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A Study of Microscopic Dynamics of Pedestrian Evacuation in High Rise Building

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Abstract: Numerous evacuation models are developed since decade ago in order to offer an appropriate design to estimate the required time for evacuating from a variety of places with various conditions. Thus, high rise traffic buildings found in governmental or huge company are essential to accurately evaluate the require time for evacuation process in order to ensure the safety of pedestrians. Thus, in order to fulfil this requirement, various models in pedestrian dynamics system, either as a whole or only in psychological interaction among pedestrians is developed during the past decade until now. However, most of the existing models only discussed their application in ground level with limited number of pedestrian and without the presence staircase. Therefore, this paper presents a model that simulates a large-scale pedestrian evacuation process in a high rise building, and provides some recommendation for improving the evacuation flow and increase public safety. From the simulation results, it shows that our proposed design for the study area improved in both the evacuation times and flow.
Keywords: Tunisian stock exchange; Firm size; Beta; January effect.

1. Introduction

Pedestrian modeling's are among the most interesting fields found in transportation science. Deepening the knowledge in pedestrian flows is the key to offer a helpful thought in designing or improving public places with aim to reduce the loss of life and properties during disasters. However, pedestrian evacuation process is a complex issue due to particular human behaviors such as awareness to danger and panic cause by incidents. Therefore, it is hard to capture a normal pedestrian flow during evacuation for study purposes. Furthermore, a real-world experiment on evacuation process is nearly impossible. This fact motivated researchers to carry out their studies in this field using different modeling methods in order to developed simulation systems for studying pedestrian behavior during evacuation process.

Recently, there are various literature reports found on modeling crowd movements that deal with unexpected disasters. Many researchers from variety of disciplines have been successfully used to study the problem on this area and obtained fruitful results. Such results are the key that help to reduce the loss of life and properties during disasters. A few of these are the particle flow model [1-3], Social Force Model (SFM) [4-8] and Cellular automata (CA) [9-15]. Particle flow and social force are using physical models to simulate movements. CA models divide the environments into cells to model the movements of pedestrians between cells. Every model mentioned has its own advantages and weaknesses. For example, social force model produces more smoother movements compare to CA models due to its continuous nature.

Kosinski and Grabowski [16] introduced an intelligent agents system using Langevin equation with additional SFM term to simulate the panic level during evacuation that taken the speed at exit area as decisive term. However, the model shows a less realistic pedestrian movement compared to SFM. Parisi and Dorso [17] presented their work on studies of different degree of panic with different exit width. However, this model is only used for simulating limited number of crowd approximately 200 pedestrians and mainly focuses on exit width effect to panic level during evacuation process.

Currently, Frank and Dorso [18] reported their investigation finding on human behavior impact during evacuation process. This work shows the clogging and pedestrian cluster forming during the escape in a room with single exit with a fix location of obstacle. In fact, literature [18] also reported that the distance of obstacle from exit play an important role for crowd panic level as well as the evacuation flow. In panic condition, pedestrians tend to push each other to rush out from the room in the shortest time, by placing an obstacle may avoid congestion that close to the exit by taking up the pressure, and so, the effects from congestion are taken to an early phase [19, 20]. It can be observed that majority of the existing models placing the assumption that pedestrians are uniformly distributed in a room with small number of pedestrians and only a limited number of models that discussed on the distribution of pedestrians around the exit area or in a room without obstacles.

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In this paper, we used the SFM to simulate a large-scale pedestrian evacuation process in a high rise building with the presence of staircase. The SFM [5] are well known for its ability to display a realistic move for simulating evacuation process by taking considers the discrete personality of the pedestrian flow that allows the setting of individual physical variables e.g. mass, shoulder width, desired velocity and target destination. The related problem in this work is what is the optimal width for staircase in order to improve the evacuation times and flows. A Part of this problem has been reported in [21] on the optimal exit doors location and width in a room without obstacles that produced a minimal evacuation time, while [22, 23] reported on condition of staircase for evacuation with presence of mobility problem. This paper aims to study the effects of staircase width during the evacuation process with the intention to provide a safer environment and reduces the amount of fatalities and injuries. Hence, the outlines of the are described as follows: Section 2 described briefly on the SFM model postulated by Helbing, *et al.* [4] for determine pedestrian movement; the discussion on the results of simulations are provided in Section 3; Finally, we conclude our finding in Section 4.

2. Social Force Model

The Social Force Model verifies that pedestrian movement is resolve by their desire to arrive at destination location along with the effects of surroundings on them [4, 5]. The recent social force model is represents with social force and granular force while the prior model is only based on a force known as the desire force.

Suppose that a pedestrian is moving at a desired speed of *VD* and in a given direction of. However, in actual situation, pedestrians are always walks a bit out of actual path toward the direction to destination place $\vec{e}_d$ and they never walks exactly at the desire speed v_d. Pedestrian actual speed $v(t)$ is mainly dependents to environmental factors (e.g. obstacles, exit size). Hence, pedestrian have to increase or decrease their speeds with the intention of reaching the destination location at desired speed v_d. This acceleration or deceleration are corresponds to the desire force as it come from their will and own motivation. Therefore, pedestrian *i* can be defined in mathematical term as

$$f_d^{(i)}(t) = \frac{v_d^{(i)}(t)\vec{e}_d^{(i)}(t) - v_i(t)}{\tau} \tag{6}$$

Where all magnitudes are assumed as a function of time, and τ represent the relaxation time required to achieve pedestrian desired speed. τ value is determined through experiment.

The pedestrians reactions to environmental stimulus are denoted by social forces. Although there exist stimulus such as family member or friends that generates attraction, but it is not included in the proposed model, but the basic rule still applied on pedestrians for tendency to preserve their private space between other pedestrians [5]. When people get nearer to each other, eventually its repulsive force would turn stronger. In other words, the repulsive force strength is mainly depending on the inter-pedestrian distance *d* that can be modeled as an exponentially decaying function defined as follow,

$$f_s^{(ij)} = A_i n_{ij} e^{(r_{ij} - d_{ij})/B_i} \tag{7}$$

with *i* and *j* corresponds to any two pedestrians, d_{ij} is the distance between the center of mass for both pedestrians, $n_{ij} = \left(n_{ij}^{(1)}, n_{ij}^{(2)}\right)$ represents the unit vector in direction of $\vec{ji}$ and $r_{ij} = r_i + r_j$ is the sum of pedestrian radius for pedestrian *i* and *j*. The parameters A_i and B_i are fixed based on experimental findings [4].

In addition, Eq. (7) is applicable to environmental factor (e.g. obstacles). Hence, pedestrian tends to maintain a distance to separate from each other so they could avoid from getting injured. Hence, r_{ij} and d_{ij} in Eq. (7) must be substitute by r_i and d_i each corresponds to pedestrian radius and their distance to the wall respectively.

The final term in SFM which expressed the sliding friction that appear between pedestrian that get in contact to each other and to the walls is known as the granular forces. Thus, by assuming pedestrians relative velocities as a linear function, its mathematical can now be expression as

$$f_g^{(ij)} = \kappa g(r_{ij} - d_{ij}) \Delta v_{ij} \cdot t_{ij} \tag{8}$$

where $\Delta v_{ij} = v_j - v_i$ is the speed difference between pedestrian *i* and *j*. If pedestrian *i* get in contact to a wall, then v_j is adjust to be zero in Eq. (8). $t_{ij} = \left(-n_{ij}^{(2)}, n_{ij}^{(1)}\right)$ is the unit tangential vector, orthogonal to n_{ij}. κ is an experimental parameter. $g(.)$ function is set to zero when the argument value is negative (that is, $r_{ij} < d_{ij}$) and equals the argument value for any other case.

Extreme crowded surroundings may cause body compression effects [4]. However, as reported in Parisi and Dorso [17], this body compression forces play no significant role during the evacuation process. Hence, it is not taking consider in the proposed model. A more details explanation on $f_s(t)$ and $f_g(t)$ can be found throughout the literature [4, 5, 17, 18]. Table 1 summarizes the most usual values for the experimental parameters appearing in Eqs. (6)–(8).

Consequently, both the desire and granular forces control the pedestrian dynamical characteristic by changing their speed. The equation for pedestrian *i* movement can be expressed by

$$\frac{dv_i}{dt}(t) = f_d^{(i)}(t) + \frac{1}{m_i}\left[\sum_{i \neq j} f_s^{(ij)}(t) + \sum_{i \neq j} f_g^{(ij)}(t)\right] \tag{9}$$

where m_i is the mass of pedestrian i. The subscript j represents all other pedestrians but excluding i and the environmental factors.

The magnitude for desire speed, v_d in Eq. (6) is correspond to the pedestrian motion in free-flow speed. Additionally, the pointing direction $\vec{e}_d$ set the anxiety for the pedestrian to reach that particular exit. An impatient pedestrian tends to rush their way out by changing their desired direction for nearest exit route available [21].

Table-1. Related variables apply for evacuation simulation

Parameter	Symbol	Value	Units
Force at $d_{ij} = r_{ij}$	A_i	2000	N
Characteristic Length	B_i	0.08	m
Pedestrian Mass	m_i	70	kg
Contact Distance	r_{ij}	0.5 ± 0.2	m
Acceleration Time	τ	0.5	s
Friction Coefficient	κ	2.4×10^5	$Kg\ m^{-1}s^{-1}$

3. Simulation Results

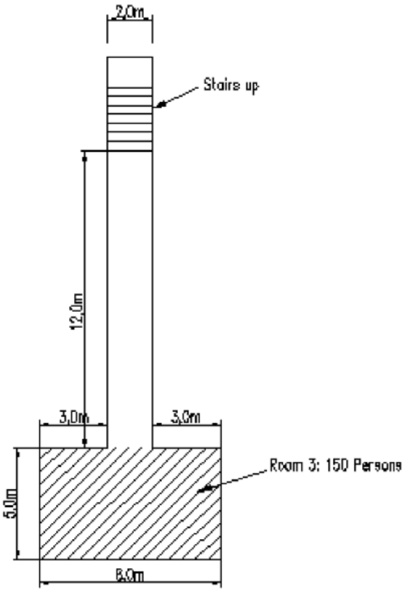
One of the interesting problems in the field of pedestrian evacuation study is finding the proper staircase width in order to reduce the evacuation time. Numerous existing models do not considered the crowd distribution in a room and they assumed that the pedestrians are uniformly distributed in a large room without staircase. However, the existence of staircase is an important parameter in gaining an accurate estimation for exit time. In this section, we will first perform a simulation in order to test and validate our model in a room without obstacle with the fundamental diagram from IMO Test 11 [24]. Next, the SFM model is applied to simulate the evacuation process in a high rise building (see Section 3.2). The optimal width of the staircase that produce a minimal evacuation time are determined, and all the mentioned simulations work is discussed in the following section.

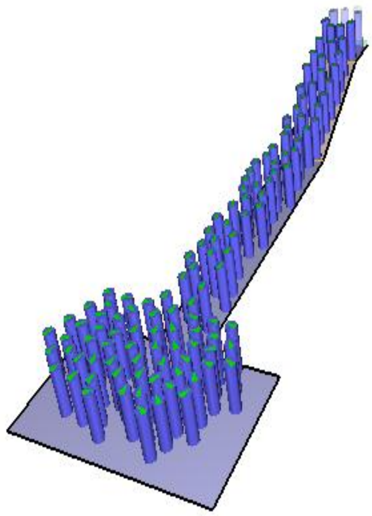
3.1. Setting up IMO Test 11 for Staircase

To test and validate the proposed model, we use the International Maritime Organization Test 11. Consider a room of 8 x 5 m^2 with 150 pedestrians is uniformly distributed in the initial stage. The room is connected to a stair via corridor of 2 x 12 m^2. The number of pedestrians and the room size are chosen to be equivalent to those reported in IMO Test 11 [24]. The pedestrian body width is set to be 0.5 m with walking speeds evenly distributed from 0.97 to 1.42 m/s. The expected result is the formation of congestion leading into the hallway and at the base of the stairs. The setup of the simulation is shown in Fig. 1(a).

Fig. 1(b) displayed the snapshot of occupant moving toward the exit. From the simulation result, it shows that the evacuation time is 73 seconds, while the standard IMO Test 11 is 74 seconds. Congestion is observed at the room exit, but no significant congestion at the base of the stairs. The reason is that although the walking speed on the stairs is reduced by 23%, there is still sufficient flow capacity on the stairs to avoid congestion at the base. After performed the evaluation, we find that these results are consistent with IMO test 11 result [24].

Fig. 1. (a) Illustration of 150 pedestrians randomly distributed in a 8 x 5 m^2 room with staircase. (b) Snapshot of evacuation simulation when all pedestrians moving toward the exit.





(a) (b)

3.2. Simulation in High Rise Building

Consider a high rise building of 5 floors, with area of 10 x 10 m^2 and 30 pedestrians for each floor. The building high is 12 m, with stairway of 1.0 m width (see Fig. 2). With the given geometry and placement of the building stair and exit, now the 150 pedestrians are all uniformly distributed in the area and the evacuation time can be calculated (see Fig. 3).

For our evaluation purposes, we consider the case where the stair width varies from 1.0 to 2.0 meter. A series of simulation on this system are performed by changing the width of stairway in order to determine the optimal evacuation time. In order to observe the effect of staircase, these pedestrians are positioned in the same places for the whole series of simulation. The effect of stairway width is analyzed. Fig. 4 shows the results for evacuation times for the building with the increase of stairway width for SFM models. We observed that the further increase beyond critical width (1.8 m wide stairway) would not contribute to much reduce in evacuation time (refer to Fig. 5). The reason is that the clogging effect at exit area inflict constrain on pedestrians movement.

In addition, we observed that the smaller the stairway, the faster the clogging effect occurs, which leads to slowing down in evacuation time, and this event similar to those reported in [10, 13]. Fig. 3 shows the evacuation times for the building area for different stairway width. The increase in width stairway helps in decreases the evacuation times as it coordinates pedestrian movement and reduces interactions. The mentioned effect is similar to those in [10, 13].

Fig.2. Simulation plan for building with stairway.

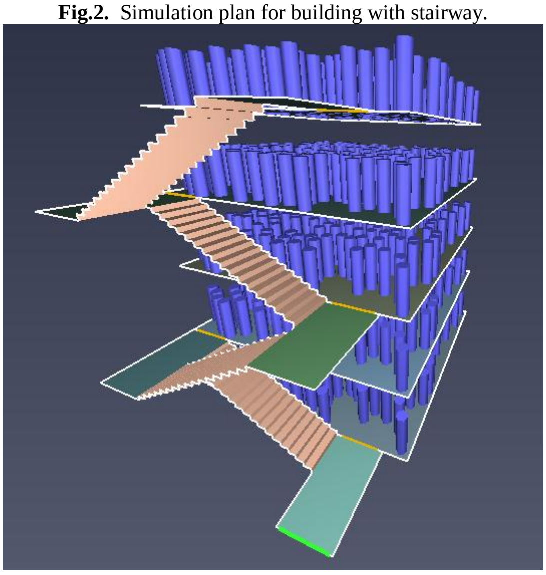


Fig.3. Snapshot of simulation running after 24.5 s.

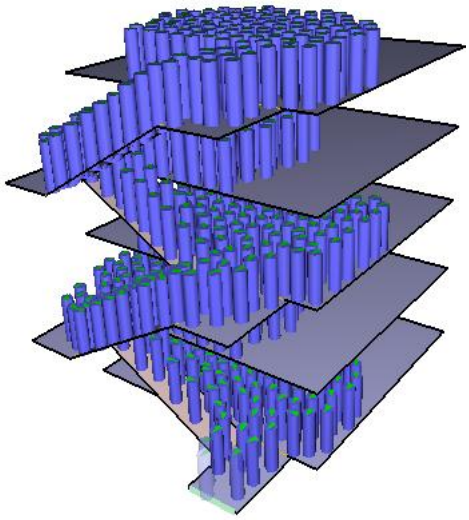


Fig.4. Evacuation time with the increases in stairway width of the building.

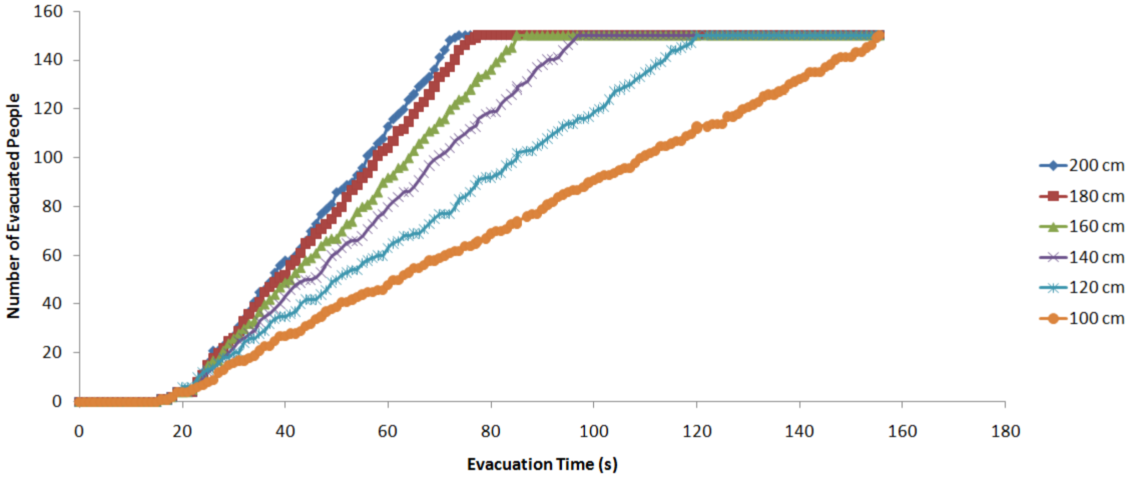
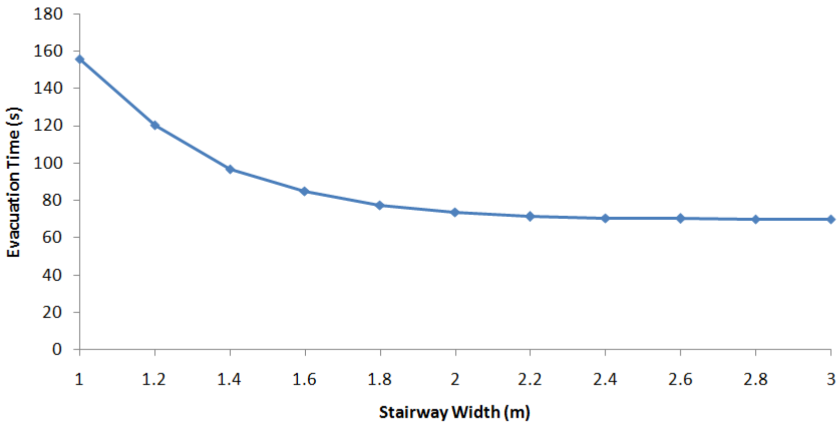


Fig.5. Evacuation time versus exit position of hypermarket area for; (a) one 5 m exit; (b) one 10 m exit. A point with abscissa *n* corresponds to a exit location occupying distance *n*, *n*+1, *n*+2, …, *n*+4 m for case (a), and *n*, *n*+1, *n*+2, …, *n*+9 m for case (b). (c) Result of comparing the evacuation time for two 5 m exit and 10 m exit cases.



The common setting in a high rise building is to have 1.4 m stairway that capable to allow 2 persons go through simultaneously. Results for different width are plotted in Fig. 5. We notice that no significant improvement in evacuation time for width greater than 1.8 m. We observed that the worse situation (highest evacuation time) arise when the width is only 1 m. This is because the 1 m width can only allow one pedestrian go through at a time, while width greater than 1.8 m allows 2 pedestrians through simultaneously, hence reduce clogging at stairway entrance.

The optimal and practical width suggested for stairway is 1.6 m. The difference in evacuation time between 1 m width and 1.6 m width is about 70.6 s that equivalent to approximately 76 pedestrians evacuate from the building. Thus, wider stairway is much better narrow stairway.

5. Conclusion

The overall results shown by the proposed model has inferred it capabilities that suits in performing a complex and crowded event simulation. We applied social force model to model the pedestrian movement and to study placement of exit effects in the evacuation process. The simulation from the proposed model shows that: (i) Evacuation time are effectively reduces using stairway with 1.6 m and above. (ii) Further increase beyond critical width (1.6 m) for the building stairway would not contribute a significant reduces in evacuation times.

Indeed, the model still consists some improvable features to be considered. For instance, parameters such as age, physical ability, psychological behaviors and group formation are to be considered to improve the system realism and this is an attractive adjustment to the social force model itself. For future work, we intend to integrate some of the mentioned features into our model and apply it to other geometries such as hall, stadium, movie theaters and etc.

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