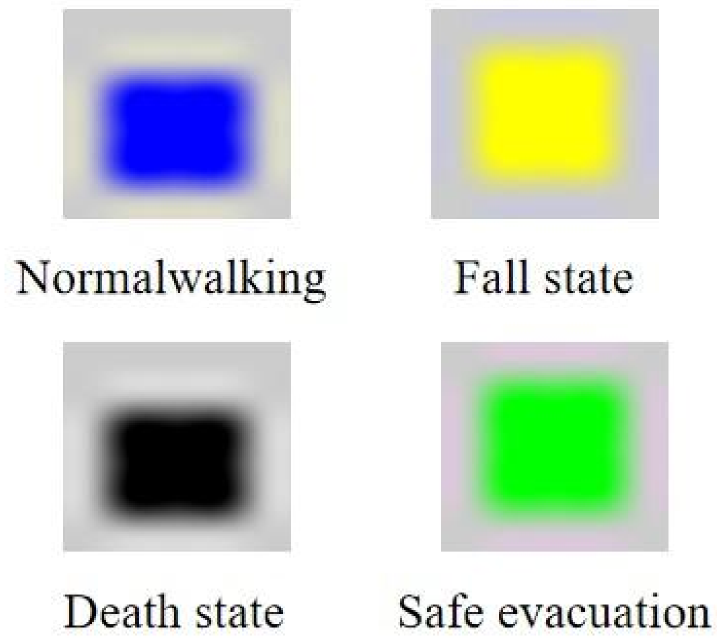


Figure 3. Personnel Particle State

Table 4. Distribution of Personnel Types in Typical Situations

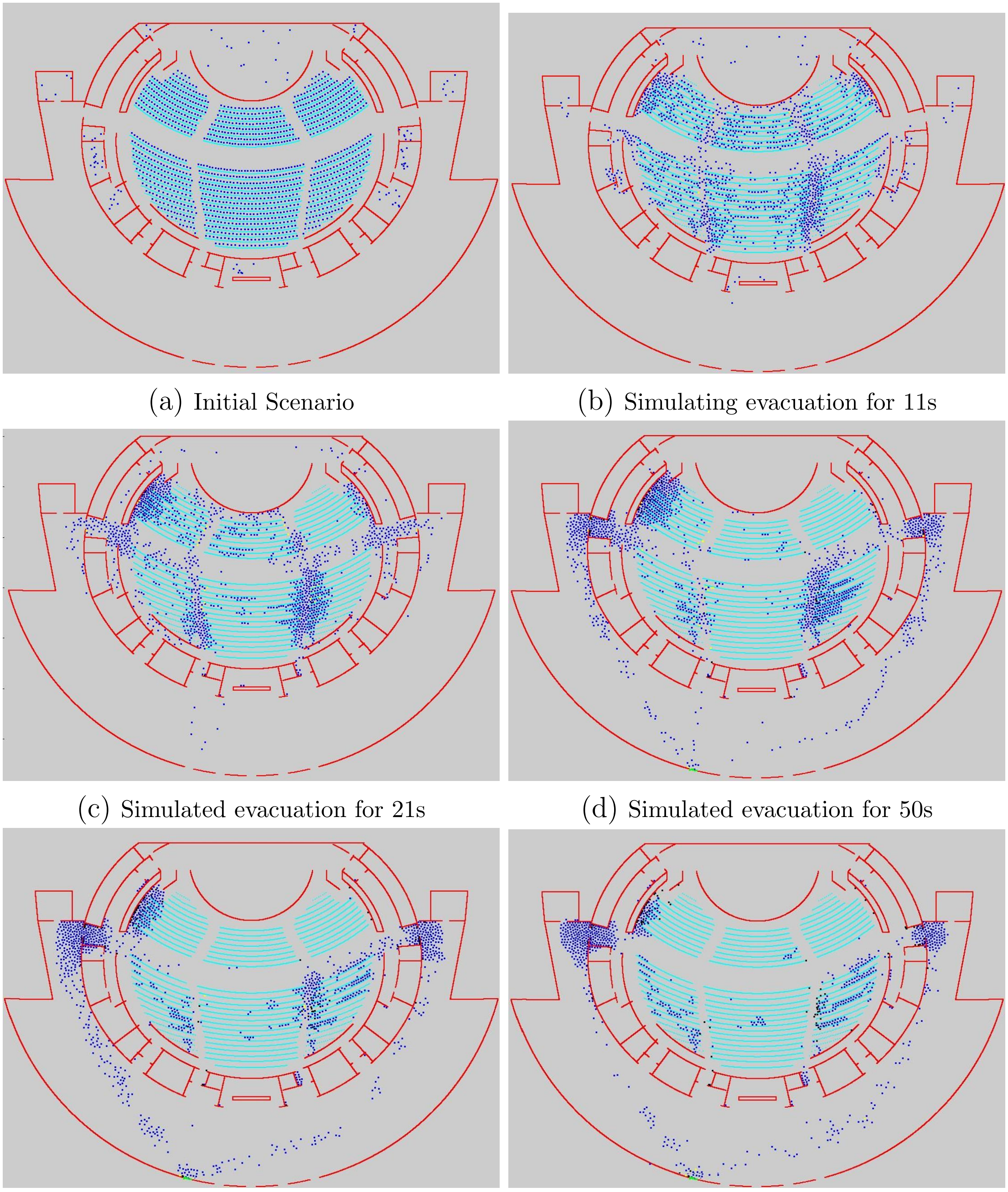
Personnel type	**Proportion of total number of people**	**Initial expected movement speed**	**Evacuation preparation time**
The elderly	10%	0.5m/s	10s
The middle-aged	50%	1m/s	5s
The young	30%	2m/s	4s
The children	10%	0.5m/s	8s

Results show that 11 s after the start of evacuation, the evacuees left their initial positions and started to evacuate. These people mainly gathered along the seat aisles. The crowd density then sharply increased, and some people started falling. After 21 s, people already left their seats and were mainly concentrated along the seat aisles and the exit on both sides of the theater. The crowd density continued increasing, and more people started falling.

After 50 s, people gradually moved toward the exits. Those people along the seat aisles started moving toward other empty aisles. The crowd density on both sides of the theater sharply increased as more people started moving toward the exit. After 110 s, most people moved from the audience hall to the external facilities, and the remaining crowd inside the theater moved from the seat aisles to the passages on both sides of the audience hall. A slight crowding was observed at the evacuation exit, and the number of safe evacuees gradually increased. Some people also fell at the exit.

After 190 s, the majority of the evacuees reached the external facilities, but some areas remained crowded. Due to conformity factors, a few people were still inside the auditorium and failed to evacuate on time.

After 526 s, a small number of people were still stranded inside the auditorium and other areas. The evacuation simulation was then terminated. A total of 1,418 people managed to evacuate safety, and 51 people died due to the stampede. Among the fatalities, 21 were elderly, 12 were middle aged, 2 were young, and 16 were children. These evacuation



(a) Initial Scenario (b) Simulating evacuation for 11s

(c) Simulated evacuation for 21s (d) Simulated evacuation for 50s

(e) Simulated evacuation for 110s (f) Simulated evacuation for 190s

Figure 4. The corresponding evacuation overview

results were in line with the expectations, and a certain correlation was observed between the number of falls and the number of deaths. According to the model, those people who fell managed to regain their strength within five time steps, stand up, and continue to evacuate.

Using the monitoring data, the curve of the relationship between the number of safe evacuations and time, between the number of falls and time, and between the number of falls and time are plotted in Figures 5 and 6.

(1) According to Figure 10, in about 50 s, people started evacuating through the safe evacuation exit. The number of people evacuating through this exit increased every

Table 5. Evacuation Time and Personnel State Table

Evacuation Time	Number of safe evacuations	Number of falls				Number of death			
		Total	The elderly	The middle-aged	The young	Total	The elderly	The middle-aged	The children
11s	0	13	8	1	4	0	0	0	0
21s	0	32	14	10	8	0	0	0	0
50s	26	51	17	18	14	14	6	4	4
110s	205	62	25	17	20	30	15	4	10
190s	723	55	40	13	2	42	17	9	14
...	...	...	...	...	...	...	...	...	...
526s	1418	0	0	0	0	51	21	12	16

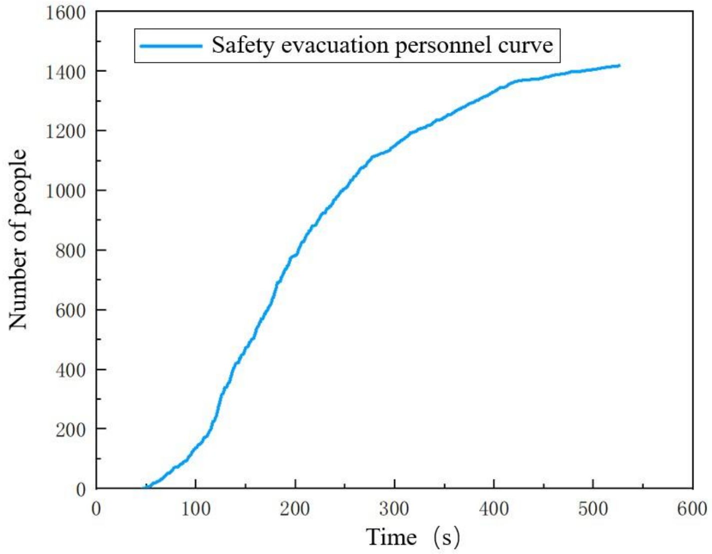


Figure 5. Typical situation safety evacuation personnel and time curve

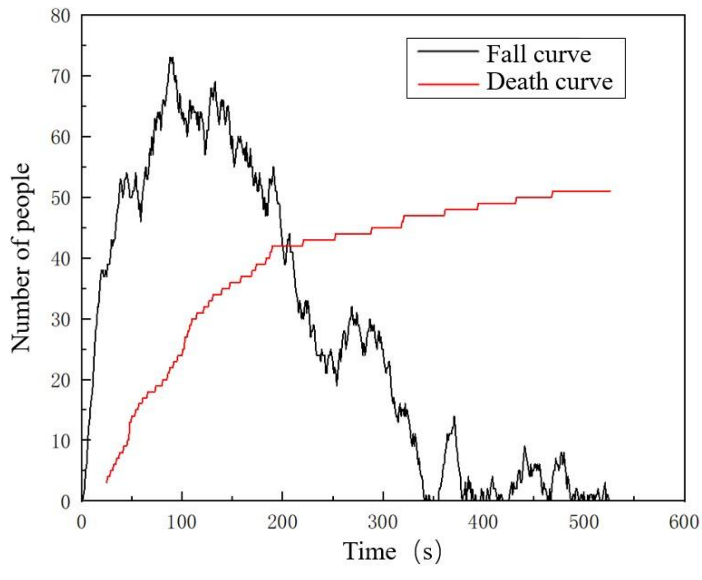


Figure 6. Curve chart of number of falls, number of deaths and time in typical situations

second, and in about 300 s, the rate of people who safely left the theater started to decrease until the simulation was terminated.

(2) According to Figure 11, the number of people who fell increased rapidly between 0 s and 100 s because at the beginning of the evacuation, the movement of people was

chaotic, the seat aisles were crowded, and the squeezing force around people was in a high-pressure state, thus increasing their risk of falling. In about 200 s, the number of people who fell decreased gradually as most people managed to evacuate the auditorium. However, some crowded areas and fallen people were still observed toward the exit. After 200 s, several peaks were observed in the fall curve because many people started crowding near the exit, thus increasing the crowd density and the risk of falling.

(3) The death curve shows that the number of deaths started increasing within 200 s. At this time, the density of people remains in the high-pressure stage, and the risk of death is high.

4. **Conclusion and Outlook.** Based on the analysis of personnel movement mechanism, squeeze pressure is used as a temporary condition to determine the risk of falls and stampedes. A stampede risk determination model based on SPH is then established to further improve the SPH evacuation model and make it more in line with the actual situation. By taking a large theater in a typical crowded place as the simulation object, simulation experiments are carried out according to the characteristics of the theater, and the fall risk and stampede risk in the evacuation process are analyzed. This simulation offers an intuitive understanding of the macro process of crowd movement and the transformation of crowded areas during an evacuation. The effectiveness of the stampede risk model and the applicability of the SPH evacuation model for large-scale dense crowd evacuation are verified through the simulation.

Future research should continue improving the proposed model and algorithm and combine them with a 3D scenario to enhance the evacuation visual effect. By considering the characteristics of people, walls, and obstacles, the properties of each particle can be set in the evacuation scene to enrich the individual state of the evacuees. The impact of certain factors, such as behavioral, psychological, and emotional changes in different scenarios, on the evacuation of people in dense places should also be considered in other evacuation scenarios.

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