MODELING OF PEDESTRIAN EVACUATIONS IN BUILDINGS*

Andrzej Grabowski, Robert A. Kosiński

Central Institute for Labour Protection — National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland

(Received March 13, 2014)

In the paper, the mathematical model and numerical program for simulations of evacuations from multi-floor buildings is presented. In the model, pedestrian motion is described using Langevin equations with the *Social Force* term — connected with the mental component in a pedestrian motion. In the modeling of pedestrian motion in the staircases, gravity force was added to make more realistic the description of pedestrian motion in the multi-floor buildings. The level of pedestrian's hazard defines desired velocity $v_{\rm D}$, which is the parameter of the model. Numerical simulations of evacuation were performed for the typical three-floor office building and different values of desired velocity. The character of the pedestrian motion during evacuation and the times of evacuations were found. Also experimental drill evacuation from the similar building was observed and registered using TV cameras. A type of pedestrians motion and time of this evacuation is discussed.

DOI:10.5506/APhysPolBSupp.7.283
PACS numbers: 46.10.+z, 34.10.+x, 89.50.+r

1. The model of pedestrians motion

Numerical simulations of the evacuations in different types of structures in public spaces were recently described in many papers [1–7], *e.g.* in a multi-floor buildings [5], a terminal subway station hall [6], a student dormitory [7], or during mass events [8]. In such numerical investigations, different types of mathematical models were used for modeling of pedestrians motion. Most of them are based on the modified Langevin equations containing *Social Force* term (see *e.g.* [1–4, 9]), or cellular automata (see *e.g.* [10–12]).

---

* Presented at the Summer Solstice 2013 International Conference on Discrete Models of Complex Systems, Warszawa, Poland, June 27–29, 2013.

In the present paper, the model based on the modified Langevin equations is used. In these equations, which are equations of motion of each pedestrian, additional term *Social Force* describes the mental component of the pedestrian motion during evacuation [1–4, 9]. In this term also interactions between pedestrians, and between pedestrian and elements of internal space of building are included. The modified Langevin equations have the following form [1–4]

$$\begin{aligned} \frac{d\vec{v}_i(t)}{dt} &= -\frac{1}{\tau_i}\vec{v}_i(t) + \vec{f}_i(t) + \sqrt{\frac{2\epsilon_i}{\tau_i}}\vec{\xi}_i(t)\,, \\ \frac{d\vec{r}_i(t)}{dt} &= \vec{v}_i(t)\,, \end{aligned} \tag{1}$$

where $\vec{r}_i(t)$ and $\vec{v}_i(t)$ are respectively position and velocity of i^{th} pedestrian, $\frac{1}{\tau_i}$ — a damping coefficient; $\vec{f}_i(t)$ — the *Social Force*; $\vec{\xi}_i(t)$ — the stochastic force with the amplitude proportional to ϵ_i. The *Social Force* depends on a result of psychological and mental processes of each pedestrian *e.g.* its aims and the general estimation of the situation connected with the level of hazard in the building. After information processing, pedestrian defines the parameters of their further motion (velocity, direction, *etc.*). The form of the social force is [1–4]

$$\vec{f}_i(t) = \vec{f}_i^{\,0}(v_{\mathrm{D}}) + \sum_{B\neq i}\vec{f}_{iB}\left(\vec{r}_i - \vec{r}_B\right) + \sum_{j\neq i}\vec{f}_{ij}\left(\vec{r}_i - \vec{r}_j\right)\,, \tag{2}$$

where the first term $\vec{f}_i^{\,0}(v_{\mathrm{D}}) = \frac{v_{\mathrm{D}}\vec{e}_{i\mathrm{D}}}{\tau_i}$ defines the tendency of the pedestrian to move in a desired direction $\vec{e}_{i\mathrm{D}}$, with a *desired velocity* v_{D} — in the present model the desired velocity is the same for all pedestrians. The second term is the sum of forces coming from granular interactions with other pedestrians and obstacles (in location $\vec{r}_B$) in the surrounding of the i^{th} pedestrian; and has the following form [4]

$$\vec{f}_{iB} = \left[\left(-\epsilon_{iB}k_{\mathrm{n}} - \gamma v_{iB}^{\mathrm{n}}\right)\vec{e}_{iB}^{\,\mathrm{n}} + \left(v_{iB}^{\mathrm{t}}\epsilon_{iB}k_{\mathrm{t}}\right)\vec{e}_{iB}^{\,\mathrm{t}}\right]g(\epsilon_{iB})\,, \tag{3}$$

where ϵ_{iB} — distance of i^{th} pedestrian from the surface of obstacle B minus the width R_i of the shoulder of this pedestrian (in the case of other pedestrians $\epsilon_{iB} = \epsilon_{ij}$); k_{n} and k_{t} — respectively, normal and tangent components of quasielastic force; v_{iB}^{n} and v_{iB}^{t} — respectively, normal and tangent components of relative velocity of i^{th} pedestrian; $\vec{e}_{iB}^{\,\mathrm{n}}$ and $\vec{e}_{iB}^{\,\mathrm{t}}$ — respectively, normal and tangent versors of the segment connecting i^{th} pedestrian with the obstacle B; $g(\epsilon_{iB}) = 1$, if $\epsilon_{iB} < 0$, otherwise $g(\epsilon_{iB}) = 0$.

The third term is the territorial effect, which is connected with the tendency of pedestrians to avoid other pedestrians and obstacles. The territorial effect is described using the repulsion force in the form $\vec{f}_{ij}(\vec{r}_i - \vec{r}_j) \sim$

$\exp(-\epsilon_{ij})\,\vec{e}^{\,\mathrm{n}}_{ij}$, where e_{ij} is the distance between pedestrians i and j, e^{n}_{ij} — is the versor normal to the segment connecting pedestrians i and j (see Fig. 1) [9].

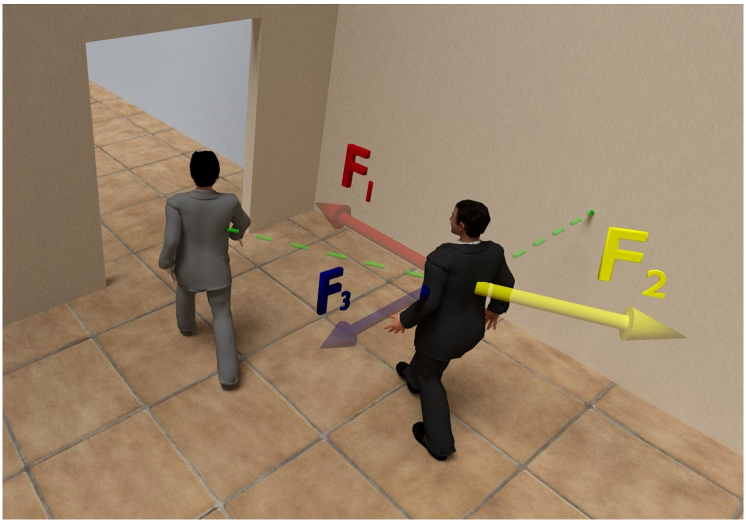

Fig. 1. Example scheme showing forces acting on a pedestrian. F_1 — movement in desired direction (to the exit), F_2 — interaction with another agent and F_3 — interaction with the wall.

In the modeling of pedestrians motion in the staircase, gravity force describing pedestrian vertical motion was added to the three types of forces in Eq. (2): $f_{\mathrm{g}} = -mg$, where $m = 80$ kg. This is a new idea which makes more realistic describing of pedestrians motion in multi-floor buildings. It also extends the applicability of the presented model. Another important feature of this model is that it considers pedestrian's behavior in the different levels of panic. This is a complex phenomenon mainly studied from the perspective of social psychology [13]. In the present paper, we use the desired velocity v_{D} as a measure of the level of panic (see Eq. (2)). The value of this parameter equals the velocity the pedestrian wants to reach. It is higher than the pedestrians real velocity v_{r}, because of its interactions with another pedestrian and obstacles and the greater the value of v_{D} the greater the level of panic.

In our paper, we assume that pedestrians do not perceive any hazard in their surrounding if v_{D} is lower than 1 m/s. Then, only social repulsion is present and no granular interactions (Eq. (3)) between pedestrians take place [4, 10].

The numerical program for solving the set of N Langevin equations (1) also contains a part for designing the internal architecture of the rooms and the building in which the evacuation process of N pedestrians will be investigated. The values of the parameters used in the computations were: $\tau_i = 0.5$ s; $k_{\rm n} = 1.2 \times 10^5 N$; $k_{\rm t} = 2.4 \times 10^5 N$; $\gamma = 100$ kg/s.

In the Langevin equations forces acting on an single pedestrian coming from interactions with near objects (other pedestrians, walls and other static elements) are taken into account (*cf.* Fig. 1). These interactions have local character. However, important role in pedestrian motion play also non-local interactions, coming from more distant surrounding of pedestrian. Such interactions determine proper path finding system of each pedestrian. In our simulations, we have used well know A^* search algorithm. Thus, each pedestrian integrate data coming from A^* star algorithm (*global* movement) and modified Langevin equations (*local* movement) [14].

2. Results of the numerical simulations

As an example, numerical simulation of evacuation in a three-floor office building with only one exit were performed for $N = 8, 16, 32, 64$ pedestrians present in the building at the beginning of the evacuation. Different values of desired velocity were used. The geometry of the floors and initial positions of pedestrians is presented in Fig. 2. The length of the longest path equals 28.4 m.

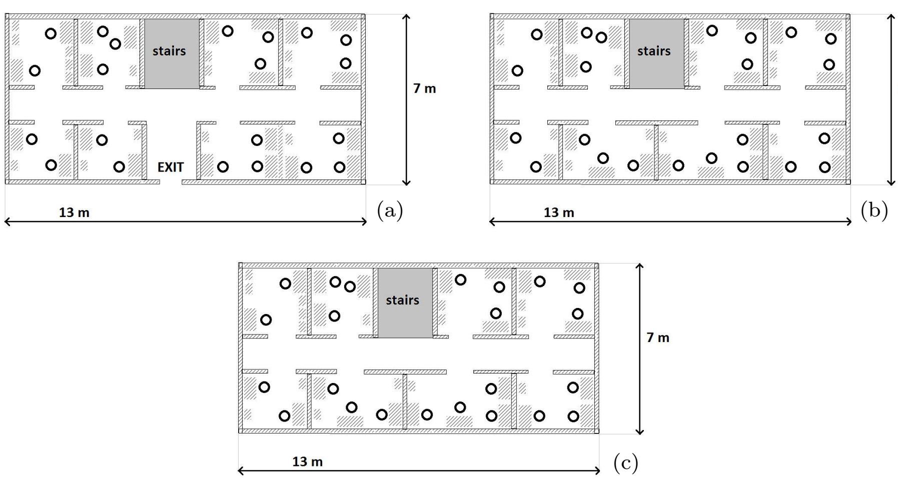

Fig. 2. The geometry of the three-floor building; ground — (a), first — (b) and second floor — (c). Initial positions of $N = 64$ pedestrians are marked with the circles, for other values of N, pedestrians were distributed in the floors uniformly. Positions of the pieces of furniture in the rooms are marked as dashed areas.

The times of evacuation for different values of desired velocity are shown in Fig. 3. Each curve is averaged over 100 simulations and in each simulation variations of the values and the directions of initial velocities of pedestrians were applied. It can be seen that the time of evacuation decreases with the increase of the value of desired velocity. The times of evacuation increase with the number of pedestrians in the building. Observations of pedestrians trajectories show that they are not dense in the corridors during evacuation process. The trajectories become denser near the entrance to the staircase as a result of a moderate clogging. For $N = 64$ pedestrians, time of evacuation increases slightly which is connected with a clogging of pedestrians in the entrances to the staircase. It can be observed that the lower the level of the staircase, the larger the number of pedestrians, coming from the upper floors.

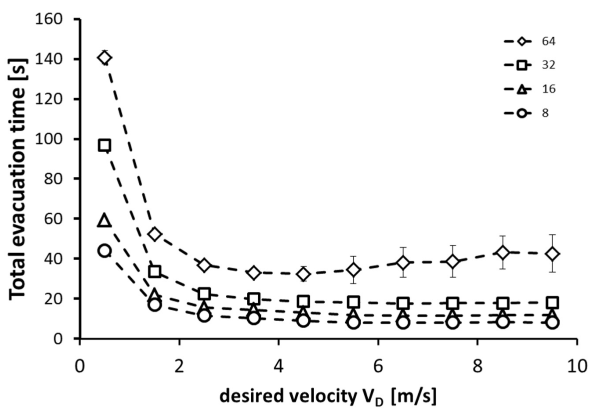

Fig. 3. Total evacuation time as a function of the desired velocity v_{D} for different number of pedestrians — as shown in the inset. For the clarity reasons, values of standard deviation is shown only for 64 pedestrians (for other cases, values of standard deviations are much lower).

3. Results of drill evacuation and discussion

With the help of firemen from The Main School of Fire Service (Warsaw, Poland), we have observed and measured the times of a drill evacuation in the nine-floor office building. The plan of the ground floor of this building is shown in Fig. 4, other floors have similar geometry. The length of the longest path equals 135.9 m. Pedestrians' movement during the evacuation was recorded by the cameras — example images from the cameras are shown in Figs. 5 and 6.

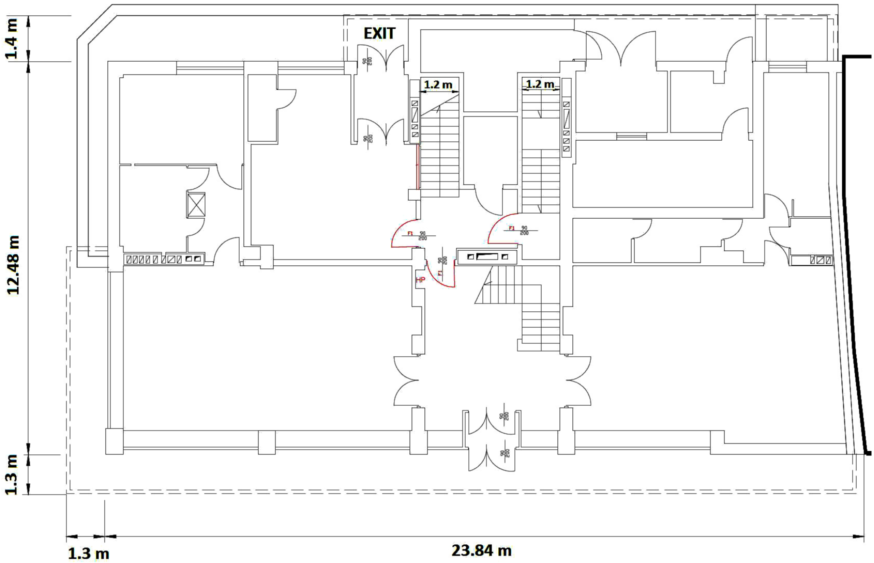

Fig. 4. Ground floor of the nine-floor building.

Fig. 5. Example images from evacuation taken by the cameras — pedestrians in the staircase.

Fig. 6. Example images from evacuation taken by the cameras — pedestrians near the main exit.

At the beginning of evacuation, 42 persons were present in the building. As results from the camera records, the motion of the pedestrians is laminar and average velocity of the pedestrians equals approximately 1 m/s. There are small cloggings observed at the floors near the exit to the staircase. An observation of individual pedestrians trajectories shows that the crowding of pedestrians near the door is a main reason of an increase of the time of evacuation. As results from the general observation, dynamical phenomena in the staircases and their geometry have distinct effect on the time of evacuation, especially in the higher levels of hazard. It is well known however, that it is difficult to force pedestrians to move with the greater values of desired velocity during a drill evacuation [15]. The measured time of evacuation equals 300 s.

It is possible to compare results of numerical simulations and experimental evacuation only partially, because both office buildings have different heights. In the experiment and in the numerical simulations, character of pedestrian motion during evacuation is similar and have laminar character. Also small cloggings are observed near the doors to the staircase in both cases. Average velocity of the pedestrians in experiment equals approximately 1 m/s, which corresponds to the results obtained in other papers [4, 7]. There is, however, significant difference in the times of evacuation, which equals 300 s for the experimental case and equals 120 s in the simulation. This is caused by the small difference of N and the heights of buildings — nine floors in the experimental evacuation and three floors in the numerical simulation.

In conclusion, it can be said that numerical description of evacuation agrees qualitatively with the experiment. The mathematical model of evacuation processes, where pedestrians dynamics is described using Langevin equations with the *Social Force* term, is an effective way for investigations and estimation of effectiveness of evacuations in different buildings and in different levels of hazard.

The publication has been based on the results of Phase II of the National Programme "Safety and Working Conditions Improvement", funded in the years 2011–2013 in the area of research and development works by the Ministry of Science and Higher Education/The National Centre for Research and Development. The Programme coordinator: Central Institute for Labour Protection — National Research Institute.

REFERENCES

[1] D. Helbing, P. Molnar, *Phys. Rev.* **E51**, 4282 (1995).
[2] D. Helbing, I. Farkas, T. Vicsek, *Nature* **407**, 487 (2000).
[3] F. Schweitzer, *Brownian Pedestrians and Active Particles*, Springer, Berlin 2003.
[4] D.R. Parisi, C.O. Dorso, *Physica A* **354**, 606 (2005).
[5] N. Pelechano, A. Malkawi, *Automat. Constr.* **17**, 377 (2008).
[6] W. Lei *et al.*, *Physica A* **391**, 5355 (2012).
[7] W. Lei, A. Li, R. Gao, X. Wang, *Physica A* **391**, 6279 (2012).
[8] X.L. Zhang, W.G. Weng, H.Y. Yuan, J.G. Chen, *Physica A* **392**, 2781 (2013).
[9] R.A. Kosiński, A. Grabowski, *Acta Phys. Pol. B Proc. Suppl.* **3**, 365 (2010) .
[10] I. Beneson, P.M. Torrens, *Geosimulation*, Wiley, San Francisco 2004.
[11] R. Chen *et al.*, *Int. J. Mod. Phys.* **C18**, 359 (2007).
[12] M.J. Mrowinski, T.M. Grabowski, R.A. Kosinski, *Acta Phys. Pol. B Proc. Suppl.* **5**, 117 (2012).
[13] X. Guo, J. Chen, S. You, J. Wei, *Physica A* **392**, 1994 (2013).
[14] P.E. Hart, N.J. Nilsson, B. Raphael, *IEEE Transactions on Systems Science and Cybernetics* **4**, 100 (1968).
[15] J. Bohannon, *Science* **310**, 219 (2005).