DEM Evaluation of Evacuation Behavior: A Case Study of "The Mosque of ASMU"

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ABSTRACT

Safety is a primary consideration in any building. There are many risk factors which can cause casualties such as earthquake and fire. An important consideration in an emergency situation is the evacuation of people. This is of great importance when a large number of people are in confined spaces such as mosques and subway stations. To evaluate the evacuation of a place, an effective way is simulation. In this paper, as a case study, we simulate the evacuation behavior of the mosque of Azarbaijan Shahid Madani University (ASMU) using Distinct Element Method (DEM) in which an analysis of the position of each person can be computed step by step by solving the equation of motion. Four cases with different number and width of exits are considered, and evacuation behavior including evacuation time, density on exits, and flow rate are estimated quantitatively. Evacuation time is calculated to be 591, 156, 138 and 114 sec for cases 1 to 4, respectively. Density on exit 1 is equal to 4.5 (person/m^2) for all four cases, and on exit 2 is calculated to be 4.23, 2.4, 2.4 and 1.47 (person/m^2), for cases 1 to 4, respectively. As results show exit widths and number of exits have great influences on evacuation behavior. It is recommended that before construction of public buildings, evacuation simulations to achieve optimum evacuation behavior to be done.

Keywords:
Evacuation behavior;
Evacuation simulation;
Emergency evacuation;
Distinct element method

1. Introduction

Safety is a primary consideration in any building. There are many risk factors which can cause casualties such as earthquake, flood, and terrorism. Structural collapses are the most important factors of casualties during a disaster. People caught in areas due to a disaster may encounter dangerous situations. One of the important considerations in an emergency situation is the issue of the evacuation of people. The prompt movement of people away from threat or natural disaster is known as evacuation. If a crowd fails to escape from a building in time, due to failure of obstacles, avoidance, congestions on exits or wrong exit selection, people may be injured or even killed. The crowd behavior (e.g. simultaneously rushing toward exits, and pushing) itself may result in injuries and death. This is of great importance when a large number of people are or gathered together in a confined space such as mosques, subway stations, and shopping malls. Important aspects of emergency evacuation can be addressed as evacuation time and density on exits. Emergency evacuation may occur in small scale as is the case of the evacuation of a building due to bombing or a terrorist attack or in a large-scale area as is the case of an evacuation because of earthquake, flood, and tsunami.

To evaluate a building evacuation, there are two ways: conducting evacuation drill and computer simulation of evacuation. Running real scale experiments might be expensive and time-consuming, based on the ability of examinees to mimic panic situation pressure, dangerous to participants, and practicable for limited scenarios and cases. That is why a suitable computer simulation can be considered as a logical mean to illustrate the dynamics of a supposed crowd in an evacuation situation.

One of the ways to help engineers to reduce the number of injuries and deaths occurring in buildings and public spaces evacuation scenarios is modeling the behavior of individuals and movement of the crowd. By conducting evacuation simulation models, evacuation behavior of a place could be obtained. Evacuation behavior includes the estimation of people movement to exits, people jam on exits and around obstacles and bottle-necks, people density on exits, and evacuation time.

Crowd simulation includes the modeling of crowd movement, their interaction with the people around them, and the physical environment, which is important for the safe design of venues where crowd management is a major issue. This simulation helps in effective prediction of potential crowd hazards in critical situations, and thus helps in reducing fatalities [1]. Crowd dynamic models have the potential to prevent fatalities through good crowd control plans. With the increasing number of "crowd situations", the hazard in crowded enclosed spaces, the complexity of city life, and capability to simulate crowd flow are becoming more important or even urgent [2].

Here as a case study, we simulated the evacuation behavior of The Mosque of Azarbaijan Shahid Madani University (ASMU) by using DEM. Different cases are considered and evacuation behavior including evacuation time and density on exits are estimated quantitatively. The results are illustrated, compared and discussed, and finally some suggestions for better evacuation behavior are given.

2. Crowd Simulation Models

Three major approaches are generally used in developing models for crowd behaviors: optimization, simulation, and risk assessment, as reviewed by Gwynne et al. [3] who examined 22 such models. The most popular method models people moving along a network of nodes. They concluded that no model to date fully addresses all the behavioral aspects of the evacuation and called for more understanding and quantification of these aspects [2].

Zheng et al. [4] classified evacuation simulation into seven methodological approaches. The first method, Cellular Automata Model, is a discrete dynamic systems consisting of a regular grid of cells. Cellular Automata evolve at each discrete time step, with the value of the variable at one cell determined by the values of variables at the neighboring cells. Next is Lattice Gas Models, which is usually used to simulate the evacuation of walkers and crawlers from a corridor with an exit or junction. Third is Social Force Model that simulates the motion of a pedestrian and is determined by setting certain destination. The evacuees keep a certain distance from other pedestrians and borders of obstacles such as walls, as they are sometimes attracted by other persons (e.g. friends) or objects (e.g. window displays) as well. The fourth approach, Fluid Dynamic model describes how density and velocity change over time with the use of partial differential equations. Fifth approach, Agent-Based Models are computational models that build social structures from the "bottom-up", by simulating individuals with virtual agents, and creating emergent organizations out of the operation of rules that govern interactions among agents. Game Theory Models approach the possibilities of evacuees assess all of the available options and select the alternative that maximizes their utility. Each evacuee's final utility payoffs will depend on the actions chosen by all evacuees. Last approach is based on experiments with animals.

Methods used for crowd computer simulation can be grouped into two areas. Firstly, the macroscopic approach which looks at the crowd as a whole, and, secondly, the microscopic approach which models each individual [2]. Another method used is Particle Swarm Optimization (PSO) that is based on swarm intelligence [5]. In this paper, DEM is used to model people evacuation.

3. DEM Approach for Evacuation Simulation

DEM is based on the numerical integration of the individual element dynamics of a system. The main advantage of DEM is that highly complex systems can be modeled with basic data without oversimplifying assumptions [6]. It has been widely used in engineering and geo-sciences. DEM can simulate crowds quite comfortably and realistically on a Personal Computer. Another significant feature of DEM is its ability to simulate complex boundaries that could include 3D buildings as multi-level 2D configurations including stairs, escalators, and lifts [2].

Discrete Element Models use a time-stepping sequence in order to track, the trajectory and rotation of each person within the system, in order to calculate their position and orientation, and then to calculate the interactions between people as well as the interactions between people and the environment, such as walls, gates, platform edges and obstacles [1].

The main advantage of DEM is that very complicated systems can be modeled with basic data without the need for oversimplified assumptions; however, valid data input is important. DEM can be considered as two different types; one is to model the crowd as a fluid such as work done by Helbing [7]. In this type of modeling, which is often used for evacuation of a wide area in the case of a widespread fire or flood, the crowd is considered as a single entity and its behavior is modeled accordingly. The second type, often used for evacuation of a small-scaled area, considers the crowd on a microscopic level and models each member individually as used in the Cellular Automata Method (Nagel and Schreckenberg [8]; Klupfel et al. [9]) and DEM (Carrion-Schafer et al. [10]) [2].

It should be taken into account that each method has its own merits. Regarding the former, it would be easier to consider the overall behavior of the people as a group; while the latter is more precise when focusing on the different characteristics of each individual such as gender, age, and walking speed separately.

4. Previous Studies Carried Out Using DEM

There are a number of evacuation simulations done using DEM, and in the following we mention some of them. Kiyono et al. [11] considered circular DEM elements as human beings, and investigated behavior of the crowd flow that evacuated an enclosed space through a passage or steps. They found that the model they proposed was able to simulate evacuation during a disaster. Kiyono et al. [12] used DEM to simulate evacuation behavior during a disaster. They used circular elements and proposed an algorithm in which the elements can avoid collision and pass each other naturally. They determined DEM parameters such as spring constants and driving force for human body based on experiments and simulated evacuation behavior for the explosion accident occurred at the underground shopping center near Shizuoka Station in 1980. Kiyono et al. [13] used the same method to simulate the evacuation of an underground mall in Kyoto. They evaluated the effect of a difference in the total population of the mall and the escape speed of evacuees. They concluded that evacuation speed becomes greater, and the time needed to evacuate becomes less in inverse proportion to the speed, but this process depends on the population and as the population increases, the element encounters many factors such as overtaking, collision with another, and a crowded exit [13]. Kiyono and Mori [14] used elliptic elements to simulate emergency evacuation behavior during a disaster, and validated the technique by comparing the simulation results with a real pedestrian flow and concluded that this model could express realistic behavior of the pedestrian movement [14].

Langston et al. [2] developed a DEM technique for modeling crowd dynamics. They presented each element by three overlapping circles. The model was tested on a single enclosure entry scenario where some model parameters were scaled, then it was used on a multi-enclosure entry scenario. The potential for further application was demonstrated on hypothetical scenarios on the London Underground [2]. Singh et al. [1] compared the predicted model behavior with actual video footage shot at various locations around University Park Campus, Nottingham. They found that it did not match well with the video footage when people were moving toward each other, as in the case of contra-flow on a walkway. In order to improve the model, they introduced an avoidance algorithm to the model to make it more realistic in those cases [1]. Alighadr et al. [15] observed the effect of exits' width, the number of people on emergency evacuation time, and the density on exits for Seghatol Islam Mosque of Tabriz Bazaar. They considered eight cases in two series and concluded that for constant exits' width by doubling the number of people, evacuation time becomes 1.47 times in average, and when exits' width is doubled, evacuation time and density of people on exits become 0.27 and 0.88 times in average, respectively [15].

Mahdavian et al. [16] used DEM to simulate tsunami evacuation behavior during the 2011 East Japan Great Earthquake. Alighadr et al. [17] did simulation of emergency evacuation of Timche Muzaffariyye of Tabriz Historical Bazaar Complex in order to evaluate the evacuation time and maximum density on exits. Eight cases were considered in two series, considering one (series 1) and two (series 2) exits, and as results show in series 1, when the number of people becomes 2, 3, and 4 times, the evacuation time also increases by 1.8, 2.78 and 3.73 times; and for series 2, it increases by 1.75, 2.46 and 3.17 times, respectively. It is also inferred that when two exits are used, evacuation time decreases by 40% [17]. Alighadr et al. [18] simulated evacuation behavior for classes building of ASMU. As results show, by doubling the number of people (650 to 1300), the evacuation time increases 1.67 times, and by considering two exits instead of one, the evacuation time reduces by 0.47 times. They concluded that location and distance of exits are important factors with regard to the evacuation time and density of exits, and it is better that exits have enough distance from each other to reduce the congestion on exits [18].

Alighadr and Fallahi [19] observed emergency evacuation of Station 5 of Tabriz Urban Railroad Organization (TURO). Five cases with different number of people on platform and concourse level were considered and evacuation simulation was done simultaneously for both levels. As results showed, by increasing the number of people from 100 (case 1) to 400 (cases 4 and 5), the evacuation time became 5.8 times for platform level. In concourse level, not only the number of people on the level itself, but also the number of people on the platform level evacuated through the concourse level was effective in evacuation time. Besides, by increasing the number of people from 100 (case 1) to 400 (cases 4 and 5), the maximum density became 2.6 times for platform level, and for concourse level, comparing case 1 to case 5, the maximum density increased by nearly 278 percent. They concluded that the number of people had great influence on the evacuation time and maximum density of people; therefore, it is essential that before construction of public buildings such as subway stations, evacuation simulations, considering a maximum expected number of people to meet safety requirements should be done [19].

5. Using DEM for Evacuation Simulation

5.1. Human Body Modeling

So far, several models have been used for representing human body. One example of these models considers human body as an ellipsoid [14], while another one makes it with three overlapping circles [1, 2, 20]. Others have used one circle (including or excluding rotation) under normal physical force and psychological force [12, 14]. In this paper, human model deployed to display each person is considered as two circles. These two circles share the same center, while having different radiuses. One circle represents human body, known as a physical circle, while the other one represents the human behavior with the radiuses of $r = 0.259$ m, and $r' = 0.72$ m, respectively, which are illustrated in Figure (1). People naturally tend to keep distance and avoid contacting each other when they are walking or even running. This constant distance is called virtual radius of human body. When one element approaches another one, a repulsive force acts and tends to keep the distance between the two elements.

Contact force acts on human body through virtual spring and virtual dashpot. Here, we set a new individual element, virtual spring, protruding outwards along normal and tangential directions, which represent the psychological distance a person keeps around himself before engaging in an avoidance movement. This notion of individual element, virtual spring, is presented in Figure (1). The individual element virtual spring is depicted by the line going through the normal line, with a parallel placement with the critical damper (damping ratio of unity). Parameters needed for modeling human body in the simulation are illustrated in Table (1) [12].

The time step Δt is a constant value that is chosen to ensure the stability and accuracy of the numerical simulation. It is determined on the basis of stiffness and mass of the element. In simulation speed of

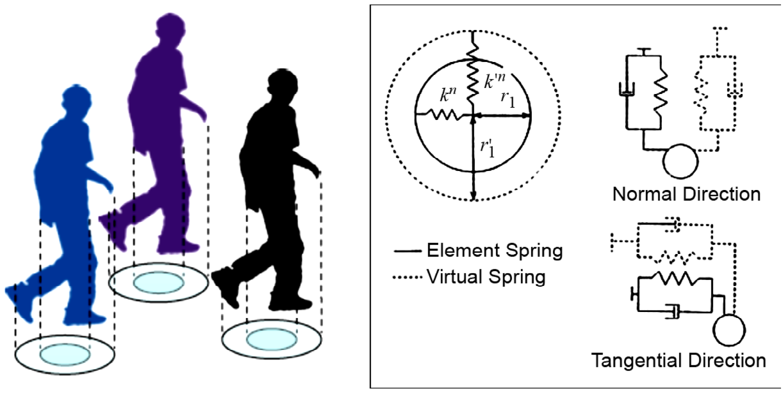

Figure 1. Spring and dashpot contact in DEM human model [12].

Table 1. DEM parameters for human body [12].

Parameter	Symbol	Value
Element Spring Constant (Normal)	K_n	1.07×10^4 (N/m)
Element Spring Constant (Tangential)	K_t	5.35×10^2 (N/m)
Element Damping Coefficient (Normal)	C_n	1.245×10^3 (Nsec/m)
Element Damping Coefficient (Tangential)	C_t	2.79×10^2 (Nsec/m)
Virtual Spring Constant (Normal)	K'_n	6.62×10^1 (N/m)
Virtual Spring Constant (Tangential)	K'_t	3.31×10^0 (N/m)
Virtual Damping Coefficient (Normal)	C'_n	9.79×10^1 (Nsec/m)
Virtual Damping Coefficient (Tangential)	C'_t	2.19×10^1 (Nsec/m)
Element Radius	r	0.259 (m)
Virtual Radius	r'	0.72 (m)
Mass	m	3.62×10^1 (kg)
Time Interval	Δt	0.01 (sec)
Acceleration of Driving Force	a	0.837 (m/s^2)
Speed	v	0.5-1.5 (m/s)

elements are assigned randomly by the simulator.

5.2. Equations of Motion

In DEM, analysis can compute the position of each element (person) step by step by solving the equation of motion. DEM can calculate the interaction force between the element and the environment and between the elements themselves. The governing equations of motions are:

$$m_i \ddot{x}_i(t) = f_i^x(t) \tag{1}$$

$$m_i \ddot{y}_i(t) = f_i^y(t) \tag{2}$$

where m_i is mass of i^{th} element, and f^x and f^y are various forces including driving force acting on the element in x and y directions, respectively. As we deal with human behavior, rotation of the element is restricted, hence rotary movement is ignored. The combined force is expressed as the sum of various forces:

$$f_i^j(t) = f_k + f_c + f'_k + f'_c + f_{wk} + f_{wc} + f_f + f_a \quad j = x, y \tag{3}$$

where f_k and f_c are the forces from the springs and dashpots of all the elements that make contact with the ith element, f'_k and f'_c are those from the virtual springs and dashpots, f_{wk} and f_{wc} are those from the surrounding walls or boundaries, and f_f is the driving force, and f_a is the attractive force that acts when the element corners. Assuming that the acceleration is constant between small time intervals, Δt, the following equations can be obtained:

$$\dot{x}_i(t) = \dot{x}_i(t-1) + \ddot{x}_i(t-1)\Delta t \tag{4}$$

$$\dot{y}_i(t) = \dot{y}_i(t-1) + \ddot{y}_i(t-1)\Delta t \tag{5}$$

$$x_i(t) = x_i(t-1) + \dot{x}_i(t-1)\Delta t + \frac{1}{2}\ddot{x}_i(t-1)\Delta t^2 \tag{6}$$

$$y_i(t) = y_i(t-1) + \dot{y}_i(t-1)\Delta t + \frac{1}{2}\ddot{y}_i(t-1)\Delta t^2 \qquad (7)$$

where $x_i, \dot{x}_i, \ddot{x}_i, y_i, \dot{y}_i$ and $\ddot{y}_i$ are displacement, velocity and acceleration in x and y directions, respectively [12].

5.3. The Simulator

The program used for this research has been first used by Kiyono [11], which was further improved by his students later on. It is a time step tracking simulation model, which follows the route and rotation of each element, in order to determine the direction and position of each entity in each time step. Target area is divided into sub-areas and elements are arranged randomly. Elements are controlled to move to nearest exit during evacuation. This program simulates movement and decision making, by means of adding the psychological forces to the physical forces. Algorithm that can consider avoidance, overtaking, and pass between elements naturally, has been used. The position of each element can be calculated sequentially by solving the above equations, step by step.

6. Case Study

6.1. The Considered Case Study

In this research, the case study takes place in the mosque of ASMU. The mosque is shown in Figure (2). The maximum number of people occupying it is determined to be about 500 people. Different cases with different number of exits and exit width are considered. It should be noted that exit 1 and 2 are main exits of the mosque.

Figure 2. Mosque of Azarbaijan Shahid Madani University.

Three different cases, according to current situation of the mosque, with different number of exits and exit width are considered (cases 1 to 3). Related geometric data are listed in Table (2), and the considered plan for each case is shown in Figure (3).

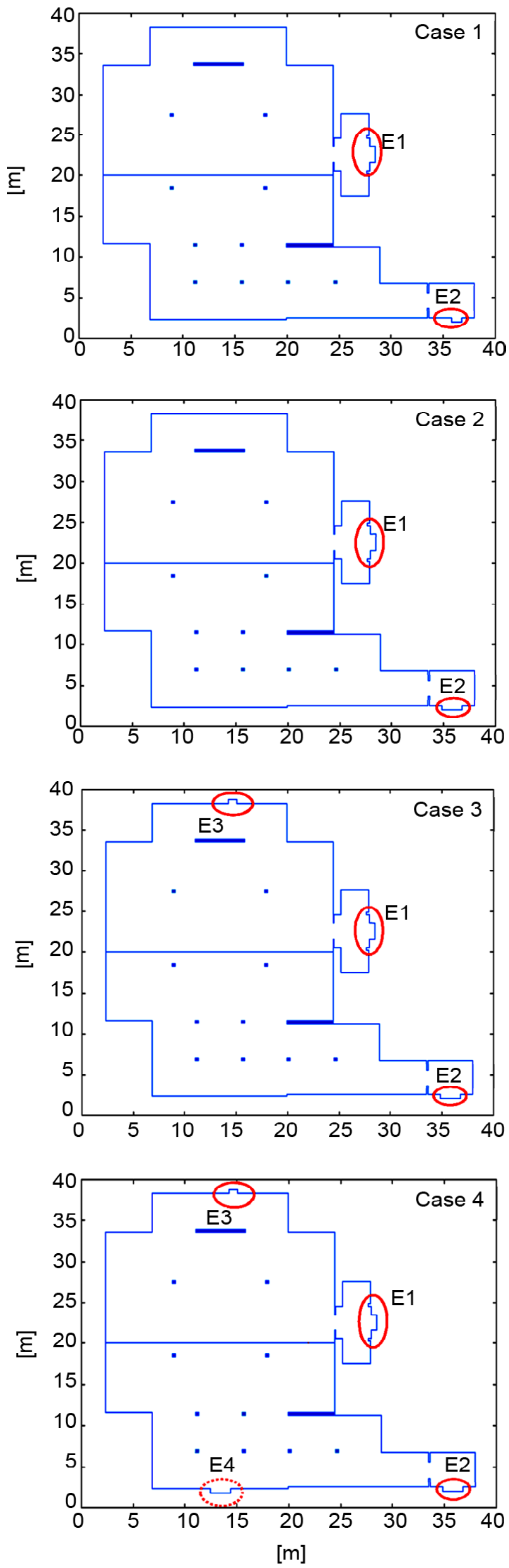

Figure 3. Plan considered for cases.

Table 2. Geometric data of cases.

Case	Width (meter)			
	Exit 1	Exit 2	Exit 3	Exit 4
1	2	1	-	-
2	2	2	-	-
3	2	2	1	-
4	2	2	1	2

In addition to the above-mentioned cases, we considered case 4 as being hypothetical as a suggestion for a better evacuation behavior. In this case, we considered an extra exit in the lower part of the mosque that is hypothetical.

Geometric data and plan considered for case 4 are also illustrated in Table (2) and Figure (3), respectively. In Figure (2), current exits are shown with solid lined ellipsoids, and the hypothetical exit in case 4 is shown with dotted line ellipsoid. Evacuation simulation is done by using DEM for all cases.

6.2. Evacuation Analysis

We did the simulation for four considered cases. Snapshots of evacuation behavior for case 1 are shown in Figure (4).

As can be seen in Figure (4), there is people jam near both exits, and arch-like blocking is apparently seen on exit 1. Snapshots of evacuation behavior for case 4 are also shown in Figure (5).

As it is seen, by adding an extra exit to the lower part, less congestion occurs, and evacuation would be more flowing. For cases 2 to 4, because of changes in the number of exits and exit widths, less congestion occurs on exits but arch-like blocking of exit 1 is also seen.

Evacuation time is calculated to be 591, 156, 138, and 114 sec for cases 1 to 4, respectively, which is shown in Figure (6).

In case 2, by doubling the width of exit 2, evacuation time decreases about 74% concerning case 1 (591 to 156); and for case 3 by adding exit 3, evacuation time decreases about 12% concerning case 2 (156 to 138). In case 4, which is hypothetical, evacuation time reduced to 114 sec that is nearly 80 and 18 percent less than the time for case 1 and case 3, respectively.

Time history of escape number and remaining evacuees are shown in Figures (7) and (8), respectively. In both Figures, slope of the curve indicates flow rate. The steeper the curve is, the more number of people will escape.

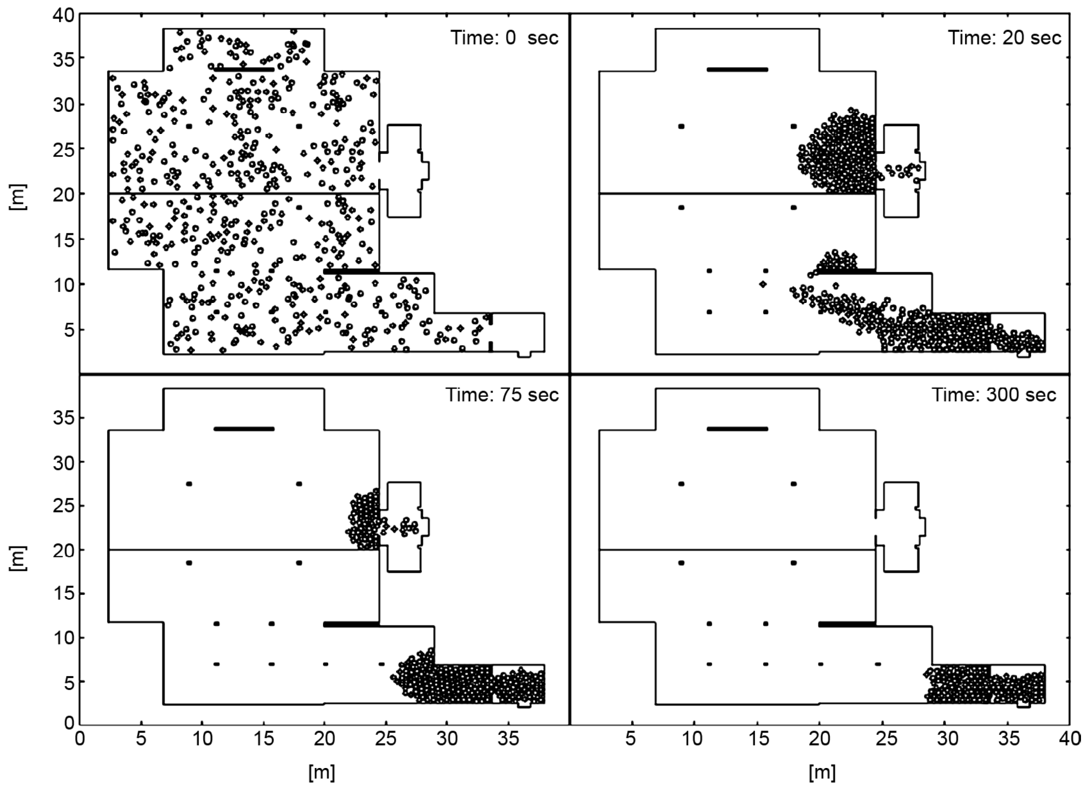

Figure 4. Snapshots of simulation for case 1.

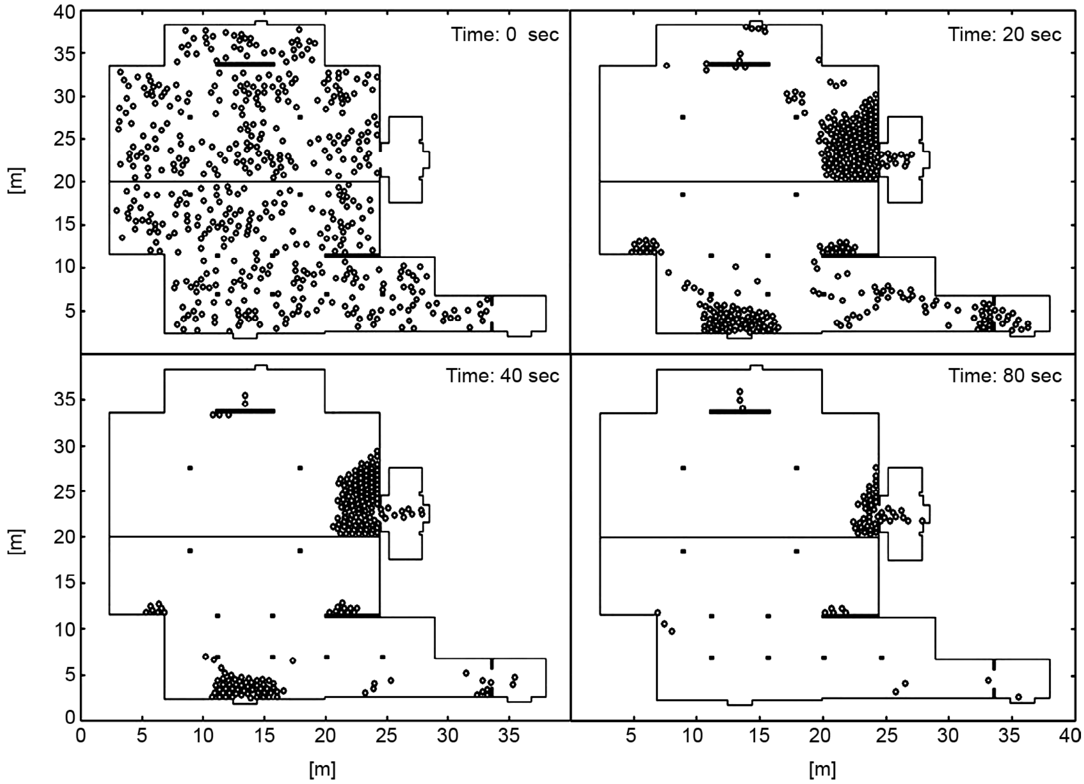

Figure 5. Snapshots of simulation for case 4.

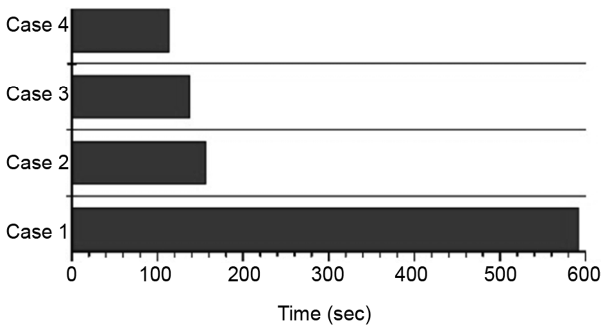

Figure 6. Evacuation time (sec).

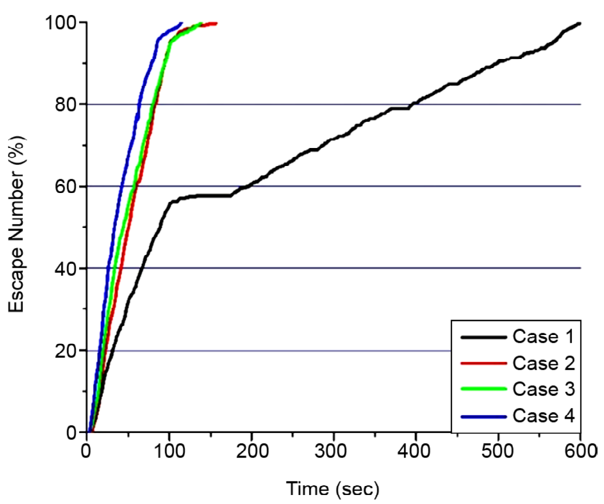

Figure 7. Time history of escape number.

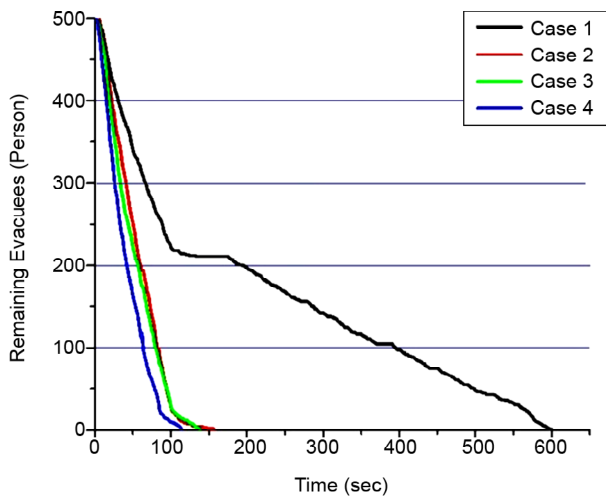

Figure 8. Time history of remaining evacuees.

As can be seen in Figure (7), flow rate (slope of curve) in case 1, because of narrower exit width, is smaller than flow rate in cases 2 to 4. After about 100 sec, flow rate decreases significantly in case 1. This is so, because of people jam at the exits for the same above-mentioned reason. As it is seen, when congestion occurs, flow rate decreases. Flow rate for cases 2 to 4 decreases around 100 sec. The reason is that some people have less velocity in comparison with others, or they are at farther distances from the exits.

The same interpretations can be made for Figure (8). Because of the same above-mentioned reasons, the number of remaining evacuees, at a certain time, for case 1 is more in comparison to other three cases.

The number of people evacuated within 10 sec time periods up to 120 sec is shown in Figure (9).

In case 1 after 100 sec, because of people congestions on exits, the number of evacuees decreases tremendously. In case 2, by doubling the widths of exit 2, more people are evacuated than case 1. Cases 3 and 4 have almost the same situation. In case 3, by adding exit 3, the number of evacuated people increased in initial times in comparison with case 2, and in case 4, by adding exit 4 to the lower part, the number of evacuated people increased in initial times in comparison with case 3; and then by completion of evacuation in the lower part, the evacuation rate decreases.

Figures (10) and (11) show time histories of density on exit 1 up to 100 sec and on exit 2 to 4, respectively. The maximum densities on exit 1 to 4 are listed in Table (3).

As it is seen, because people jam near exit 1 in all cases, density of people increases in initial times of evacuation and continues up to 80 sec.

As is seen, by doubling the width of exit 2 in cases 2 to 4, people density and evacuation time of this

Table 3. Maximum density on exits 1 to 4 (person/m^2).

	Exit 1	Exit 2	Exit 3	Exit 4
Case 1	4.5	4.23	-	-
Case 2	4.5	2.4	-	-
Case 3	4.5	2.4	3.88	-
Case 4	4.5	1.47	3.88	4.33

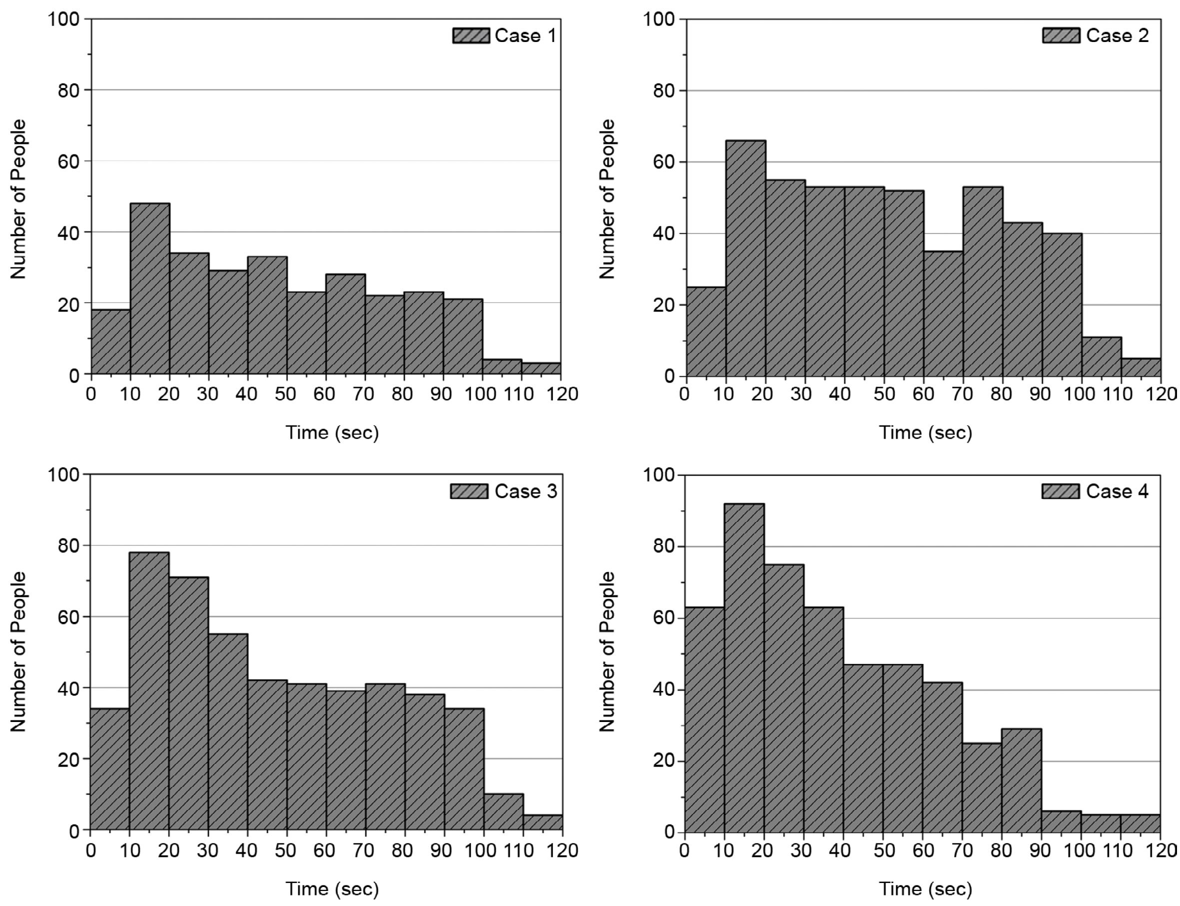

Figure 9. Number of people evacuated in cases 1 to 4.

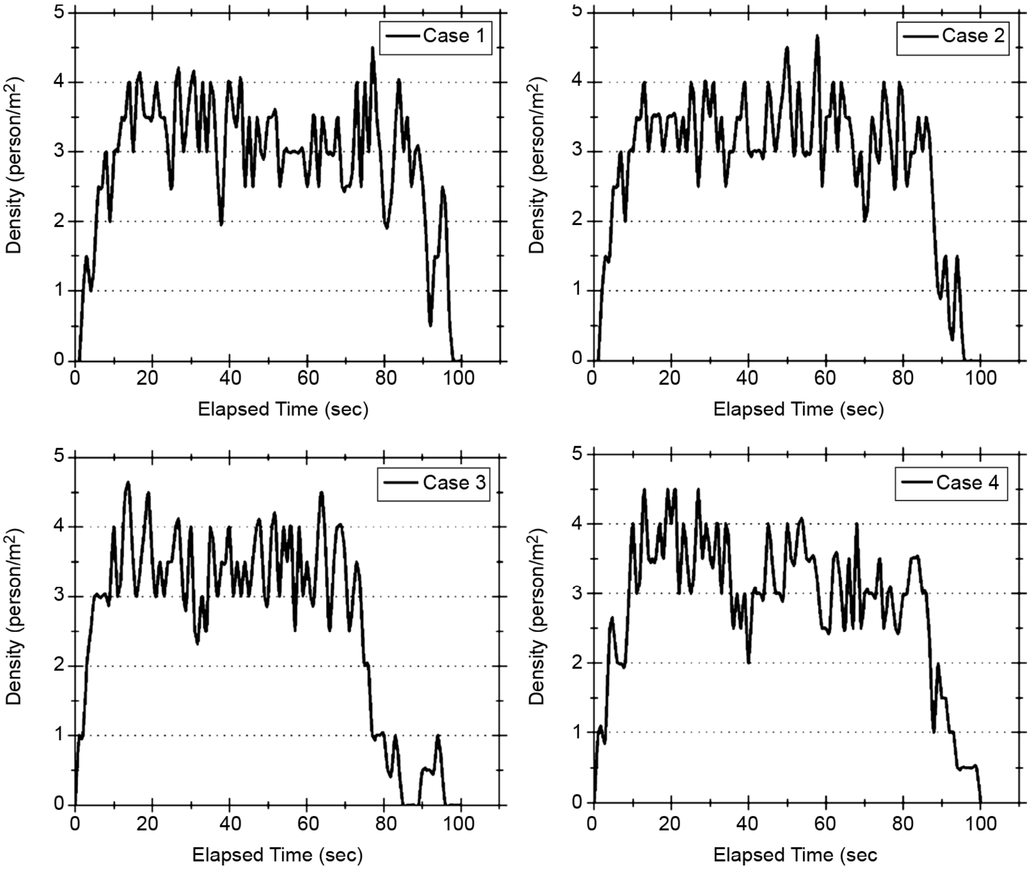

Figure 10. Time history of density on exit 1 up to 100 sec.

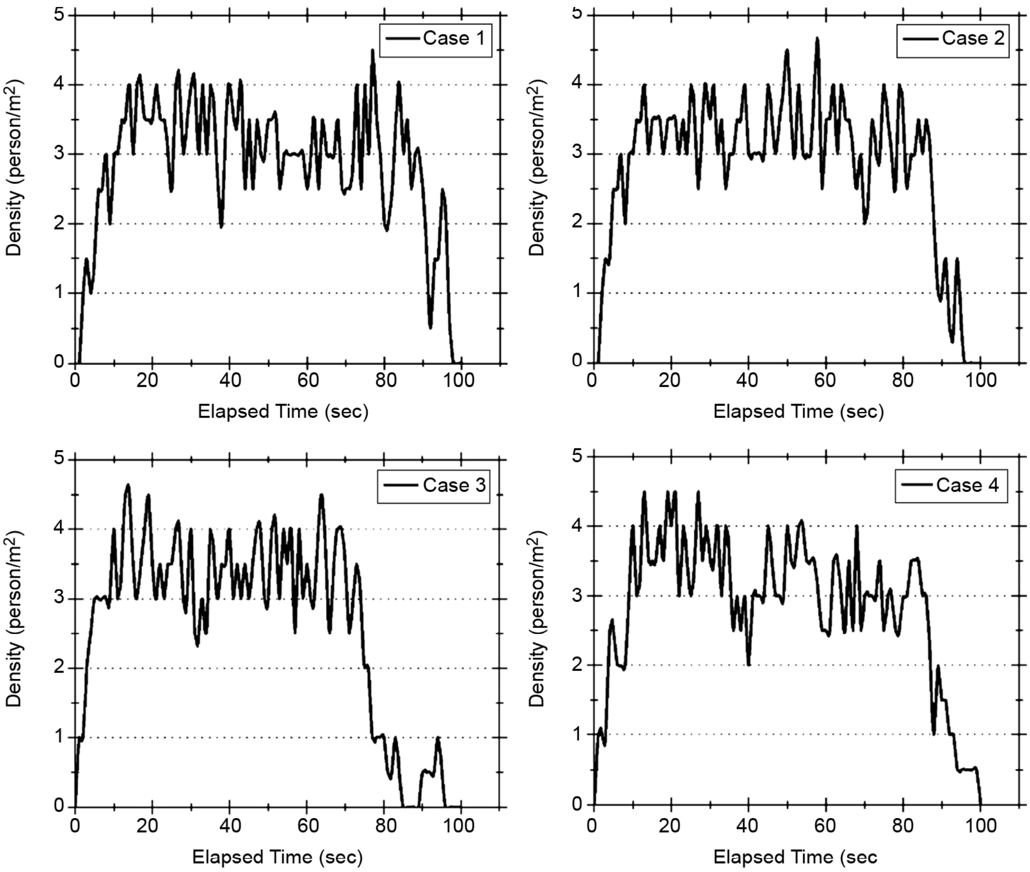

Figure 11. Time history of density on exit 2.

exit decreases tremendously.

Maximum density on exit 1 is calculated to be 4.5 for all cases. It is because the exit width is considered the same, and for the most parts similar behavior in people jam and arch-like blocking occurs. As results of Table (3) show, the existence of exit 3 (cases 3 and 4) does not have any effect on maximum density on exit 1.

When width of exit 2 is doubled in cases 2 and 3, the maximum density on exit 2 in both cases reduces nearly 43% in comparison with case 1. By adding a hypothetical exit (exit 4) in case 4, the maximum density on exit 2 is reduced to 1.47, which is nearly 65% less than that for case 1, and 40% less than that for cases 2 and 3. The maximum density on exits 3 and 4 is calculated to be 3.88 and 4.33 (person/m^2), respectively. As it can be concluded, exit widths and the number of exits have great influences on the evacuation behavior, including evacuation time, density of exits, and flow rate.

7. Conclusion and Suggestions

One of the important considerations in an emergency situation is evacuation of people. This is of great importance when a large number of people are gathered together in a confined space such as mosques, subway stations, and shopping malls. To predict the evacuation of a place, an effective way is to simulate evacuation behavior. We did the simulation of evacuation behavior by using DEM for the Mosque of Azarbaijan Shahid Madani University. Different cases with different number of exits and exit widths were considered. Evacuation behavior and time needed for evacuation were estimated quantitatively. As results showed, numbers of exits, as well as the exit width, had great influence on flow rate. When congestion occurred, flow rate decreased. Evacuation time was calculated to be 591, 156, and 138 sec for cases 1 to 3, respectively. As a suggestion for a better evacuation behavior, we considered case 4 that was hypothetical, and in this case we considered an extra exit. For this case, the evacuation time was 114 sec, which was 80 percent less than the time for case 1. The maximum density on exit 1 was calculated to be 4.5 for all cases, and the existence of exit 3 (cases 3 and 4) did not have any effect on it. The maximum density on exit 2 was calculated to be 4.23, 2.4, 2.4, and 1.47 for cases 1 to 4, respectively. When the width of exit 2 was doubled in cases 2 and 3, the maximum density in the both cases reduced nearly 43% in comparison with case 1. In case 4, by adding a hypothetical exit (exit 4), the maximum density on exit 2 is reduced to 1.47, which is nearly 65% less than that for case 1, and 40% less than that for cases 2 and 3. It was seen that exit widths and the number of exits had great influence on evacuation behavior including evacuation time, density of exits, and flow rate.

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