# Required width of exit to avoid the faster-is-slower effect in highly competitive evacuation*

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A group of competitive people escaping through an exit could lead to the formation of a deadlock, which significantly increases the evacuation time. Such a phenomenon is called the faster-is-slower effect (FIS) and it has been experimentally verified in different systems of particles flowing through an opening. In this paper, the numerical simulation based on discrete element method (DEM) is adopted to study a group of highly competitive people through an exit of varying widths. The FIS effect is observed for a narrow exit whilst it is not observed for the exit wide enough to accommodate two people through it side-by-side. Experimental validation of such a phenomenon with humans is difficult due to ethical issues. The mouse is a kind of self-driven and soft-body creature and it exhibits selfish behaviour under stressed conditions. Particles flowing through an opening in different systems, such as pedestrian flow, animal flow, silo flow, etc. have similar characteristics. Therefore, experimental study is conducted by driving mice to escape through an exit of different widths at varying levels of stimulus. The escape time through a narrow exit (i.e., 2 cm) increases obviously with the increase of stimulus level but it is quite opposite to a wider exit (i.e., 4 cm). The FIS effect is avoided for an exit wide enough to accommodate two mice passing through it side-by-side. The study illustrates that FIF effect could be effectively prevented for an exit when its width is twice the size of particles.

**Keywords:** faster-is-slower effect, DEM, exit width, highly competitive evacuation

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## 1. Introduction

The highly competitive evacuees through an exit could lead to the deadlock due to the formation of arches, which may trigger deadly consequence. For example, on 20 September 2008, people were packed at a nightclub in Longgang district, Shenzhen, China. When a fire broke out by midnight, all people dashed for a narrow exit and led to a total blockage of the exit, resulting in 43 people dying and 88 people injured. Therefore, an effective means to prevent the flow rate through an exit from dramatically decreasing, particularly under highly competitive condition, could prevent potential disaster from happening.

Helbing *et al.*[1] proposed a social force model based on Newton's second law to quantitatively describe the crowd behavior in highly stressed conditions. The desired velocity represents the degree of competitiveness. In a certain regime, the greater desired velocity leads to the slower flow rate through the exit. This is the so-called "faster-is-slower" (FIS) effect. The authors[2,3] further proposed an evolutionary optimization algorithm to determine optimal parameter specifications for the social force model. A centrifugal social force model[4,5] was proposed by taking into account the distance between pedestrians as well as their relative velocities. Hoogendoorn and Daamen[6] discussed experimental findings of microscopic pedestrian behavior in the case of bottlenecks. Seyfried *et al.*[7] experimentally studied pedestrian flow through bottlenecks under laboratory conditions and found a linear growth of the flow with the width of the bottlenecks. Liddle *et al.*[8] investigated the spatial and temporal variation of the observables at bottlenecks. Sticco *et al.*[9] investigated the relationship between the door separation and the evacuation performance and found that there exists a separation distance range that does not improve the evacuation time. Carlini *et al.*[10] proposed an efficient scheme to approximate the solution of the PDE equation of pedestrian flow under different types of congestion effects and investigated the macroscopic effects of congestion phenomena. Nicolas *et al.*[11] studied the dynamics of pedestrian flows through a narrow doorway by means of controlled experiments and investigated the influence of the behaviours of pedestrians on global flow and microscopic dynamics. Frank and Dorso[12] studied the statistical behavior of a mixture of individuals and couples in a (panic) escaping process. Kabalan *et al.*[13] proposed a two-dimensional (2D) discrete crowd movement model to study the nature of pedestrian collision. Dong *et al.*[14,15] studied

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the self-organized phenomena of pedestrian counter flow.

Garcimartín *et al.*[16] conducted tests on a group of students passing through a door and analyzed the probability distribution of the time lapses between consecutive people. A power-law tail is observed and the exponent of the power law is smaller for a competitive egress, meaning that longer time lapses are more likely to appear for competitive egress than non-competitive egress. Non-human entities were adopted to study the evacuation behavior of competitive crowd. Pastor *et al.*[17] and Garcimartín *et al.*[18] experimentally studied different systems of discrete particles flowing through an opening, including humans evacuating from an exit, a herd of sheep passing through a door, and grains flowing through a 2D hopper. The authors concluded that FIS effect is a universal phenomenon for active particles passing through an exit. Lin *et al.*[19] conducted a series of experiments by using mice driven by a varying number of joss sticks. The escape times significantly increase with the increased levels of stimulus. The formation of FIS effect may be deadly in the evacuation process as the flow rate is dramatically reduced or even worst reduced to zero (i.e., the deadlock) by competitive evacuees. Zuriguel *et al.*[20] tried to improve the flow rate by placing an obstacle in front of a gate at different positions in the flow of sheep.

Discrete element method (DEM)[21–24] is a numerical method of computing the motion and effects of a large number of particles. The forces acting on each particle are calculated and force balance is integrated explicitly and acceleration velocity, velocity and the coordinate at each time step are deduced accordingly by applying the second Newton's law. It provides the local information about particle position and velocity, inter-particle contact forces, needed to investigate the relationship between microscopic and macroscopic behavior. Lin *et al.*[22,25] proposed a discrete element method to study the crowd through an exit at different desired velocities and found that clogging occurs more easily and the exit may be totally blocked (i.e., deadlock situation) when the desired velocity is high enough.

The objective of this study is to explore a possible way to prevent the FIS effect from occurring for highly competitive evacuees. The rest of this paper is organized as follows. In Section 2, a numerical simulation based on DEM is adopted to study the validity of FIS for competitive people escaping from an exit of different widths. In Section 3, a series of experiments is conducted in a bi-dimensional container and mice are driven to escape through an exit of different widths under high competition. The conclusions are drawn in Section 4.

## 2. DEM simulation of competitive people

Lin *et al.*[22,25] proposed a discrete element method (DEM) to study a highly competitive crowd through an exit. In the DEM, human bodies are modeled as a finite number of discrete, soft spherical particles interacting by means of contact or non-contact forces. The translational and rotational motions of human bodies are described by Newton's law of motion. The algorithms proposed by Hirshfeld *et al.*[21] and Adams and Nosonovsky[24] are adopted in this study.

A room with a size of 15 m×15 m and an exit of varying widths $D$ as shown in Fig. 1 is taken in the simulation. The human bodies are treated as soft spherical particles with diameters ranging from 0.52 m to 0.58 m. A total of 100 people are randomly distributed and they escape through the exit at different desired velocities in a range from 1 m/s to 3 m/s. The different desired velocities represent the different levels of competition as suggested by Helbing *et al.*[1] Generally speaking, the desired velocities of 1 m/s, 2 m/s, and 3 m/s represent a normal evacuation, competitive evacuation, and highly competitive evacuation respectively. Due to randomness during simulation, five repeated simulations are conducted for each scenario. The leaving time of 100 persons through a 1-m-wide exit at a desired velocity of 1 m/s is around 89 s, or a flow rate of 1.1 person/(s/m), which is basically consistent with the flow rate of 0.92 person/(s/m) as observed by Fruin.[26]

The simulation is conducted for a 0.8-m-wide exit and the snapshots of evacuation processes are shown in Fig. 2. At a desired velocity of 1 m/s, the leaving times of 100 persons through the exit range from 124 s to 146 s as shown in Fig. 3. At a desired velocity of 2 m/s, the leaving times are reduced to 106 s in some instances, whilst the deadlock at the exit is observed in 1 of the 5 runs, which leads to an infinite clearance time. At a desired velocity of 3 m/s, the flow is more intermittent and the deadlock is observed in 4 of the 5 runs as shown in Fig. 3. The clogging occurs easily at the exit if people try to get out at a high desired velocity irrespective of the distance/space available. The over-competiveness of a crowd leads to the deadlock at the exit. This phenomenon is consistent with the faster-is-slower effect as observed by Helbing *et al.*[1] For comparison, the clearance time is taken to be 200s if a deadlock occurs. A summary of the simulation results is presented in Fig. 4. This is the well-known faster-is-slower effect.

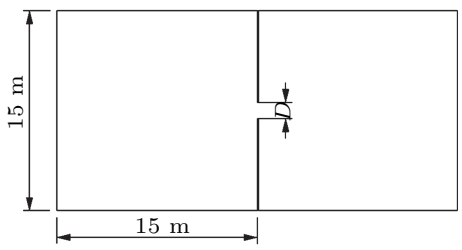



**Fig. 1.** Layout of room for numerical simulation.

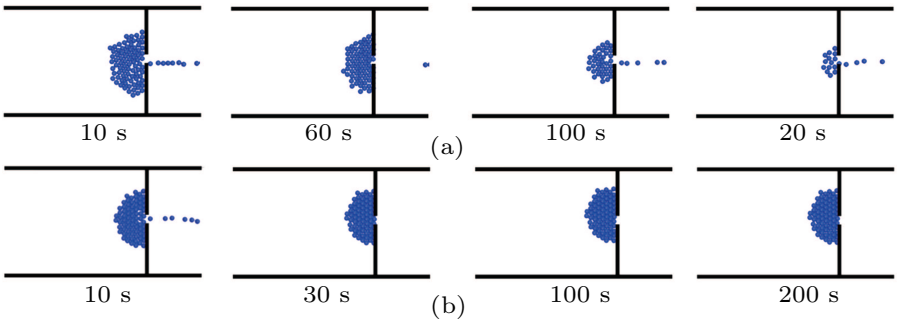



**Fig. 2.** (color online) Snapshots of the evacuation of people through a 0.8-m-wide exit at desired velocities of (a) 1 m/s and (b) 3 m/s, respectively.

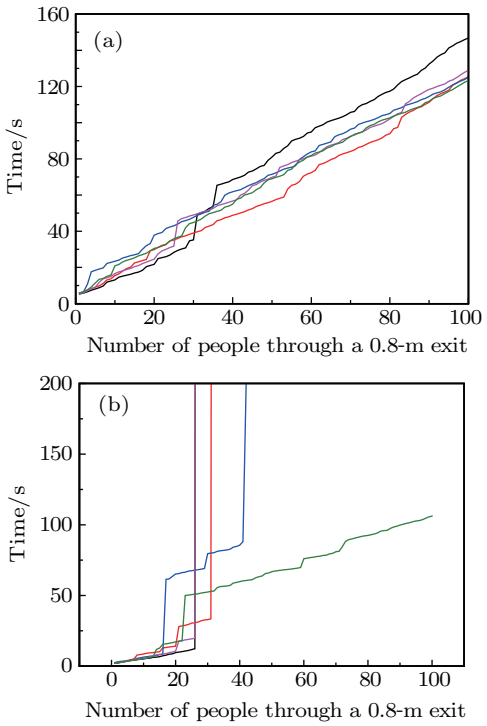



**Fig. 3.** (color online) Evacuation processes from a 0.8-m-wide exit at desired velocities of (a) 1 m/s and (b) 3 m/s, respectively.

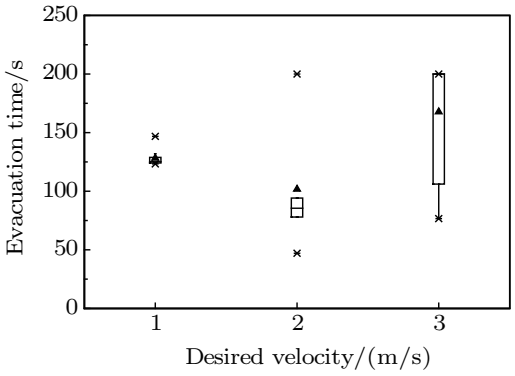



**Fig. 4.** Evacuation time from a 0.8-m-wide exit at different desired velocities where mean evacuation time is denoted as the triangle.

Then the simulations are conducted for a 1-m-wide exit and 1.2-m-wide exit respectively. The deadlock is observed in 1 of the 5 runs for the 1m wide exit at a desired velocity of 3 m/s as shown in Fig. 5(a). However, the deadlock is not observed in the evacuation through a 1.2-m wide exit as shown in Fig. 5(b). A summary of the evacuation times for the 1.2-m-wide exit at different desired velocities is presented in Fig. 6. A higher desired velocity leads to a quicker evacuation, which is totally contrary to what we observe for a 0.8-m-wide exit and 1-m-wide exit. A wider exit can prevent the clogging/deadlock from forming, thus avoiding the FIS effect.

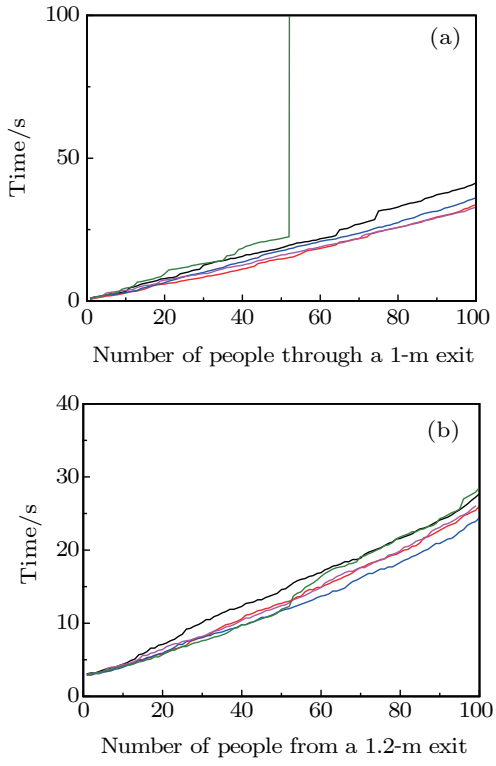



**Fig. 5.** (color online) Evacuation processes at a desired velocity of 3-m/s for the evacuations from (a) 1-m exit and 1.2-m exit, respectively.

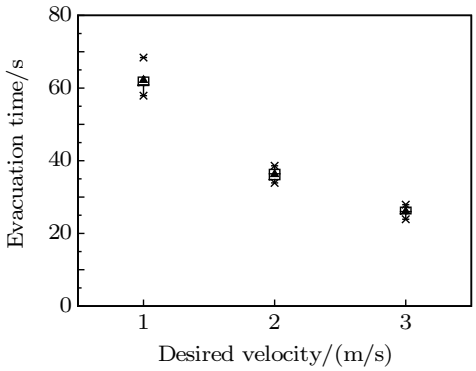



**Fig. 6.** Evacuation times from a 1.2-m-wide exit at different desired velocities.

## 3. Experimental validation with mice

To validate the finding of numerical simulation, experimental study is quite necessary. However, it is difficult to conduct experiments with people due to ethical issues. The mouse is a kind of self-driven and soft-bodied creature with selfish behaviour under stressed condition. Granular particles flowing through an opening in different systems, such as pedestrian, animal and silo flow, etc., have general characteristics. Therefore, we adopted the mice, in lieu of humans, to validate our numerical simulation.

The experiment set-up was introduced by Lin *et al.*[19] as shown in Fig. 7(a). The set-up is composed of three zones, i.e., zone A and zone B for test, and zone C for food/water/rest. The size of zone A is 0.7 m×1.5 m×2.5 cm, the size of zone B is 0.8 m×1.5 m×2.5 cm, and the size of zone C is 3 m×1.5 m×0.3 m. Zone A and zone B are separated by a bar. Zone B and zone C are connected by an exit of different widths as shown in Fig. 7. The test container is only slightly higher than the mice to prevent the mice from overlapping during evacuation and the movements of mice in zones A and B are strictly constrained at the bi-dimensional space. The experimental process is recorded by video cameras as shown in Fig. 7(b).

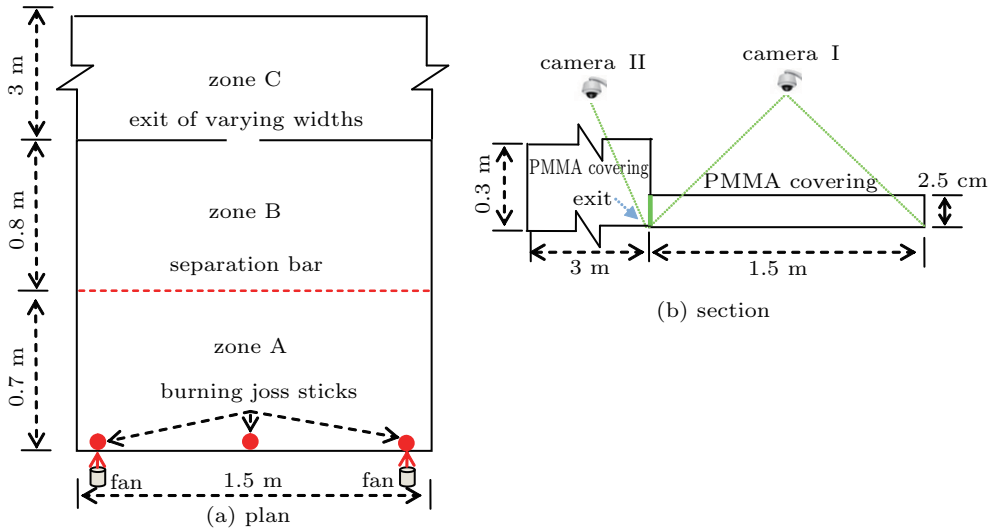



**Fig. 7.** (color online) (a) Plan and (b) section of the experiment set-up (not to scale).

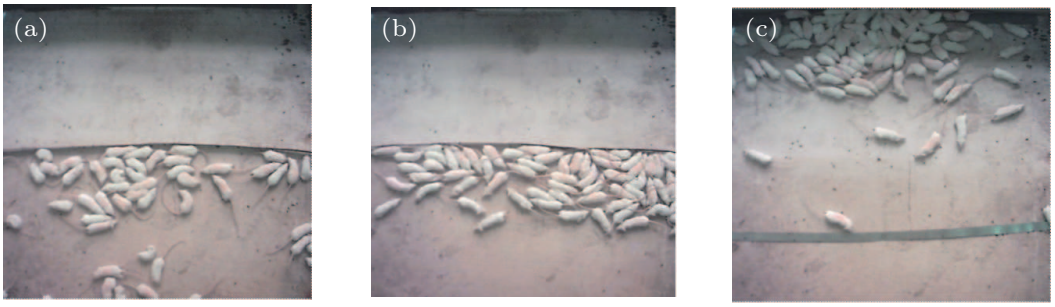



**Fig. 8.** (color online) Experimentally recorded movement patterns of mice in (a) zone A, at (b) 5 s and (c) 10 s after the insertion of the joss sticks.

The mice used in the experiment are described as follows: 95 female mice, at the ages of 3–6 weeks, their body parameters are the widths of 2.8 cm–3.2 cm, heights of 2.3 cm–2.4 cm, lengths of 9.5 cm–10 cm, and weights of 25 g–35 g. Initially, the mice are unfamiliar with the environment and they escape randomly in all directions when the burning joss sticks are placed into zone A. After being trained for a few weeks, they remember the location of exit. The well-trained mice can escape toward the exit as soon as the burning joss sticks are inserted into zone A as shown in Fig. 8. To produce different levels of stimulus, a varying number of joss sticks as introduced by Lin *et al.*[19] are used to drive the mice to escape. The number of joss sticks changes to 12, 24, 48, and 96 respectively, which present I, II, III, and IV levels of stimulus respectively. Considering the randomness of evacuation process, a number of repeated tests are conducted for each level of stimulus.

Firstly, a 2-cm-wide exit is adopted to study the escape process. The 2-cm-wide exit allows only a single mouse to pass through it at once. With increasing the level of stimulus, the mice show that they are more desiring to escape. A summary of the mean evacuation times per mouse at various levels

of stimulus is presented in Fig. 9. The average evacuation time per mouse through the exit increases significantly with the increase of stimulus, which is the faster-is-slower effect. More detailed information is presented in Ref. [19].

Secondly, the experiment with a 4-cm-wide exit is conducted by following a similar procedure. The 4-cm-wide exit allows two mice to pass through it side-by-side as observed in the experiment. The five repeated tests are conducted for each scenario and the evacuation processes are presented in Figs. 10(a)–10(d). A summary of the mean evacuation times per mouse at various levels of stimulus is presented in Fig. 11. The average evacuation time per mouse through the exit decreases with increasing the level of stimulus, which is totally contrary to what we have observed in the test with using the 2-cm-wide exit. Clearly, a wider exit can effectively reduce the probability of clogging/deadlock, thus preventing the FIS effect.

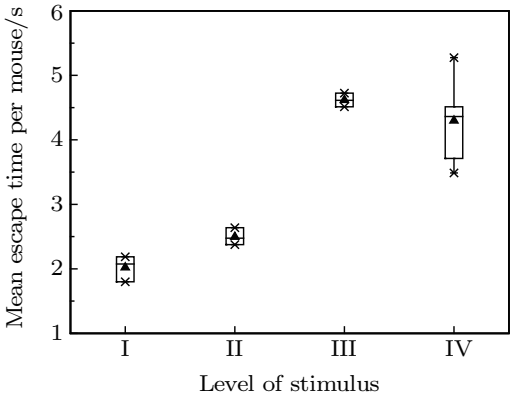



**Fig. 9.** Mean escape time per mouse from a 2-cm-wide exit at different levels of stimulus.

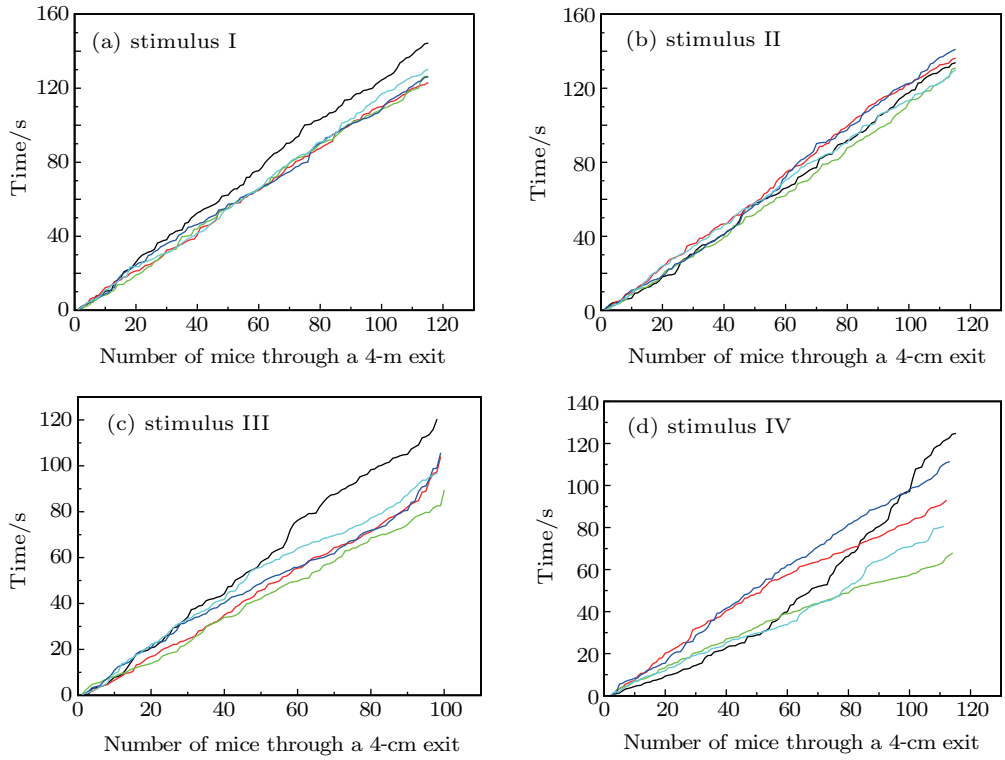



**Fig. 10.** (color online) Evacuation processes from a 4-cm-wide exit at different levels of stimulus.

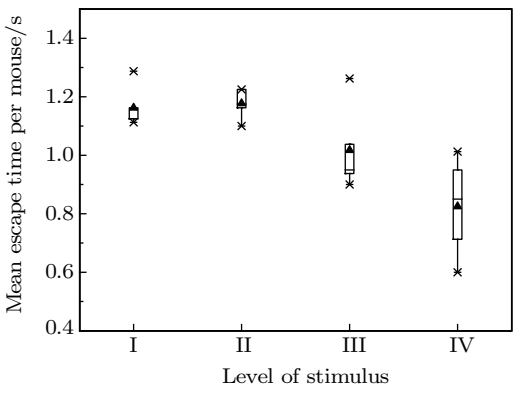



**Fig. 11.** Mean escape times per mouse from a 4-cm-wide exit at different levels of stimulus.

## 4. Conclusions

The faster-is-slower effect as proposed by Helbing[1] is lethal for a crowd passing through a bottleneck or an exit in an emergency. A number of disasters have been caused by a stampede of a crowd in past decades due to the competition among people, which leads to a dramatic reduction in the flow rate.

To explore the possible means to avoid the FIS in the evacuation of highly competitive people, numerical simulation based on the discrete element method (DEM) is adopted to study competitive people through an exit. The FIS is validated for narrow exits (i.e., 0.8 m and 1 m in width) whilst it is not

observed for wider exit (i.e., 1.2 m in width). The 1.2-m-wide exit can accommodate two people (each with a maximal body size of 0.58 m) passing through it simultaneously.

It is difficult to experimentally validate the finding by using people due to ethic issue. Instead, we use the mice under high competition. The mouse is a kind of self-driven and soft-bodied creature with selfish behaviour under stressed condition. They have general characteristics of granular particles, such as silo flow, pedestrian flow, animal flow, etc. Experimental study is firstly conducted with mice through a narrow exit and FIS effect is observed. However, when the exit is wide enough to accommodate two mice passing through it simultaneously, the FIS effect is prevented.

Through both numerical simulation and experimental study, the FIS can be prevented for an exit when its width is around twice as large as particles passing through it. In building evacuation design, the exit should be wide enough to allow two persons to pass through it as a minimum to avoid forming the deadlock for competitive evacuees.

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