Numerical Study of Occupants' Evacuation from a Room for Requirements in Codes

HL MU
JH SUN
University of Science and Technology of China
State Key Laboratory of Fire Science
Hefei 2300326, CHINA
muhl@mail.ustc.edu.cn

FILIPPO NERI

University of Naples
Department of Computer Science
Naples, Italy
filippo.neri@unina.it

SM LO

City University of Hong Kong
Department of Architecture and Civil Engineering
Hong Kong
bcsmli@cityu.edu.hk

Abstract: - During fires or other emergencies, occupants of buildings or specific areas need to escape from the hazardous location as quickly as possible. Efficient and safe evacuation of these occupants is a core research topic in the public security field. With reference to the provisions in various codes, some specific requirements are not the same, such as the required number of occupants in a room with a single exit, the minimum width of the exit and the angle between two exits in a room. Combined with the detailed evacuation requirements, research of constructing an optimized building environment to facilitate the evacuation of occupants is of important realistic significance. The evacuation simulation model employed is based on a social force model in order to investigate the effect of each influence factors on clearance (evacuation) time. The research results have the potential to provide a theoretical foundation and the technical support for improving evacuation processes as well as the relevant evacuation standards implemented in various countries.

Key-Words: - Occupants' Evacuation, Simulation, Clearance Time, Requirements in Codes, Social Force Model

1 Introduction

It is known that absolute prevention of fire or other hazardous events in a building and restricting their spread may be impossible. Therefore the immediate evacuation of people from hazardous locations can effectively reduce the risk of disasters involving the loss of human life. Therefore, the provision of exits in a zone is a critical component of building design and safety engineering. Given that the spatial layout of a building is significantly affected by relevant prescriptive requirements, especially for the escape system, it is important to provide a reasonable and flexible architectural design on the basis of performance-based fire safety engineering criteria.

In recent years, computer modeling has been considered as a major research method for studying occupant evacuation or traffic. Researchers from different disciplines around the world have proposed various models, including the optimal-control-theory-based pedestrian motion model [1], social force model [2], cellular automaton (CA) model [3], and lattice gas (LG) model [4]. Generally, these models can be classified into discrete models where the space is divided into grids and continuous models where pedestrian can continually move to any available space in accordance with the treatment of space and time. Both of these models treat the evacuees as particles that occupy a given size of space.

When a considerable number of occupants are located in a single zone, the number of exits and their corresponding width can influence the clearance time of these occupants. To help building designers in design room exits, various building and fire regulations or codes have prescribed a minimum number and dimension of exits according to the number of occupants in a room. Such requirements are proposed on the basis of the carrying capacity of each building component. However, these requirements vary across each country.

This study examines the evacuation of occupants from rooms by numerical simulation based on social force model considering the required number of occupants in a room with a single exit, the minimum width of the exit and the angle between two exits in a room. Further extension to this study involves the exploration of agent based simulations and machine learning techniques to model the evacuation process [5-7].

2 Reviews of Requirements in Various Prescriptive Codes

2.1 Required number of people corresponding to single exit

The Code of Practice for Fire Safety in Buildings [8] by the Building Department of Hong Kong suggests that the number of exits in a room is determined by the number of occupants. However, such a requirement has not been fully explained in the code or in any practice notes issued by the Hong Kong Government. The same situation is observed in the fire safety codes of other countries.

Building codes generally suggest that a single enclosed space must have a minimum of two exits, unless such space has a low risk level and accommodates merely a limited number of occupants. Table 1 shows the requirements in the Code of Practice for Fire Safety in Buildings [8] by the Building Department of Hong Kong. This code does not specify the usage of the space, which indicates that the hazard level of different types of space usage is not considered in the code. This code merely stipulates that a room with more than 30 occupants must have two or more exits. A relatively conservative number of occupants (19) are examined in this study.

Similar requirements can be found in the building codes of some countries. For example, the Russian National Fire Safety Code [9] specifies that at least two exits must be provided for rooms with more than 50 occupants, for rooms that are located in basements, and for rooms of special usage (e.g., child care centers, homes for the elderly, and industrial buildings) with a specific number of occupants. The Code of Practice for Fire Precautions in Buildings by the Singapore Civil Defence Force [10] stipulates that the number of exits must comply with the provisions presented in Table 2. This code also stipulates that rooms with more than 50 occupants must have two exits. Moreover, referring to the International Building Code of the by International Code Council [11], when the occupancy maximum occupant load is 49, one exit or exit access doorway can be permitted for the spaces.

Table 1 Minimum number and width of exit doors and exit routes in a room as prescribed by the Code of Practice for Fire Safety in Buildings [8]

Occupant Capacity of room, fire compartment or storey (No. of persons)	**Minimum No. of exit doors or exit routes**	**Minimum total width**		**Minimum width of each**	
		Exit doors	**Exit routes**	**Exit door**	**Exit route**
4 - 30	1			750 mm	1050 mm
31 - 200	2	1750 mm	2100 mm	850 mm	1050 mm
201 - 300	2	2500 mm	2500 mm	1050 mm	1050 mm
301 - 500	2	3000 mm	3000 mm	1050 mm	1050 mm
501 - 750	3	4500 mm	4500 mm	1200 mm	1200 mm
751 - 1000	4	6000 mm	6000 mm	1200 mm	1200 mm
1001 - 1250	5	7500 mm	7500 mm	1350 mm	1350 mm
1251 - 1500	6	9000 mm	9000 mm	1350 mm	1350 mm
1501 - 1750	7	10500 mm	10500 mm	1500 mm	1500 mm
1751 - 2000	8	12000 mm	12000 mm	1500 mm	1500 mm
2001 - 2500	10	15000 mm	15000 mm	1500 mm	1500 mm
2501 - 3000	12	18000 mm	18000 mm	1500 mm	1500 mm
	>3000 persons - the number of exit doors, exit routes and their width to be determined by the Building Authority				

Notes:

(1) In the case of Places of Public Entertainment, the requirements in should be complied with.

(2) The width of an exit door should be the least clear width measured between the vertical members of the door frame.

(3) The width of a required staircase, staircase landing, passage or corridor comprising an exit route should be measured between the finished surfaces of the walls or of the inner sides of any balustrade and should not be decreased by the introduction of any projections other than handrails the projection of which should not exceed 90 mm.

(4) The Table shows the minimum requirement on the assumption that doors can be readily and freely opened by occupants in case of fire.

Table 2 Minimum number of exits as prescribed by the Code of Practice for Fire Precautions in Buildings by the Singapore Civil Defence Force [10]

Number of Occupancy (persons)	**Minimum number of Doors**
51 - 200	2
201 - 500	2
501 - 1000	3
exceeding 600	4

Table 3 Minimum number of exits as prescribed by the Ontario Fire Code [12]

Occupancy Loading (persons)	**Minimum number of Exits**	**Aggregate width of required means of egress**	**Remarks**
Not exceed 60	**1**	(a) 6.1 mm per person for ramps with a gradient of not more than 1 in 8, doorways, corridors and passageways, or (b) 9.2 mm per person for ramps with a gradient of more than 1 in 8 and stairs.	Floor areas in buildings not exceeding 2 storeys in building height; the floor area does not exceed 200 m^2; travel distance from any point on the floor area does not exceed 15 m
61 - 600	2		
601 - 1000	3		
More than 1000	4		

The Fire Protection and Prevention Act of 1997 by the Ontario Regulation [12] stipulates that the number of occupants in rooms with a single exit must not exceed 60. Table 3 summarizes the requirements for assembly usage. The Scottish Building Standards [13] prescribe that the minimum numbers of exits depend on the occupancy capacity of a room. Table 4 shows that the maximum occupancy loading of a single exit room is 60 occupants.

The examples show that the prescribed maximum number of occupants in a room with a single exit varies from 30 to 60. The prime concern of the layout design may be the flow pattern of the occupants and the clearance time from the space, which mainly depend on the number of occupants.

2.2 Required minimum width of single exit

The minimum exit width requirements of various codes have been inconsistent. For instance, the Code of Practice for Fire Safety in Buildings [8] by the Building Department of Hong Kong suggests that the exit of rooms or floors with more than three occupants must not be less than 750 mm in width. The Code of Practice for Fire Precautions in Buildings stipulates that the minimum clear width of an exit door opening shall be not less than 850 mm [10]. The International Building Code by the International Code Council [11] suggests that minimum width of each door opening shall be sufficient for the occupant load thereof and shall provide a clear width of 32 inches (813 mm). The Building Regulations Part B - Fire Safety [14] by the government of Ireland suggests that the width of escape routes and exits depends on the number of persons who need to use them and must not be less than the dimensions listed in Table 5. Moreover, Table 6 summarizes the minimum exit width requirements prescribed by various codes.

2.3 Required angle between two exits in a room

With respect to the requirements of a room with two exits, the way of placing the two exits is a major concern in relevant codes. However, the codes of several districts have varying prescriptions with regard to the placement of two exits in a single room. For example, the Code for Fire Protection Design of Buildings GB 50016-2014 by the Ministry of Public Security of China [15] prescribes that the distance between the nearest edges of two exit doors in a single room must be longer than 5 m. The Building Regulations Part B - Fire Safety [14] by the government of Ireland suggests that choosing from multiple escape routes is insignificant if such routes tend to be blocked or disabled simultaneously. Every escape route in a building level must be independent of any other escape route that can be directly accessed by the occupants. Alternative escape routes should satisfy the criteria that they are in directions 45° or more apart. Fig. 1 shows that two directions of escape are assumed if the escape routes are more than 45° away from each other. Additionally, in shaded areas where the angle is less than 45° at any point, only one direction of escape must be assumed and dead-end conditions will be applied.

Table 4 Minimum number of exits as prescribed by the Scottish Building Standards [13]

Occupancy capacity (persons)	Minimum number of room exits
Not more than 60	**1**
61 - 600	2
More than 600	3

Table 5 Width of escape routes and exits as prescribed by Building Regulations Part B - Fire Safety [14]

Maximum number of persons	Minimum width (mm) (1)(2)(3)
50	750 (4)
100	850
150	950
220	1050
More than 220	5 mm per person (5)

Notes:
(1) Refer to Para B1.0.10 (c) Methods of Measurement - Width.
(2) The minimum widths given in the table may need to be increased in accordance with the guidance in TGDM: Access for People with Disabilities.
(3) Widths less than 1050 mm should not be interpolated.
(4) May be reduced to 530 mm for gangways between fixed storage racking other than in public areas of buildings of purpose group 6 or 7.
(5) 5 mm/person does not apply to an opening serving less than 220 persons.

Table 6 Minimum width of exits as prescribed by various codes

Requirement in District	Minimum Width	Prescriptive Code
Hong Kong	750 mm	(BD, 2011) [8]
Ireland	750 mm	(TGB, 2006) [14]
IBC	813 mm	(IBC, 2012) [11]
Singapore	850 mm	(SCDF, 2013) [10]
China	900 mm	(MPS, 2014) [15]

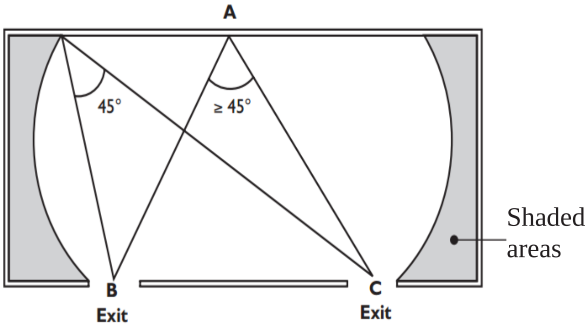

Fig. 1 Alternative escape routes as prescribed by the Building Regulations Part B - Fire Safety by the government of Ireland [14]

The Code of Practice for Fire Safety in Buildings by the BD of Hong Kong (2011) assumes two directions of escape if the angle between the two exits is greater than 30° [8]. For any room or story where two or more exit doors are required to be provided as shown in Table 1, a line that is drawn from any point on the floor of that room or level to one of the exit doors must form an angle of not less than 30° with a line that is drawn from the same point to the other exit door. Fig. 2 illustrates such a requirement of alternative escape routes.

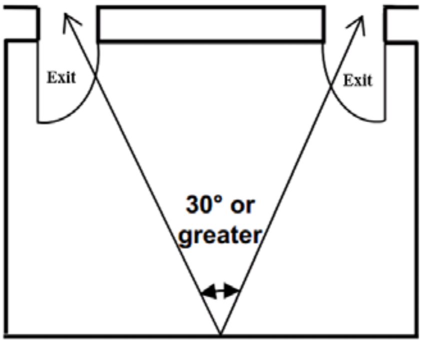

Fig. 2 Alternative escape routes as prescribed by the Code of Practice for Fire Safety in Buildings by the Building Department of Hong Kong [8]

3 Simulation Model

The social force algorithm is employed in this study to describe the essential movement rule of the evacuees. In the social force model, the interaction among people and that between people and the building environment can be described and adopted to affect the movement dynamics [2]. Each person occupies a given space in time, and the motion of one person is governed by Newton’s law of motion. For the sake of completeness, the main equations of the social force model are presented as follows:

$$m_i \frac{dv_i}{dt} = m_i \frac{v_i^0(t)e_i^0(t) - v_i(t)}{\tau_i} + \sum_{j(\neq i)} f_{ij} + \sum_W f_{iW} \quad (1)$$

In equation (1), a person i of mass m_i moves with a desired speed of v_i^0 in a direction e_i^0, while the actual velocity v_i in a characteristic time τ_i is adjusted in time as influenced by other people f_{ij} and walls f_{iW} [2].

$$\begin{aligned} f_{ij} = {} & \{A_i \exp[(r_{ij} - d_{ij})/B_i] + kg(r_{ij} - d_{ij})\}n_{ij} \\ & + \kappa g(r_{ij} - d_{ij})\Delta v_{ji}^t t_{ij} \end{aligned} \quad (2)$$

$$\begin{aligned} f_{iW} = {} & \{A_i \exp[(r_i - d_{iw})/B_i] + kg(r_i - d_{iw})\}n_{iw} \\ & - \kappa g(r_i - d_{iw})(v_i \cdot t_{iw})t_{iw} \end{aligned} \quad (3)$$

In equation (2) and (3), $r_{ij} = r_i + r_j$, $d_{ij} = \| r_i - r_j \|$ denote the sum of the radii and the distance between person i and j, respectively. Furthermore, the repulsive and attractive psychological forces follow the form that is assumed in these two equations. For example, the social force among people is described as $A_i \exp[(r_{ij} - d_{ij})/B_i]\vec{n}_{ij}$, in which A_i and B_i are constants. In accordance with the original social force model, physical interactions are determined by these parameters, τ_i =0.5 s, k =1.2×10^5 kg^{-2}, κ =2.4×10^5 kgm^{-1}s^{-1}, A_i =2×10^3 N and B_i =0.08 m [2].

The evacuees are represented by circle dots with different diameters because representing the human body as a point is unreasonable. Given that the mean horizontal projection area of an adult body is 0.113 m^2 [16], the diameters follow a uniform distribution from 0.35 m to 0.42 m (from 0.096 m^2 to 0.138 m^2) to add the essential factor of different body sizes. The partial person-to-person and person-to-wall overlaps are allowed.

The social force model does not focus on modeling a complicated escape system from an overall perspective. However, this model can describe the evacuation process according to the behavioral characteristics of the evacuees by representing their interactions. To be different with the original social force model, certain movement rules have been included, such as allowing the evacuees to move and choose the doors randomly. The other rules are described as follows:

(a) The evacuees move forward with a specific desired velocity in a rectilinear direction instead of having a fixed target point at the exit. The desired velocity refers to the speed at which an evacuee is willing and able to walk in uncongested conditions.

(b) When the evacuees arrive at the outer side of the exit zone or its extension line, which is defined beforehand, the nearest point at one of the doors would be chosen for approaching.

(c) The destination point with the shortest distance is updated at every time step (0.1 s for this simulation) in the model. The evacuees then reach and pass through the exit.

Besides, in each simulation, when all people have escaped at time *T*, the time *T* they leave from the space is recorded as the evacuation or clearance time.

4 Results and Discussion

4.1 Effect of number of people on evacuation with single exit

4.1.1 Examination of desired velocity

In the aforementioned expressions of pedestrians' movement, the parameter v_i^0 in the social force model represents the desired velocity for a person to move toward a specific object. To examine if the desired velocity v_i^0 of a person can affect evacuation time, the different value of must also be analyzed in the simulation.

The inputs for the analysis are presented as follows. The numbers of persons are selected as 19, 30, 50, and 60. The desired velocities vary from 0.8 m/s to 2.2 m/s. The room size is 10 m 10 m and the width of the exit is 0.75 m, which is consistent with Hong Kong's Code of Practice for Fire Safety in Buildings.

In the beginning of the simulation, all people are generated and randomly distributed in the room, as shown in Fig. 3 (a). After the people are placed in their respective locations, they will be activated to move toward the exit simultaneously. The original positions of the agents can also be manually assigned in the plan. The model also has a constant or random delay time for each agent before moving. For instance, if the maximum delay time is 1 minute, every agent stays at the initial position for no more than 1 minute and then starts to evacuate when the time following a stochastic distribution has already passed. In these simulations, the delay time is assumed as zero. Fig. 3 (b) shows a screenshot of the simulation of occupants' evacuation from a room with a single exit.

The data of the average desired velocity are collected from the evacuation simulation, which is conducted 50 times corresponding to each parameter. Table 7 shows the clearance time for a series of desired velocities. In accordance with the clearance time, the curves in Fig. 4 show the relationship between the clearance time and the different desired velocities of the evacuees. From this figure, it can be found that an increase in the desired velocity of a specific number of evacuees can significantly decrease the clearance time when the desired velocity ranges from 0.8 m to 1.2 m, slowly decrease the clearance time when the desired velocity ranges from 1.3 m to 1.7 m, and can slightly decrease the clearance time when the desired velocity ranges from 1.8 m to 2.2 m. This result reflects a phase change from a normal condition when people move at an ordinary speed to an emergency condition when people begin to move at a comparatively rapid velocity. In addition, in this present study of examining the relevant standards on the specific number of occupants in a room with a single exit, it is noticed that a faster desired velocity is not considered in view of the "faster is slower" phenomenon [2].

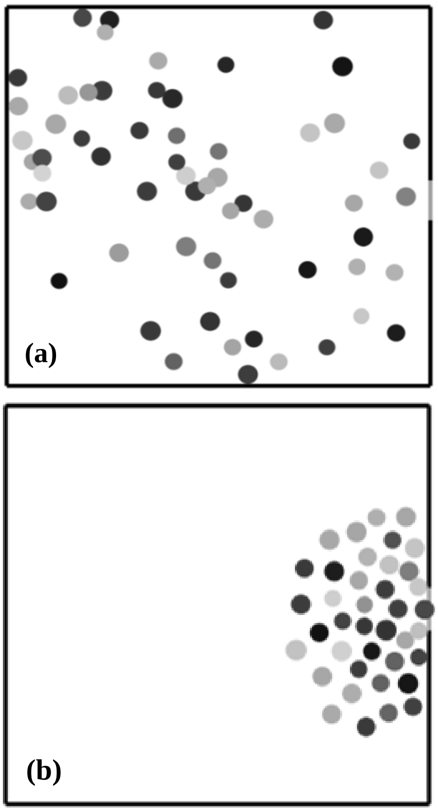

Fig. 3 Screenshot of the evacuation simulation from a room with a single exit: (a) Random distribution of people in the room, and (b) evacuation though a single exit

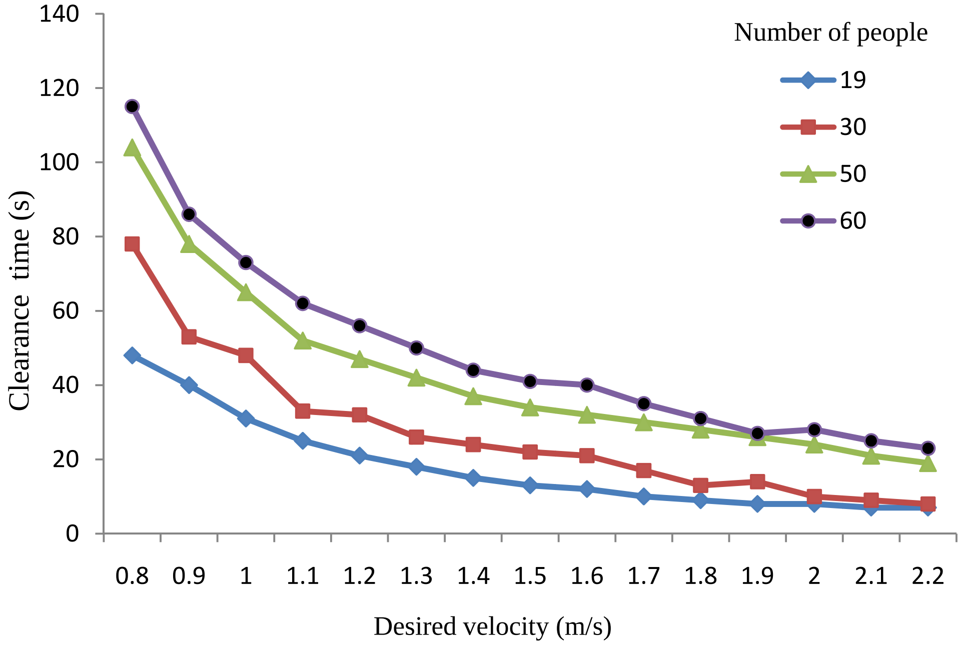

Fig. 4 Relationship between clearance time and desired velocities for different numbers of people

Table 7 Clearance time in the evacuation simulation for a series of desired velocities

Number of people	Desired velocity (m/s)	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2
19	**Clearance time (s)**	48	40	31	25	21	18	15	13	12	10	9	8	8	7	7
30		78	53	48	33	32	26	24	22	21	17	13	14	10	9	8
50		104	78	65	52	47	42	37	34	32	30	28	26	24	21	19
60		115	86	73	62	56	50	44	41	40	35	31	27	28	25	23

4.1.2 Mean evacuation time per person

Furthermore, the evacuation efficiency of the escape is measured based on the mean evacuation time per person. Corresponding to each specific number of people, Fig. 5 shows the mean evacuation time per person of three ranges of desired velocity. It can be discovered that when the desired velocity ranges between 1.3 m/s and 1.7 m/s, the mean evacuation time per person remains at approximately 0.7 s for each specific number of people. When compared with the curve of the desired velocity that ranges from 0.8 m/s to 1.2 m/s, the mean evacuation time for each person significantly decreases by approximately 50%.

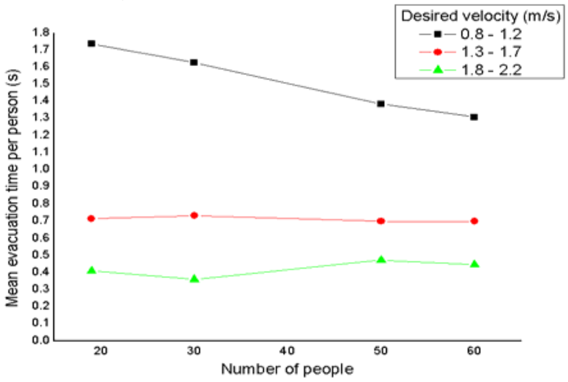

Fig. 5 Mean evacuation time per person corresponding to the specific number of people for three ranges of desired velocity

As mentioned above, emergencies are generally accompanied by a comparatively rapid velocity. When the desired velocity ranges from 1.8 m/s to 2.2 m/s, the mean evacuation time per person is significantly reduced as compared with the data from other curves. Especially, the shortest mean evacuation time per person can be achieved when a room only contains 30 people. Therefore, the evacuation from a single-exit room with 30 occupants is considered the most efficient. This result is consistent with the requirements prescribed in Hong Kong’s Code of Practice for Fire Safety in Buildings, which indicates that no more than 30 people can be placed in a room with a single exit. However, the requirements of codes from other districts with regard to the maximum number of people in a room with a single exit may have to be examined further.

4.2 Effect of Single Exit Width on Evacuation

Furthermore, several exit widths are examined in this study, namely, 650, 700, 750 … 1600, 1650, and 1700 mm. The sizes of rooms in the simulation model are 10 m × 10 m (Room 1), 10 m × 5 m (Room 2), and 13.33 m × 7.5 m (Room 3). The exit is placed in the middle of the long side of the rectangular room. Thirty agents are selected and randomly distributed in the room at the beginning of the simulation. To reflect an emergency situation better, the desired velocity of people follows a uniform distribution (from 1.8 m/s to 2.0 m/s). The relationships between single exit width and clearance time for each room are calculated and shown in Fig. 6.

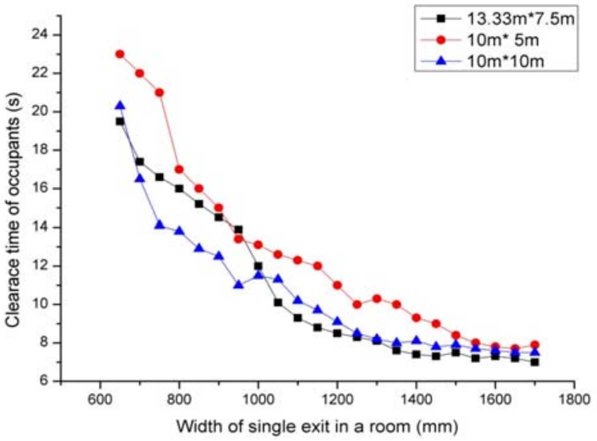

Fig. 6 Relationship between single exit width and clearance time for rooms with different sizes and 30 occupants

Fig. 6 shows a rapid decrease in clearance time as the exit widths increase from 650 mm to 750 mm for Room 1 (10 m × 10 m), from 750 mm to 800 mm for Room 2 (10 m × 5 m), and from 950 mm to 1050 mm for Room 3 (13.33 m × 7.5 m). The clearance time then reduces slowly and remains constant when the width exceeds 1500 mm. The result indicates that along with exit width, other factors such as travel time (from the initial position of the evacuee to the exit) and waiting time (waiting to pass through the exit) can significantly influence the time for the occupants to evacuate their rooms.

Moreover, it is observed from the evacuation simulation that an intense congestion of agents around the exit can extend the clearance time. The occupants in Room 2 require more time to escape than those in Room 1 even though Room 2 is half the size of Room 1. The occupants of a smaller room need lesser time to approach the exit, which easily causes congestion around the exit area.

By comparing Rooms 1 and 3, which have the same acreage, the occupants in a rectangular room need more time to evacuate when the exit width of is less than 1050 mm. The reason is still that the exit areas of rectangular rooms are congested more easily than those of square rooms because of the limit capacity of exit with. In this case, the occupants may not be able to evacuate quickly despite reaching the exit at an earlier time. However, as shown in Fig. 6, the clearance time for the occupants in a rectangular room is slightly shorter than that for the occupants in a square room when the exit width is more than 1050 mm.

In general, the minimum exit width as prescribed in Hong Kong and Ireland (750 mm) can cause a relatively efficient evacuation for Room 1 (10 m × 10 m). However, there is a significant improvement for occupants' evacuation when the exit width is 800 mm in Room 2 (10 m × 5 m). However, given that the factors that influence evacuation time are complex, it is difficult to determine the minimum width of exits of a specific building space without a systematic numerical computation.

4.3 Examination on Angle between Two Exits in a Room

4.3.1 Examination of different exit choice of pedestrians

In consideration of there are two exits in a room, the exit choices of occupants are then examined. Five patterns of exit choice are considered, namely, the ratios of 50–50, 60–40, 70–30, 80–20, and 90–10. In the simulation model, the room has a floor area of 10 m × 10 m and 100 randomly distributed occupants. Two 1-m wide exits are placed at the same side of the room. The desired velocity of the occupants ranges from 1.8 m/s to 2.0 m/s and is subject to a uniform distribution. The angle between the two exits increases from 11.42° to 48.46° as the spacing between the two exits is increased. In the evacuation simulation, the agents remain still in the room and then move toward the exits simultaneously in accordance with each ratio of exit choice. The time for these people to evacuate from the room is recorded as the clearance time. The curves in Fig. 7 demonstrate the relationship between different angles and clearance time for each ratio of exit choice.

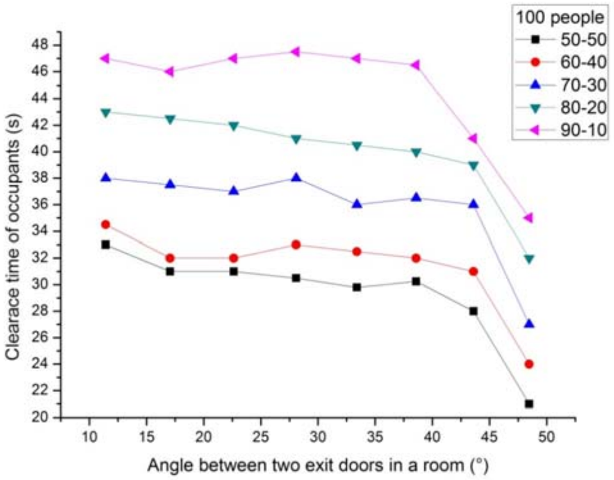

Fig. 7 Relationship between different angles and clearance time for each ratio of exit choice

Each curve in Fig. 7 shows that an increase in the angle between two exits slightly reduces the clearance time and especially may rapidly reduce the clearance time when the angle almost reaches the maximum value corresponding to the room. For the exit choice ratio of 90–10, the clearance time is significantly reduced when the angle between the two exits exceeds 38.58°.

Moreover, when the exit choice ratio increases from 50–50 to 90–10, the clearance time of the occupants is extended for each increase in angle. The result indicates that the imbalanced use of exits has a negative effect on evacuation efficiency. In the following simulation, the exit choice ratio of 50–50 is employed to determine the target destinations of the occupants.

4.3.2 Influence of number of people and different room sizes

The influence of number of people on clearance time for different angles is then investigated after examining the exit choices. Fig. 8 shows the relationship between different angles and clearance time for the evacuation of 60 people and 100 people. The two curves demonstrate similar tendencies, except that the clearance time decreases at 33.4° for the evacuation involving 60 people, but decreases at 38.58° for the evacuation involving 100 people.

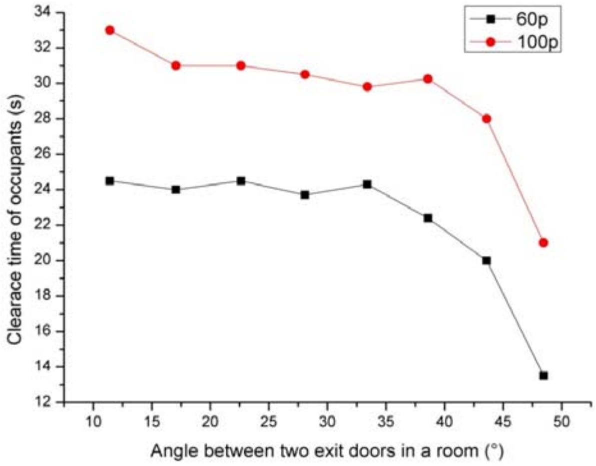

Fig. 8 Relationship between different angles and clearance time for the evacuation with 60 people and 100 people

Therefore, the requirements in the Code of Practice for Fire Safety in Buildings by the Building Department of Hong Kong [8] may not be suitable for this scenario because such code stipulates that the angle between two directions of escape should be greater than 30°. However, the Building Regulations Part B - Fire Safety [14] by the government of Ireland suggests that the angle between two exits exceeds 45°, which can achieve a relatively efficient evacuation. Given that the evacuation of 100 people requires more time, performing a systematic numerical computation is crucial for a specific scenario and condition.

4 Concluding Remarks

The behaviour of room occupants during fires or other emergencies is a complex phenomena that can be studied with specially designed simulative methodologies such as that here described. This study examines the evacuation process by numerical simulation based on a social force model fully discussed in the paper. We have then shown a detailed and reproducible methodology that can be used to study the same phenomena under different type of constraints. Such a methodology may be particularly useful when used to assess the validity of laws and regulations that control the construction of buildings.

For instance, with reference to the provisions in various codes, some requirements are given explicitly, such as the required number of occupants in a room with a single exit, the minimum width of the exit and the angle between two exits in a room. And the evacuation simulation method here proposed can investigate the effect of each factor on the clearance (evacuation) time. Therefore, we believe that the reported results have the potential for providing a theoretical foundation and a methodological support for improving the factors affecting the evacuation process in a new building as well as the relevant evacuation standards implemented in various countries.

Acknowledgments

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