Risk Analysis of Pedestrians Evacuations Based on Crowd Energy

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Abstract. The crowd energy is newly proposed to evaluate the crowd safety level and has a positive correlation with the risk of crowd injuries. But how to manage overcrowded pedestrians and to avoid crowd injuries from the energy-release view are still difficult problems. In this article, the crowd energy model of evaluating the risk of pedestrian evacuation is introduced based on social forces function firstly. The crowd energy model takes pedestrian kinetic energy, pedestrian potential energy and crowd internal energy into consideration, and can be used as a quantitative risk analysis on both the global level and the local level. Then, diversion railings are also discussed as a management tool to eliminate the risk in large mass-gathering and pedestrian’s evacuations scenarios. In order to test our method, an agent-based simulation tool is developed to simulate the pedestrians. So the crowd energy can be calculated automatically. Finally, the influences of management measures on crowd safety is investigated in our simulated experiments and designed scenarios. The results show that additional railings can eliminate the risk of the crowd injury risk while it can avoid excessive crowds gathered in a small area and in a very short time. But those additional diversion railings will generate more global crowd energy as a result of increases in the evacuation time. Therefore, in some emergency cases, railings are not good choices.

1. Introduction

Large transport stations and large activity venues in particular are the places of frequent and large mass gathering, which sometimes generates extreme crowding in relatively small spaces and short time [1~5]. And to eliminate the risk of large crowd disaster in such places is a big challenge of crowd management for humans. In past few years, huge engineering efforts have been made to solve the problem. As the first step of crowd management, we proposed a crowd energy model to evaluate crowd safety in crowded areas and to reveal the nature of crowd disaster based on the energy transfer view in accident-causing theory[7]. The crowd energy model took pedestrian kinetic energy, pedestrian potential energy, and pedestrian internal energy into consideration. The results of the empirical study in the crowded subway station showed that the crowd energy had a positive correlation with the count of pedestrian and intensity of the collision among pedestrians. This research caused a series of follow-up studied. Li et al. applied a classic continuum macroscopic model to simulate the crowded pedestrian flow in typical scenarios such as at bottlenecks or with an obstacle and the Lax–Wendroff finite difference scheme and artificial viscosity filtering method were used to discretize the model to identify high-density risk areas [8]. Seriani et al. created a framework to help
designers and planners identify and benchmark the degree of interaction in the platform train interface (PTI) and the degree of interaction between passengers was defined as high, medium or low based on the density and perception of risk, and each of the variables is assigned one degree of interaction [9]. However, some problems are still unsolved before it comes into practical applications. Some key parameters in our crowd energy model should be invalidated. Besides, the impact of engineering or operational measures on the safety of overcrowded pedestrians is still difficult to estimate.

Crowd management is also an interdisciplinary area, and it requires understanding of engineering and technological aspects, along with an understanding of crowd behaviour and crowd flow management, i.e. psychological and sociological aspects [10]. Therefore, the motivation of this paper is to estimate the effect of engineering or operational measures on crowd safety risk in our designed both simulated crowd scenarios from the energy view. The remaining parts are organized as follows: the section 2 introduces the methods to reach our goal, including crowd energy formulations, the crowd simulation model, and the management measures. In the section 3, a set of pedestrian evacuation experiments in a single-exit classroom are designed. And some interesting results are reported. Conclusions are given in the section 4.

2. Methods

In our crowd energy model, pedestrian kinetic energy, pedestrian potential energy and crowd internal energy are used to describe the local and global crowd energy. The crowd energy model are extended in this paper based on previous study [7].

2.1. Crowd Energy

**Pedestrian kinetic energy.** Pedestrian kinetic energy is to describe the single pedestrian’s energy in state of motion. The higher the velocity of pedestrian is, the more the kinetic becomes. According to Newtonian mechanics, pedestrian kinetic energy can be defined as in Equation 1. Where \( \vec{v}_j(\vec{r}, t) \) is the velocity of pedestrian \( j \) at the position \( \vec{r} \) and time \( t \).

\[
e_k^j = m_j \vec{v}_j^2(\vec{r}, t)
\]  

(1)

**Pedestrian potential energy.** Pedestrian potential energy is to describe the single pedestrian’s energy considering its position, just like the gravitational potential energy. Pedestrian potential energy can be defined as:

\[
e_p^j = m_j g \hat{h}_j(\vec{r})
\]  

(2)

Where, \( \hat{h}_j \) indicates the theoretical height of pedestrian \( j \), just like the \( h \) in gravitational potential energy. The theoretical height of pedestrian \( j \) is defined in Equation 3 and shown schematically in figure 1. H is fixed height the of platform. \( \alpha \) is the tilt angle of stair or slop. A, B and C are different pedestrians. \( r_j \) stands for the distance of pedestrian \( j \) from point O. And R is only parameter need to be validated.

\[
\hat{h}_j = \begin{cases} 
  h_c \sin \alpha, & j = C, r_j < 0 \\
  \frac{H \sin \alpha \cdot \frac{R - r_j}{R}}{r_j}, & j = A, 0 \leq r_j < R \\
  0, & j = B, r_j \geq R 
\end{cases}
\]  

(3)
Figure 1. Different place has different risk of falling down, as indicated in Equation (3).

Pedestrian internal energy. Pedestrian internal energy is used to describe the potential energy generated from body compression among the pedestrians. Inspired by crowd pressure, pedestrian internal energy can be defined as:

Firstly, each pedestrian $i$ is characterized by its current position $\vec{x}_i$ and speed $\vec{v}_i$, which can be collected by Video based systems. Base on the auto-collected data, body compression force can be calculated:

$$C_j(t) = \sum_i \| \vec{f}_{ij}(t) \|$$  \hspace{1cm} (4)

$$\| \vec{f}_{ij}(t) \| = A_j e^{(\frac{v_i + v_j - d_{ij}}{B_j})}$$  \hspace{1cm} (5)

Where, $C_j(t)$ is the compression forces of pedestrian $j$. $\vec{f}_{ij}(t)$ is the contact forces of pedestrian $i$ from pedestrian $j$. $r_i$ is the radius of private space of pedestrian $i$. And $\vec{n}_{ij}$ is the direction of $\vec{f}_{ij}(t)$. In Equation 5, $A_j$ is the pedestrian impact strength, and $B_j$ indicates the impact scope of pedestrian $j$. D. Helbing (2002) recommended that the values of $A_j$ and $B_j$ should be 2000 and 0.08m[5]. But, I. Taras’s suggestion (2005) is that $A_j$ should be some value ranging from 300 to 900, and $B_j$ should be 0.5m[11]. According to an amount of empirical studies, we accept 200 for $A_i$ and 0.3 for $B_i$. The impact of different values is shown in Figure 2.

Secondly, crowd internal energy is established based on body compression force, and the calculation formula and its derivation process are shown as equation 6:

Figure 2. Body compression force varies for distance between two pedestrians.
(a) is D. Helbing’s recommendation for values of $A_i$ and $B_i$, which are 2000 (b) and 0.08. (b) is the values in our proposed model, which is 200 and 0.3.
\[ e_j^C = \sum_i \left\| \int_0^{t_{ij}+d_{ij}} \vec{f}_y(t) \, dx_y \right\| \]
\[ = \sum_j \int_0^{t_{ij}+d_{ij}} \| \vec{f}_y(t) \| \, dx_y \]
\[ = \sum_i \int_0^{t_{ij}+d_{ij}} A_{ij} e^{x_i/B} \, dx_y \]
\[ = \sum_i A_{ij} B_j \left( e^{t_{ij}+d_{ij}/B_j} - 1 \right) \] (6)

That is \[ e_j^C = \sum_i A_{ij} B_j \left( e^{t_{ij}+d_{ij}/B_j} - 1 \right). \]

**Crowd energy.** The crowd energy is an integration of pedestrian kinetic energy, pedestrian potential energy and pedestrian internal energy. The general crowd energy can be defined as:

\[ e_j = e_j^p + e_j^p + e_j^C \] (7)

\[ CE = \sum_j e_j \] (8)

Bring Equations (1), (2), (6), (7) into Equation (8), the final **Global Crowd Energy** formula is as follows:

\[ CE^{\text{global}} = \sum_j \left( m_j \vec{v}_j^2 + m_j g \hat{h}_j + \sum_i A_{ij} B_j \left( e^{t_{ij}+d_{ij}/B_j} - 1 \right) \right) \] (9)

Besides, in order to investigate the local risk of crowd disaster, **Local Crowd Energy** are modelled as in Equation (10).

\[ e(\vec{r}, \vec{t}) = \sum_i (e_i \ast f(d_{ij})) \] (10)

Where \[ f(d_{ij}) = \left( 1/R \right) \ast (R - d_{ij}), \] \[ d_{ij} \] is distance of location \( r \) and pedestrian \( i \). \( R \) is a measurement parameter, and we adopted \( R = 0.7 \) m just as M. Moussaid did in 2011[12].

2.2. Crowd simulation

Based on the model of social force and multi-agent technology, a simulation tool named “PEDSYMS” is developed to simulate the crowd behaviour, while an efficient neighbourhood search algorithm is proposed in this paper.

**Efficient neighbourhood search algorithm.** Social force model is a continuous space model, for pedestrian \( i \) searches the neighbour pedestrian \( j \), he must traverse the whole pedestrians set \( N \), so the algorithm complexity is \( \Theta(N^2) \). In order to solve this problem, a meshing space model is introduced and the simulation space is divided into the meshes of the same size. Each mesh adds the identity information of pedestrian \( j \) once he enters this area, so the pedestrian \( i \) can quickly find \( j \) by consulting the dictionary of pedestrian set, this algorithm complexity is \( \Theta(N) \). The vision sight of pedestrian is also considered in the model so that the real searching area is the yellow area in Figure 3.

![Efficient neighbourhood search algorithm.](image-url)
Pedestrian moving algorithm. The pedestrian moving algorithm is showed as follows:
Step1: Divide simulation space into the m*n meshes of the same size.
Step2: according to the current position coordinates, assign the identity of pedestrian i into the corresponding mesh.
Step3: search the neighbour pedestrians and obstacles; calculate the attractive and repulsive force from pedestrians and obstacles nearby, then calculate the resultant force and acceleration.
Step4: using collision detection and crossing detection algorithm, then update the speed and position of pedestrian.

2.3. The Role of Crowd Management
Crowd management involves a diversity of situations that require competencies in observing, sense-making, anticipating and acting. In the overview of the crowd management studies, Wijermans et al. points out that actual operational support is provided only scarcely [13]. Many works still need to be done. Many measures are taken to guarantee the safety of crowded pedestrians in different occasions. However, in this article, a single common operational measure is focused, so-called the diversion railing.
Diversion railings are the common measure to be used to mitigate the injury risk of overcrowd pedestrians. Figure 4 shows application of diversion railings in the practical cases. In addition, the Figure 5 presents a solution of a flexible diversion railing widely used in subway stations in megacities of China.

![Figure 4. The actual case of diversion railings’ application](image)

![Figure 5. A type of a flexible diversion railing widely used in subway stations in China](image)

3. Scenarios Set and Case Study

3.1. Simulation Scenarios Set
In order to estimate the impact of diversion railings on crowd energy distribution in different conditions, a set of pedestrian evacuation scenarios are implemented. The pedestrian evacuation room with a single-exit is built in the simulation tool. And the size of the room is 10m*10m.
Table 1. The parameters in different group of pedestrian evacuation experiments.

| Number | set of diversion railings | Crowd condition (High=100p, Low=50p) | Passage width(m) | Individual expected speed(m/s) |
|--------|----------------------------|-------------------------------------|-----------------|------------------------------|
| 1      | No railing                 | High                                | -               | 1 m/s                        |
| 2      | No railing                 | High                                | -               | 1.5 m/s                      |
| 3      | No railing                 | High                                | -               | 2 m/s                        |
| 4      | No railing                 | Low                                 | -               | 1 m/s                        |
| 5      | No railing                 | Low                                 | -               | 1.5 m/s                      |
| 6      | No railing                 | Low                                 | -               | 2 m/s                        |
| 7      | Railings with 2 passages  | High                                | 1               | 1 m/s                        |
| 8      | Railings with 2 passages  | High                                | 1               | 1.5 m/s                      |
| 9      | Railings with 2 passages  | High                                | 1               | 2 m/s                        |
| 10     | Railings with 2 passages  | High                                | 1.5             | 1 m/s                        |
| 11     | Railings with 2 passages  | High                                | 1.5             | 1.5 m/s                      |
| 12     | Railings with 2 passages  | High                                | 2               | 1 m/s                        |
| 13     | Railings with 2 passages  | High                                | 2               | 1.5 m/s                      |
| 14     | Railings with 2 passages  | High                                | 2               | 2 m/s                        |
| 15     | Railings with 2 passages  | High                                | 2.5             | 1 m/s                        |
| 16     | Railings with 2 passages  | High                                | 2.5             | 1.5 m/s                      |
| 17     | Railings with 2 passages  | High                                | 2.5             | 2 m/s                        |
| 18     | Railings with 2 passages  | High                                | 2.5             | 2.5 m/s                      |
| 19     | Railings with 3 passages  | High                                | 1.5             | 1 m/s                        |
| 20     | Railings with 3 passages  | High                                | 1.5             | 1.5 m/s                      |
| 21     | Railings with 3 passages  | High                                | 1.5             | 2 m/s                        |

3.2. Results Analysis

(1) **Global crowd energy.** As defined in section 2, the global crowd energy reflects the general injury risk of the pedestrians in the pedestrian evacuation scenarios, as is shown in Figures 6-8. The Figure 6 shows that the global crowd energy will increase with the growth of the pedestrian’s individual expected velocity under the same dense. The 100 pedestrians with velocity of 2m/s can reaches the highest instantaneous global crowd energy to 15000J at about 20s, the 100 pedestrians with velocity of 1.5m/s reaches to 11000J at most at about 30s, and the 100 pedestrians with velocity of 1m/s reaches to 8000J at most at about 65s. The 50 pedestrians with velocity of 2m/s, 1.5m/s and 1m/s can reach 5600J, 4200J, and 3100J at most all at about 0s because of the serious conflicts at the beginning of evacuation.

![Figure 6. Global crowd energy with different crowd density and expected evacuation velocity.](image)

And the Figure 7 represents that the global crowd energy will go down if the passage between two adjacent railings becomes wider because of the decline in body conflicts. The 100 pedestrians with
velocity of 1.5m/s in the scenario of 2 railing passages with width of 1m can reaches the highest instantaneous global crowd energy to 18000J. The 100 pedestrians with velocity of 1.5m/s in the scenario of 2 railing passages with width of 2.5m can reaches the highest instantaneous global crowd energy to 12800J at about 15s.

Besides, the Figure 8 shows more railing will result in an increase in the evacuation time. It can also be seen that the additional diversion railings will generate more global crowd energy as a result of increases in the evacuation time. So in some emergency cases, additional diversion railings are not good choices from the global energy view.

![Figure 7](image7.png)

**Figure 7.** Global crowd energy under railing passages in different widths, but with the same initial crowd density and expected evacuation velocity.

![Figure 8](image8.png)

**Fig. 8.** Global crowd energy under different numbers of railings but with the same initial crowd density and individual expected velocity.

(2) **Local crowd energy.** Local crowd energy indicates the risk of crowd injuries at each position, as is shown in Figures 9-11. Figure 9 shows the dynamic distribution of local crowd energy under no railings, 100 persons and an individual expected velocity of 1.5m/s. Figure 10 indicates the local crowd energy under 2 railings, 100 persons and an individual expected velocity of 1.5m/s. Figure 11 represents the local crowd energy under 3 railings, 100 persons and an individual expected velocity of 1.5m/s. It can be seen from those results that: although additional railings can result in an increase in global crowd energy, it can make the distribution of the local crowd energy become more balanced. That is to say, additional railings can eliminate the risk of the crowd energy while it can avoid excessive crowds gathered in a small area and in a very short time.

![Table 2](image2.png)

| Color | Threshold       |
|-------|-----------------|
|       | ≥300J           |
|       | ≥600J           |
|       | ≥900 J          |
|       | ≥1200 J         |
|       | ≥1500 J         |

Table 2. Thresholds of crowd energy map
Figure 9. The dynamic distribution of local crowd energy under no railings, 100 persons and 1.5m/s.

Figure 10. The dynamic distribution of local crowd energy under 2 railings, 100 persons and 1.5m/s.

Figure 11. The dynamic distribution of local crowd energy under 3 railings, 100 persons and 1.5m/s.
4. Conclusions
The global and local crowd energy is formulated based on pedestrian kinetic energy, pedestrian potential energy and crowd internal energy. Many sets of the pedestrian evacuation experiments in different scenarios are conducted to examine our crowd energy model and the influence of management measures on it. And some main conclusions can be drawn:
(1) Increasing the width of the diversion railings passages appropriately will help reduce the generation of global crowd energy compared with the narrow channel.
(2) Additional railings can eliminate the risk of the crowd injuries while it can avoid excessive crowds gathered in a small area and in a very short time.
(3) Additional diversion railings will generate more global crowd energy as a result of increases in the evacuation time. Therefore, in some emergency cases, railings are not good choices.

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