Pedestrian movement simulation for stadiums design

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Abstract. It is shown in the paper how pedestrian movement simulation could be applied to check stadium constructions from people comfort and safety point of view. There are number demands which stadiums should be met. They arise from level of event, type of event, safety and comfort criterions and features of people flow as a physic-and-social process, and the price is one of the main issues. Some requirements may compete with each other. The only way to verify decisions on people safety and comfort is to simulate pedestrian flow under different scenarios from normal to emergent.

1. Introduction

Stadiums (and other objects of mass stay) are a source of threat because there are a lot of people concentrated in a limited space.

Therefore, the stadium designers (and then the organizers of the events) have a great responsibility: the sports arena and the surrounding area should be arranged to ensure a comfortable stay of the audience, to prevent the possibility of the formation of dense clusters of people, and in an emergency to ensure safe evacuation from the facility.

These tasks can be solved with the help of computer simulation of pedestrian movement: it allows estimating the capacity of corridors, passages and stairways, to determine the maximum number of people for each zone, the time for evacuation, loading/unloading of a facility for different variants of the organization of processes, configuration of paths.

2. Mathematical model

Here a mathematical model of pedestrian movement is presented. Continuous modeling space $\Omega \in \mathbb{R}^2$ and an infrastructure (obstacles) are known. People may move in a free space. To orient in the space they use the static floor field $S$ \cite{1}. The nearest exit is assumed as a target point.

Shape of each agent is a disk with diameter $d_i$, $i = \overline{1, N}$, $N$ - number of people, $\bar{x}_i(0) = (x_i^1(0), x_i^2(0))$, $i = \overline{1, N}$ - initial positions of each person which are coordinates of disks centers (it is supposed that they are coordinates of body's mass center projection). Each person is assigned with the free movement speed $v_i^0$, $i = \overline{1, N}$ (which ranges from 0.5 to 2 m/s), square of projection. We assume that free movement speed is random normal distributed value with some
mathematical expectation and dispersion, [2]. It is supposed that while moving people do not exceed maximal speed (free movement speed), and persons control velocity according to local density.

Each time step $t$ each agent $i$ may move in one of predetermined directions $\vec{e}_i(t) \in \{\vec{e}^\alpha(t), \alpha = 1, q\}$, $q$ - number of directions, model parameter (here a set of directions uniformly distributed around the circle $\{\vec{e}^\alpha(t), \alpha = 1, q\} = \{\cos \frac{2\pi}{q} \alpha, \sin \frac{2\pi}{q} \alpha\}, \alpha = 1, q\}$ is considered). Agents that cross target line leave the modeling space.

Thus, at each time instant $t$, the position of each person is determined by the previous coordinate by the formula:

$$x_i(t) = x_i(t-\Delta t) + v_i(t) \Delta t, \quad i = 1, N,$$

where $x_i(t-\Delta t)$ denotes the particle's position at previous time step, $v_i(t)$, $i = 1, N$ is the particle's current speed measured in [m/s]; the time shift $\Delta t$ is assumed to be fixed 0.25 s.

Person's speed is dependent on density [2, 3]. It is assumed that only conditions in front of the person influence speed. It is motivated by the front line effect (that is well pronounced while flow moves in open boundary conditions) in a dense people mass. It results in the diffusion of the flow. Thus, only density $F_i(r^*_i)$ in the direction chosen is required to determine the speed. The current speed of the particle may be calculated, for instance, in the way:

$$v_i(t) = \begin{cases} v_i^0 (1 - 0.295 \ln \frac{F_i(r^*_i)}{F_{sp}}), & F_i(r^*_i) > F_{sp}, \\ v_i^0, & F_i(r^*_i) \leq F_{sp}. \end{cases}$$

where $F_{sp}$ is the limit people density under which free movement is possible.

Numerical procedures which is used to estimate local density is presented in [4, 5]. An area where density is determined is reduced by chosen direction and visibility area.

As a result, the movement of each individual and the phenomena peculiar to the flow of people are simulated: merger, reshaping (spreading, compaction), non-simultaneous merging of flows, formation and deformation of congestions, flow around turns, movement in rooms with a developed internal layout, counter-flows and intersecting flows [1, 4 - 6].

Calculations for stadiums with a capacity of up to 20 thousand spectators can be performed on a modern personal computer. Larger stadiums already require more powerful computational capacities.

3. Case studies

The use of computer simulation allows studying the development of the situation in accordance with different scenarios. Based on the analysis of the results of calculations it is possible to predict where a dangerous situation may occur, and what are the prerequisites for its development.

For facilities of mass stay there are several levels of comfort from A to F, which are characterized by density of people [7]. According to the existing recommendations, in the waiting area a comfortable distance between people is a little less than one meter. When people move then a comfortable distance is 2-3 meters between persons. A critical situation begins when this distance is reduced to physical contact between people.

In case of fire or other emergency, it is necessary to ensure the safe evacuation of visitors. Russian regulations require that two conditions should be met during evacuation: unhindered and timely [3]. Unhindered means that evacuation routes are not congested with a density of more than 3.5 persons per square meter lasting more than 6 minutes. Timely evacuation means on the way to a safe place for people not going on the impact of hazardous factors (e.g., smoke) at concentrations exceeding the maximum allowable value.
3.1. Event status and clients groups
The status of the competition, which is planned to be held at the facility, is of great importance in the design of the space-planning solution. So, for many large events there is the concept of "client groups". Visitors of different client groups have different levels of access and comfort of staying at the facility.

If the problem of providing the required level of service for VIP-guests at the design stage is not solved, then during an operation it may be done only at the expense of comfort and, sometimes, safety, of all other spectators.

For example, in Figure 1, red crosses indicate a path that is closed to ordinary spectators, because this area is available to visitors of a higher status (and the crossing of this zone is not allowed according to the requirements of the organizers of the competition). Therefore, to get out of the stadium, spectators from the South-West tribunes must overcome a path half a kilometer in size to the gate E7. It is possible to direct these people on a shorter way using food-court of the 3-d level of the Western tribune (to reach gates E1 and E2), but this means that about 10 thousand spectators for a long time – up to 15 minutes (which is determined by the simulation of the corresponding scenario), will be in a restricted space, which is risky in itself. Moreover, such a path is not obvious, and its implementation requires to manage people and to control (direct) flow.

**Figure 1.** A movement directions of spectators.

3.2. Shape of the route
The fastest flow of people (especially dense) moves along straight paths, so the gate to the exit should be designed to provide the straightest path. However, in some stadiums, there are opposite situations, when to achieve the goal the flow must change the direction of movement up to 180 degrees, as in figures 1 and 2. It is possible to estimate the consequences of such decision by means of computer simulation of pedestrian flows, as it is shown in Figure 2, local congestions are formed in the zone of turns.

Figure 3 shows one of the technical solutions for the reorganization of the outer perimeter of the adjacent territory, which will allow to straighten the flow of spectators coming out from the North side of the stadium.
Figure 2. Stadium design which tend people to jam and decries speed.

3.3. Stadiums design
A design of a building can create difficulties for people to move in the way (the left arrow in Figure 4) or lead to the fact that flows can block the movement of each other (the right arrow in Figure 4). The most clearly such features manifest themselves in extreme situations – the maximum load of the object and/or an emergency, when the paths at the same time accumulate a critical mass of people. The use of computer simulation of pedestrian flows allows seeing such situations and taking actions.

So, for an existing object, one can relieve tension through management of the flows and redirect spectators. Figure 5 shows the situation at the same time as in Figure 4, but due to the flow redistribution taken into account in the simulation, the duration of the congestion formed under full loading of the stadium is reduced (up to 40%).

4. FIFA 2019 Stadiums. Conclusion
As a result of computer simulation of pedestrian flows in the 2017 FIFA Confederations Cup stadiums and adjacent territories (including temporary infrastructure) and analysis of the results, areas where a potential threat to people in the case of maximum loading of the stadiums were found.

These zones can be divided into two categories: disposable / disposable conditionally (even in the conditions of the completed construction, this applies especially to temporary infrastructure, restricts access according to the principle of client groups, the outer perimeter) and adjustable by means of the organizational measures.

Identification of such features at the stage of preparation for the FIFA World Cup 2018 allows planning the measures to minimize potential threats.

Unfortunately, currently only formal control of compliance with the relevant standards is used for stadiums, which are not always able to foresee possible risks that can be predicted by computer simulation.
Figure 3. Suggestions to redesign of the outer perimeter.

Figure 4. Congestions due to design of the stadium, \( t=200 \) s.

These software tools allow at the stage of designing the stadiums or organization of events to create a safe decision to avoid situations like happened at the opening of the stadium “Luzhniki” 11 Nov 2017 (https://www.sport-express.ru/football/friendly/reviews/davka-v-luzhnikah-narod-gnali-peshkom-do-parka-kultury-1334041/). The price of the using of computer simulation is incomparable with the potential losses.
Figure 5. A reduction of the congestions due to organization of the flows, $t=200$ s.

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References
[1] Kirik E, Malyshev A and Senashova M 2016 On the evacuation module SigmaEva based on a discrete-continuous pedestrian dynamics model Lecture Notes in Computer Science, Proc. 11th Int. Conf. “Parallel Processing and Applied Mathematics”, Poland, 7-11 September 2016, Wyrzykowski R, Deelman E, Dongarra J, Karczewski K, Kitowski J, Wiatr K (eds) 9574 pp. 539-549
[2] Kholshevnikov V and Samoshin D 2009 Evacuation and human behavior in fire (Moscow: Academy of State Fire Service, EMERCOM of Russia) p 220
[3] Fire Risk Code for Buildings 2009 (Moscow: EMERCOM of Russia)
[4] Litvintcev K, Kirik E, Dektarev A, Kharlamov E, Malyshev A and Popel E 2016 Computer simulation module to model fire spread and evacuation “Sigma FS” Pozharnaya Bezopasnost’ No 4 51-59
[5] Kirik E and Malyshev A 2014 On testing computer evacuation sumulation modules using SigmaEva program Pozharnaya Bezopasnost’ No 1 78-85
[6] Kirik E and Malyshev A 2014 On validation of SigmaEva pedestrian evacuation computer simulation module with bottleneck flow J. Comp. Science 5 847
[7] Fruin J J 1971 Pedestrian Planning and Design (New York: Metropolitan Association of Urban Designers and Environmental Planners) p 206