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IMPROVEMENT OF THE METHODOLOGY FOR DETERMINING THE MOVEMENT PARAMETERS OF INDIVIDUALS WITH VISUAL IMPAIRMENTS DURING EVACUATION FROM HIGHER EDUCATION INSTITUTIONS WITH INCLUSIVE EDUCATION USING A SIMPLIFIED ANALYTICAL MODEL

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The object of the study is the movement parameters of mixed evacuation flows, which include participants with visual impairments. Such parameters are the speed of movement, density and the percentage of participants with visual impairments in the flow.

Solving the problems of calculating the duration of evacuation of the population from educational institutions with inclusive education is very relevant, since this process has a significant feature that is not typical for evacuation from most residential and public buildings. In such educational institutions, all students move in groups under the control of scientific and pedagogical workers. This feature is not taken into account in the regulatory documents that fix the methods of calculating the duration of evacuation. The numerical parameters obtained by authors allow to solve this problem.

According to the results of the experiment, 241 measurements of the speed and density of the flow were made on horizontal sections, 204 – during the descent of the stairs and 206 – during the ascent. The dependences between these parameters were established by conducting regression analysis. As part of the experiment, flows were monitored with a variable value of the percentage of people with visual impairments in the flow. Thanks to this, the impact of the increase the number of people with visual impairments in the flow on the speed of movement on various sections of the evacuation routes was established.

The analysis of the obtained results shows that the appearance of the first participant with visual impairments in the flow leads to a decrease in the speed of movement. In the future, the relationship between a decrease in speed and an increase in the percentage of traffic participants with visual impairments is linear.

The obtained dependencies can be used as input parameters for calculations of the duration of evacuation in educational institutions with inclusive education according to a simplified analytical model and allow obtaining smaller deviations from the results obtained in real conditions (3.4–25 %) compared to the current individual model (35, 5–52.3 %)

Keywords: fire safety, evacuation of people, visual impairment, evacuation time, inclusiveness

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1. Introduction

There are currently 36 million blind people in the world, and by 2050 this number may reach 115 million. Such conclusions were reached by the authors of the study [1].

As of 2023, out of about 1.5 million students of higher education in Ukraine, about 12,000 are people with special needs. At the same time, over the past 10 years, their number has increased more than 10 times [2]. There is a clear rejection of the standards of the Soviet education system, according to which such persons did not have full access to education and were forced to choose the correspondence form of education. These changes are enshrined in relevant regulatory documents [3–5]. It is obvious that the number of students with special needs in higher education institutions tends to increase [1, 2]. At the same time, the development of inclusive education requires significant changes from higher education institutions aimed at ensuring unhindered access to educational resources. In particular, ensuring an appropriate level of security is an important component. The value of individual risks for such students should not exceed the permissible norms.

The duration of evacuation from buildings and structures in the event of a fire is an important parameter necessary for calculating the values of individual fire risks. As of January 1, 2024, issues of evacuation from educational institutions are regulated by a number of documents. Requirements for evacuation routes and exits from educational institutions are given in [3]. Recommendations for the organization of inclusive education are highlighted in [4]. Methods for calculating the duration of evacuation from buildings and structures are presented in [5]. At the same time, none of these documents allows taking into account the influence of the presence of students with special educational needs in the study groups on the duration of the evacuation in the calculation process. The lack of input data makes it impossible to calculate the duration of evacuation in the event of a fire from the building of a higher education institution with inclusive education. Experimental studies of evacuation from such objects make it possible to obtain input data for such calculations. Therefore, scientific research devoted to establishing the relationship between the density and speed of movement of evacuation participants in educational institutions with inclusive education is important.

2.Literature review and problem statement

In [6], a series of experiments was presented in which 252 participants with and without visible defects, moving in a crowd, took part. Each experiment involved groups of participants moving down a corridor with a narrowing path at the end. Such parameters as the moment of acceptance of the speed, the distance between the participants and their behavior were analyzed. Participants with disabilities were found to slow down more after the taper than participants without disabilities. It was also noted that participants without disabilities were closer to those who had disabilities than to those who did not. They actively communicated and interacted with each other to organize the movement before the taper. The obtained results emphasized the importance of using representative and diverse samples when studying crowd dynamics.

However, the study did not take into account such parameters as the moment of acceptance of the speed and the distance between the participants, these parameters were quite general and did not take into account other important aspects that influence the behavior in the crowd, such as psychological factors. Also, the participation of observers during the experiment influenced the behavior of the participants, which could lead to an incorrect representation of the real situation.

In the study [7], persons with various types of disabilities, such as visual, hearing, physical and mental disabilities, intellectual disabilities, as well as persons without disabilities, participated, comparing them with groups of elderly people. As part of the study, the peculiarities of the movement of mixed flows of people on horizontal evacuation routes were analyzed. The obtained results indicate that persons with mental and intellectual disabilities showed a higher speed of movement than the rest of the crowd.

The analysis of the results given in [7] showed that the range of density of mixed flows of people with disabilities (from 0.48 to 2.25 m^2) was narrower compared to the group of elderly people (from 0.27 to 2.64 m^2). In the same density range, the difference in speed and specific flux between both groups was observed, which was 0.00 ± 0.09 m/s and 0.04 ± 0.11 (m·s) – 1, respectively. The increase in the specific flow of the mixed group of people with disabilities was 3.84 ± 10.67 % compared to the group of elderly people.

Next, an analysis of the mixed flow evacuation time of the group of people with disabilities, which is inversely proportional to the width of the exit, was carried out, similar to the group of elderly people. The flow density of the mixed group of people with disabilities was higher than that of the elderly.

As a result of the analysis of the received data, the researchers used pie charts. It is observed that the spatial distribution of the nearest neighbor for a mixed group of people with disabilities has the shape of an ellipse, and with increasing density, it tends to change to a circular shape.

The study looked at only a few types of disability, which does not reflect the full range of people with different disabilities. Although flow velocity and density were analyzed, other factors, such as the influence of room structure and the psychological aspects of evacuation, were not considered sufficiently.

The work [8] gives the results of an experiment on the influence of persons with limited mobility on evacuation processes indoors. A total of 60 people took part in the experiment. In the experiment, a different ratio (0 %, 5 % and 10 %) of people from different groups was provided. Video recordings and the average speed algorithm were used to determine and track the movement trajectories of the experiment participants. Evacuation time, speed, sequence of evacuation and human flows were analyzed by movement trajectories. It was found that compared to experiments without the presence of persons with disabilities, the evacuation time in experiments with the presence of visually impaired persons, crutches and wheelchairs increases, and the average speed and specific consumption decrease. The spatial distribution obtained using the analysis indicates that the crowd of people without limited opportunities near the exit is formed more slowly compared to the human flow in which there are people belonging to less mobile groups. This was especially evident when people in wheelchairs took part in the experiment.

In work [9], indoor evacuation was carried out according to 15 scenarios, which involved different numbers of people (20, 40 and 60). Trajectories and coordinates of agents were obtained in real time. It was established that with the increase in the share of people with disabilities, the individual evacuation time of agents increases. This trend was consistent with the results of a previous controlled experiment. Agents' average evacuation speed negatively affected the mixed proportion of persons with disabilities. The fundamental diagrams obtained by simulation were similar to the experimental results. The presence of people with disabilities in the scenario was found to result in higher crowd density compared to scenarios without disabilities. As the proportion of pedestrians with disabilities increases, the danger in crowds increases, which confirms experimental findings. These findings are useful for safe evacuation using computer simulations to reduce various crowding during building fire evacuation. The problem with this study is that although the experiments were conducted under controlled conditions and in a model environment, they may not fully reflect real evacuation situations. Actual evacuation conditions can be much more complex and unpredictable, taking into account factors such as stress, panic, limited exit routes and other unforeseen circumstances. Thus, results obtained under controlled conditions may require additional verification and validation in real evacuation scenarios to confirm their applicability and suitability.

The study [10] carried out a simulation of the evacuation of people who have a limited field of vision and are influenced by people nearby in decision-making and subsequent actions. This simulation was performed using an enhanced dynamic parameter model (DPM) to simulate evacuation with varying visibility. Visibility change is modeled through each person's viewing radius. The room for evacuation was divided into two zones visible and invisible for the evacuation exit. In the visible zone, people use normal movement strategies, while in the invisible zone, they follow each other intuitively. Agents in the invisible zone are observed to cluster near the walls. The number of people trapped in a room depends on temporal and spatial parameters such as initial density, exit width, and view radius. To ensure effective evacuation, it is important to consider these parameters. Compared with the blind random model, the improved model, which takes into account blind following in the invisible zone, is found to reduce the evacuation time and the dependence on the human view radius. The possibility of developing an extended model with internal planning and heterogeneous traffic rules is considered as a promising direction of research. The problem with this study is the limited application of simulation results to real evacuation scenarios. Even if the improved model shows a reduction in evacuation time and dependence on human sight radius compared to a blind random model, these results may be limited in applicability to real-world situations. The model may not fully take into account all aspects and factors affecting evacuation, such as people's psychological reactions to stress, interactions with other evacuation participants, and unforeseen circumstances that may occur during a real evacuation. Thus, it is necessary to take into account the limitations and possible artifacts of the model when interpreting the results and using them in practical situations.

In work [11], the authors focused on the study of the actual problem of evacuating low-mobility population groups from high-rise residential buildings during a fire. They investigated the possibility of safe self-evacuation of these populations using fire elevators. In addition, mathematical and graphical calculations of people's evacuation time were carried out using the Pathfinder software complex, with alternative options for using fire elevators or without using them. Specific recommendations for the evacuation of low-mobility population groups from high-rise residential buildings are offered. The problem with the study is that it may not take into account all aspects and possible negative consequences of using fire elevators to evacuate people with reduced mobility from high-rise buildings during a fire. During a fire, there is a possibility of technical malfunctions or failure of fire elevators. The use of fire elevators can cause panic among residents and overcrowding of the elevator space, which can lead to emergency situations. Therefore, it is important to take into account these aspects and possible risks when developing recommendations for the evacuation of low-mobility population groups from high-rise residential buildings during a fire.

In work [12], an analysis of methods for calculating the duration of evacuation was carried out. The work substantiates the need for the formation of an empirical database regarding the parameters of the movement of evacuation flows in secondary education institutions with inclusive education. This will become a scientific basis for standardizing requirements for fire safety, in particular for evacuation routes and exits in these educational institutions. It was found that normative documents and scientific literature do not contain sufficient information about the patterns of movement of a mixed flow, which consists of school-age children of different levels of mobility.

In work [13], a partial case of evacuation from schools with inclusive education was considered, which allowed taking into account the presence of students in wheelchairs in the flow. At the same time, the study of the effect of changing the number of participants in wheelchairs on the flow parameters was not conducted. This in turn has led to insufficient analysis and may lead to an incomplete understanding and consideration of the needs and requirements of persons with disabilities during evacuation.

In [14], the dependence of the area of the horizontal projection of school students on their age was established. These dependencies make it possible to increase the accuracy of evacuation duration calculations for school education institutions. However, the diversity of students, their physical characteristics, and their abilities can vary much more than simple age can account for.

Work [15] investigated a scenario that is as close as possible to the real situation – an unannounced evacuation, when neither staff nor visitors had information about its conduct. With the help of video cameras, the behavior of people and the movement of human flows were recorded from the moment the alarm system was activated until the exit from the building and the completion of the evacuation of people from fire-safe zones with the help of fire and rescue units. Data were obtained on the movement of evacuees who moved in wheelchairs from the most distant points to the fire-safe zones, from where the evacuation was carried out. The total evacuation time of these persons was established, which included the time of travel to the fire safety zone, waiting for fire and rescue units and evacuation from fire safety zones. The time of evacuation of people in wheelchairs from fire-safe zones with the help of fire-rescue units has also been determined. Data were obtained on the evacuation of persons who moved only in wheelchairs from fire safety zones using fire elevators in conditions that are as close as possible to real ones. The dependence of the speed of movement of human flows during evacuation on the presence of disabled people in wheelchairs among them was determined, and their density on different sections of the road was calculated. Based on the results of the experiment, the evacuation plan from the building was adjusted and the actions of personnel in fire conditions were analyzed. However, the study did not take into account the psychological aspects of evacuation in unannounced situations, such as panic, stress or carelessness, which can significantly affect the behavior of evacuees.

In these studies, insufficient attention was paid to the aspect of evacuation of a mixed flow of people who have visual impairments. Researchers do not have sufficient vision or understanding of the needs and limitations of visually impaired people during evacuation. This leads to the fact that this aspect was not considered a priority for inclusion in the study. Different researchers have different approaches to prioritizing research, which leads to differences in the inclusion of the aspect of visually impaired evacuation.

Further study is needed on the relationship between mean free motion velocity (V_0) and flow density (D_0), where increasing density results in decreased motion velocity after a certain level is reached. This dependence depends on the number of visually impaired traffic participants and the coefficient of adaptation of the human flow to changes in density. Fire evacuation from different types of buildings, including inclusive higher education institutions, has not yet been adequately researched. To solve this problem, it is necessary to conduct experimental studies, create an empirical database on evacuation parameters, and investigate the influence of these parameters on the speed of movement of evacuation participants.

3. The aim and objectives of the study

The aim of this study is to reveal the influence of factors on the speed of movement of evacuation flows, which include students with visual impairments. This will increase the effectiveness of fire safety in higher education institutions with inclusive education.

To achieve the aim, the following research objectives have been defined:

– establish the dependence of the flow movement speed, which includes students with visual impairments, on its density;

– establish the impact of the share of visually impaired evacuation participants in the flow on the overall evacuation speed;

– conduct a computer simulation of evacuation from a higher education institution with inclusive education using data obtained from the results of field observations.

4. Materials and methods of the study

The object of scientific research is the process of evacuating people with visual impairments, which are part of various evacuation flows in higher education institutions with an inclusive approach.

In educational institutions with inclusive education, the evacuation of all students in a single flow under the control of scientific and pedagogical workers creates obstacles for modeling the process using individual flow models. Therefore, the possibility of applying a simplified analytical model, characteristic of homogeneous flows, is put forward as a research hypothesis. To lead to this model, it is necessary to consider a heterogeneous flow, which includes visually impaired evacuation participants, as homogeneous. To this end, it is necessary to determine to what extent the percentage of visually impaired participants reduces the overall flow rate.

The relationship between the movement speed of the evacuation participants and the flow density is generally described by a relationship of the form (1):

$$V_D = V_0\left[1 - a\ln\frac{D}{D_O}\right], \text{ at } D > D_O, \qquad (1)$$

where V_D – the flow speed at the flow density D; D – the current value of the flow density, persons/m^2; D_0 – the threshold value of the flow density, after reaching which the density becomes a factor affecting the speed of movement, people/m^2; V_0 – the random value of the speed of free movement (in the absence of the influence of surrounding people), which depends on the type of path and the emotional state of people, m/min.; a – coefficient reflecting the degree of influence of the density of the human flow on its speed;

The physical meaning of this relationship is that when a certain threshold of flux density D_0 is exceeded, the speed of free movement V_0 will decrease to the value V_D. Thus, the absolute decrease in speed will be $\Delta V = V_0 - V_D$, and the relative – $R = (V_0 - V_D)/V_0$. Such a regression is built based on empirical data approximated by a theoretical function that describes the effect of flow density on speed of movement based on the Weber-Fechner law $R = a \cdot \ln(D/D_0)$ [13].

Therefore, for a mathematical description of the movement of the evacuation flow, it is necessary to determine the values of V_0, a and D_0.

In order to form empirical databases of evacuation parameters, field experimental studies were conducted. To solve the task, the method of a natural experiment was used, during which the process of evacuation from an educational institution of higher education with inclusive education was observed. This method is one of the most effective for collecting data in real conditions, as it allows to reproduce real situations and obtain reliable results. Observation of the evacuation process in a real environment provides objective information about the conditions and factors affecting the speed of movement of the flow of persons with visual impairments. Establishing relationships between movement speed and flow density made it possible to study how the number of people with visual impairments affects the overall dynamics of the evacuation process. The obtained results are important information for the development of effective evacuation management strategies in institutions of higher education with inclusive education.

An empirical research method was used to determine the impact of the share of visually impaired evacuation participants on the overall evacuation speed. This method is based on conducting a natural experiment and observing real evacuation processes. During the experiment, data on the composition of the flow of evacuation participants, their motor activity and the time required for evacuation were recorded. The obtained results were analyzed to establish the relationship between the proportion of persons with visual impairments in the flow and the overall evacuation speed. This method was chosen for its ability to provide objective data reflecting real-world conditions and factors influencing the evacuation process.

The use of data obtained from field observations made it possible to take into account the real conditions and features of the evacuation process, in particular, regarding the behavior and movement of participants with visual impairments. Mathematical modeling analyzed different evacuation scenarios, while computer simulations allowed these scenarios to be reproduced in a controlled environment to obtain numerical results. The use of these methods helps to improve the understanding of the dynamics of the evacuation process and the development of effective evacuation management strategies, taking into account the characteristics of participants with visual impairments.

The behavior of people with visual impairments was reproduced by students who were provided with zero visibility during the evacuation process by using special masks. The movement of such people was ensured by the provision of appropriate assistance by other participants. Since in the event of a fire, evacuation is carried out in an organized manner as part of training groups, such conditions of conducting the experiment were close to real conditions. The horizontal test section was 49.91 m long and 3.07 m wide. Stair movement was studied on spans 1.2 m wide. Each span had 15 steps, each 28 cm wide.

As part of the experiment, dynamic video recording was used, in which the video recording of the process was carried out directly by several participants of the evacuation. For data collection, camera recordings were synchronized [16].

Experimental data were processed using MS Excel software (USA), which provided opportunities for analysis, visualization and interpretation of the obtained results.

In order to compare and evaluate the correctness of the conducted experiment and to expand the limits of experimental research on the reproduction of the evacuation processes of people with visual impairments, a computer simulation was carried out. The simulation was performed in the Pathfinder software (USA), which implements an individual flow model of the movement of people during evacuation. The program has a graphical interface for specifying the output data, as well as tools for 2D and 3D visualization of the results.

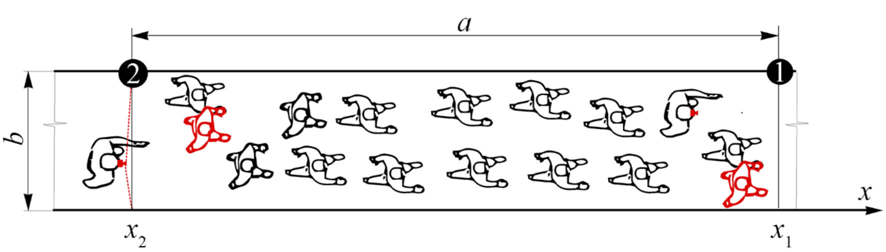


Fig. 1. Dynamic video recording of a natural experiment

At a certain moment of time t_n, the coordinates of the participants of the movement 1 (x_1) and 2 (x_2) on the movement section were fixed. Thus, the distance between participants 1 and 2 was determined by formula (2):

$$a(t_n)=x_1(t_n)-x_2(t_n). \quad (2)$$

The flow density at time $t_1$was calculated according to formula (3):

$$D(t_n)=\frac{N}{\left(x_1(t_n)-x_2(t_n)\right)\cdot b}, \quad (3)$$

where N – the number of evacuation participants in the observation area; b – the width of the traffic section.

At the next moment of time t_{n+1}, similar values x_1 (t_{n+1}), x_2 (t_{n+1}), a (t_{n+1}), D (t_{n+1}) were determined in the same way.

In each time interval between the measurements, the average value of the flow speed on the traveled section of the path was determined (4):

$$V_{av}=\frac{1}{2}\cdot\frac{\left(E_1(t_{n+1})-E_1(t_n)\right)+\left(E_2(t_{n+1})-E_2(t_n)\right)}{(t_{n+1}-t_n)}. \quad (4)$$

Also, in the intervals between two consecutive measurements, the average value of the flux density was determined (5):

$$D_{av}=\frac{1}{2}\cdot\left(D(t_n)+D(t_{n+1})\right). \quad (5)$$

5. Results of the study of the influence of participants with visual impairments on the density and speed of the flow

5. 1. Establishing the dependence of the movement speed on the flow density

During the experiments, scenarios were worked out with the participation of groups with different percentages of visually impaired participants. According to [4], the maximum number of students with special educational needs in one group is determined based on the individual characteristics of the educational and cognitive activity of such students, specialty, suitability of classrooms, etc. As a rule, it does not exceed 10 %. Based on this, the total number of observations for each type of flow on different sections of the evacuation routes is given in the Table 1.

Eahch measurement required the determination of a pair of values – the speed of movement and the corresponding flow density. The results of the measurements are presented in Fig. 2.

The results were summarized in variational series by density intervals in the order of its growth. At the same time, anomalous errors were removed from the total array of measurements. For each density interval (0...1], (1...2], (2...3], (4...5], (5...6], (6...7) mathematical expectations were determined). Curves were built based on these mathematical expectations). These curves were approximated by a logarithmic function of the form $y=A\ln D+B$. Hence, the value V_0 for each scenario was determined by the abscissa of the trend line of the form $y=A\ln D+B$ with the line $y=V_0$.

According to the results of the processing of data arrays of the performed measurements, the curves of dependence of speed on density for different compositions of evacuation flows have the following form (Fig. 3).

Table 1

The number of speed measurements for each type of evacuation flow on different sections of evacuation routes

Percentage of visually impaired participants in the flow	Type of evacuation route (exit)		
	Horizontal	Stairs down	Stairs up
0 % (total number of agents – 40, visually impaired – 0)	70	50	49
2.5 % (total number of agents – 40, visually impaired – 1)	45	40	43
5 % (total number of agents – 40, visually impaired – 2)	44	37	40
7.5 % (total number of agents – 40, visually impaired – 3)	42	40	38
10 % (total number of agents – 40, visually impaired – 4)	40	37	36

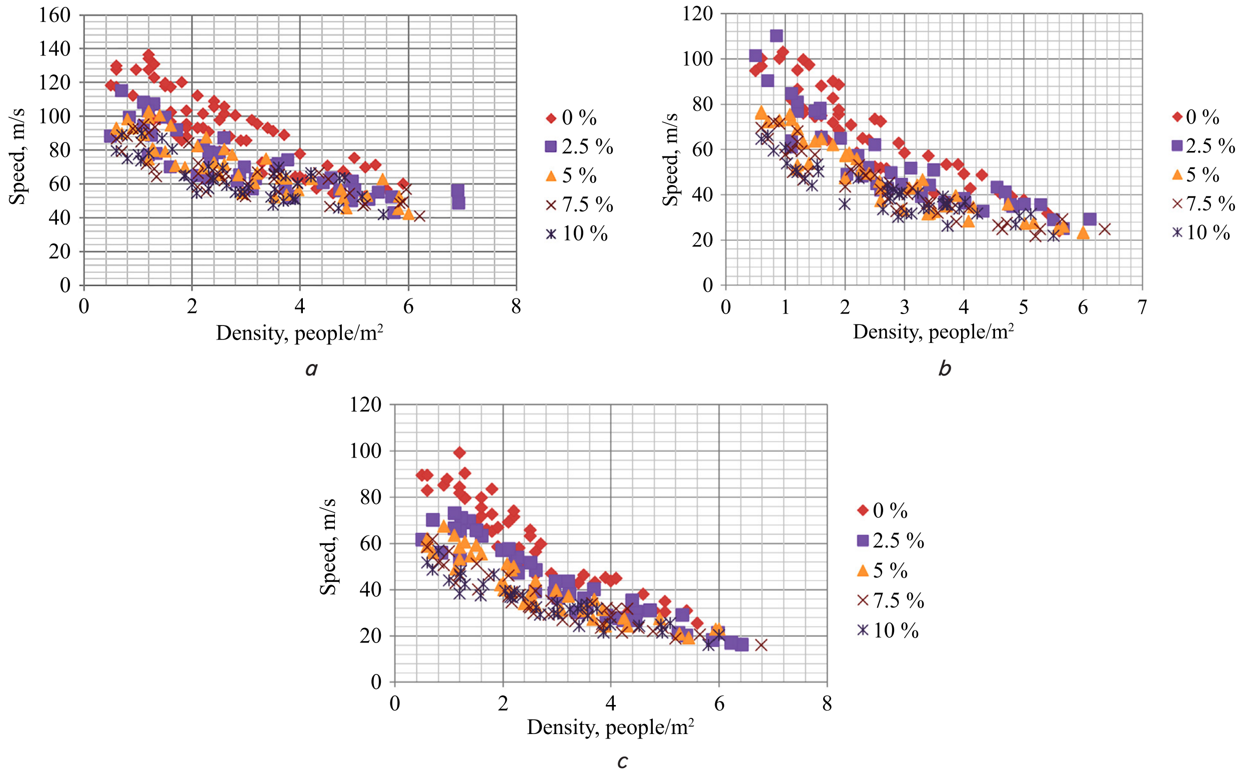


Fig. 2. The results of measurements of the movement speed of the evacuation participants: *a* — movement on a horizontal section; *b* — movement down the stairs; *c* — movement up the stairs

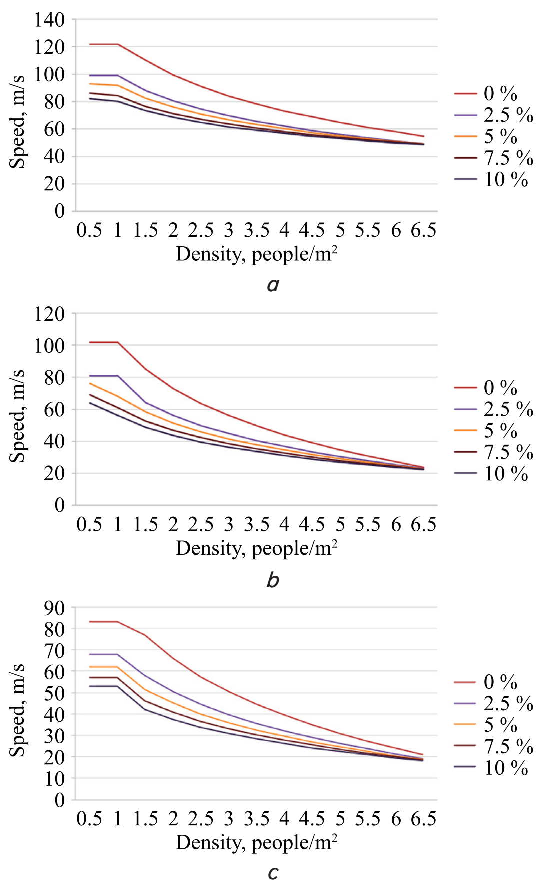


Fig. 3. Movement parameters of evacuation flows, which include visually impaired participants: *a* — movement on a horizontal section; *b* — movement down the stairs; *c* — movement up the stairs

The results of mathematical processing of the dependencies obtained in Fig. 3, presented in Table 2.

Table 2

Evacuation parameters at different percentages of visually impaired participants

Percentage of visually impaired participants in the flow	Parameters	Horizontal	Stairs down	Stairs up
2.5 % (total number of agents – 40, visually impaired – 1)	V_0, m/min	99	81	68
	D_0, people/m^2	1	0.82	1.03
	a_j	0.269	0.345	0.389
5 % (total number of agents – 40, visually impaired – 2)	V_0, m/min	93	76	62
	D_0, people/m^2	0.95	0.73	0.94
	a_j	0.246	0.318	0.361
7.5 % (total number of agents – 40, visually impaired – 3)	V_0, m/min	86	69	57
	D_0, people/m^2	0.91	0.68	0.85
	a_j	0.219	0.298	0.331
10 % (total number of agents – 40, visually impaired – 4)	V_0, m/min	82	64	53
	D_0, people/m^2	0.89	0.65	0.78
	a_j	0.205	0.293	0.31

Table 2 shows the ratio of the speed of free movement V_0 to the density of the flow D_0, taking into account the coefficient of the degree of influence of the density of the human flow on its speed.

5. 2. The influence of the share of visually impaired evacuation participants in the flow on the overall evacuation speed

The results of the regression analysis for different percentage ratios of visually impaired evacuation participants in a mixed flow indicate that for the percentage values of visually impaired evacuation participants in ω>0 %, the parameters V_0, D_0, a change according to a dependence close to linear (Fig. 4).

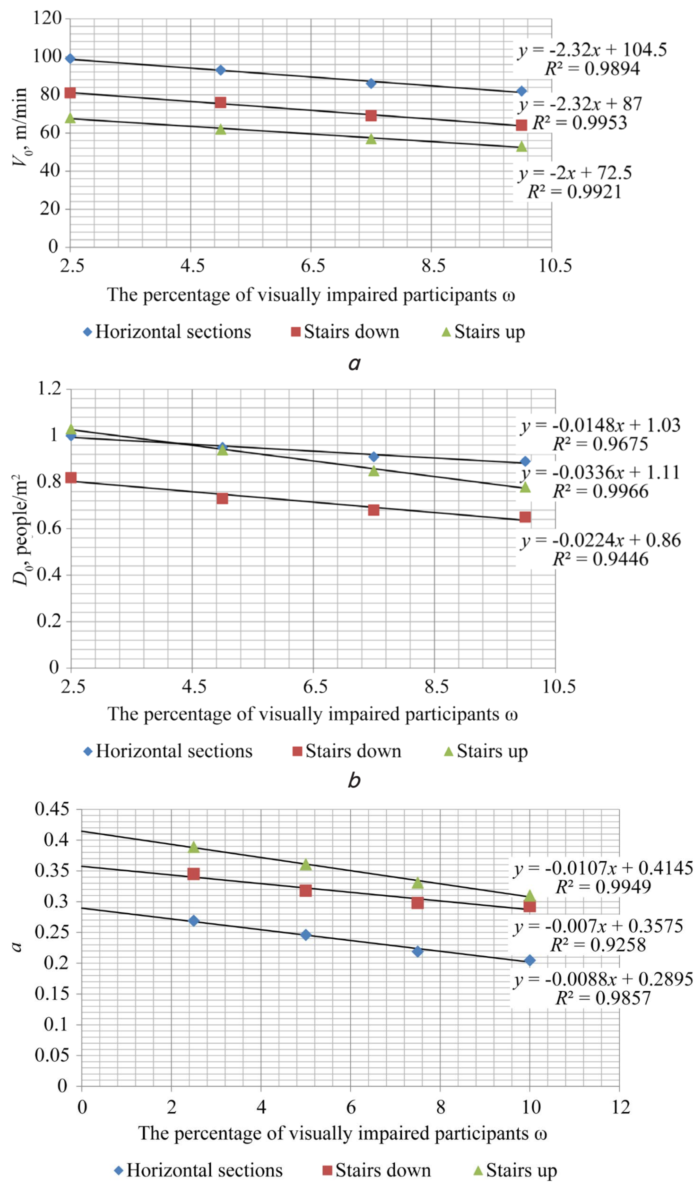


Fig. 4. Dependence of evacuation flow parameters on the percentage of evacuation participants with visual impairments ω: *a* – V_0; *b* – *a*; *c* – D_0

For the points shown in Fig. 4, an approximation was made for the range of values of ω>0 % and the linear dependences presented in (6)–(14) were obtained.

After adding the data for the values of ω=0 %, let's obtain a system of equations:

– for movement on horizontal sections (6)–(8):

$$V_0=-2.32\cdot\omega+104.5 \text{ at } \omega>0, \quad (6)$$

$$D_0=-0.148\cdot\omega+1.03 \text{ at } \omega>0, \quad (7)$$

$$a=-0.0088\cdot\omega+0.2895 \text{ at } \omega>0; \quad (8)$$

– for moving down the stairs (9)–(11):

$$V_0=-2.32\cdot\omega+87 \text{ at } \omega>0, \quad (9)$$

$$D_0=-0.0224\cdot\omega+0.86 \text{ t } \omega>0, \quad (10)$$

$$a=-0.007\cdot\omega+0.3575 \text{ t } \omega>0; \quad (11)$$

– for moving up the stairs (12)–(14):

$$V_0=-2\cdot\omega+72.5 \text{ at } \omega>0, \quad (12)$$

$$D_0=-0.0336\cdot\omega+1.11 \text{ at } \omega>0, \quad (13)$$

$$a=-0.0107\cdot\omega+0.4145 \text{ t } \omega>0, \quad (14)$$

where ω – the percentage of visually impaired evacuation participants in the flow.

5. 3. Computer modeling of evacuation based on the data of field observations in institutions of higher education with inclusive education

Fig. 5, 6 present the results of computer modeling of experimental studies using the Pathfinder software complex. The duration of evacuation was determined for each of the considered scenarios.

Also, the duration of evacuation for similar conditions was calculated according to a simplified analytical model [5], for which changes in parameter values were taken into account according to dependencies (6)–(14). The data obtained from the results of computer simulations, as well as from the calculation results, were compared with the experimentally obtained values of the evacuation duration under various scenarios. The comparison is given in the Table 3.

Table 3 presents the results of computer simulation and field experiment with their difference in percentages.

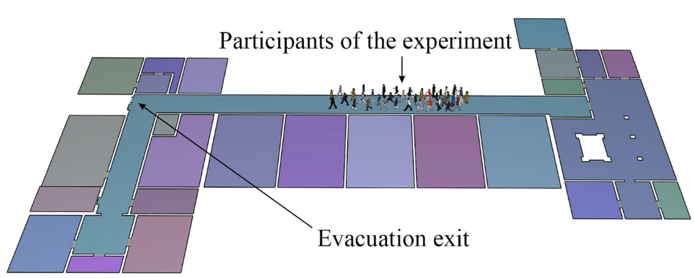
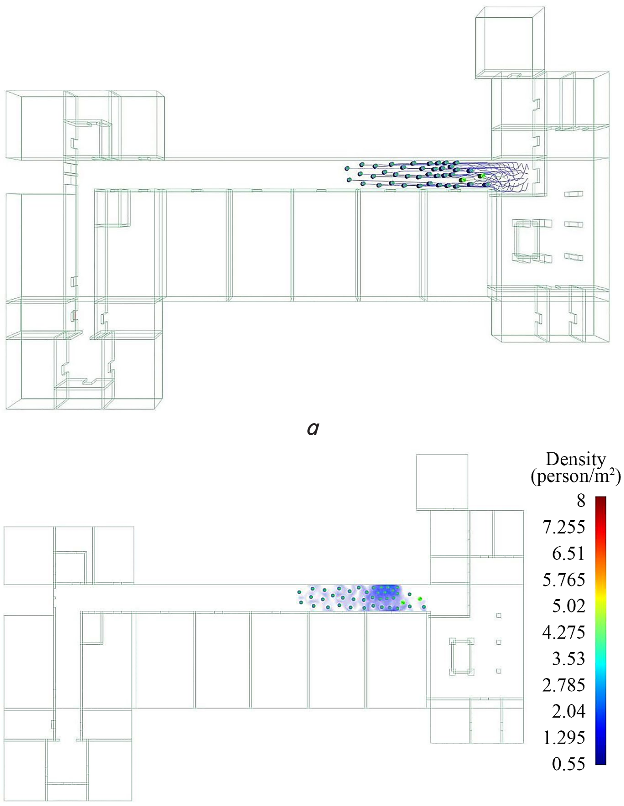


Fig. 5. Model of the experimental section of the evacuation route



a

b

Fig. 6. Visualization of the results of simulation of the flow movement, which includes agents with impaired vision: *a* — following agents; *b* — density of agents

Table 3

Comparison of evacuation duration determined by different methods (in seconds)

ω	Experiment results	Simulation results in Pathfinder	Deviation from the experiment results	Calculation based on dependencies (6)–(14)	Deviation from the experiment results
Movement on horizontal sections					
2.5 %	64	93	45.3 %	71	10.9 %
5 %	69	99	43.5 %	75	8.7 %
7.5 %	73	101	38.4 %	76	4.1 %
10 %	75	104	38.7 %	80	6.7 %
Movement down the stairs					
2.5 %	44	66	50.0 %	52	18.2 %
5 %	44	67	52.3 %	55	25.0 %
7.5 %	46	70	52.2 %	57	23.9 %
10 %	49	72	46.9 %	58	18.4 %
Movement up the stairs					
2.5 %	56	78	39.3 %	59	5.4 %
5 %	59	80	35.6 %	61	3.4 %
7.5 %	60	83	38.3 %	64	6.7 %
10 %	62	84	35.5 %	65	4.8 %

6. Discussion of the results of the study of the influence of participants with visual impairments on the density and speed of the flow

The conducted experiments at different values of ω made it possible to obtain the values of V_0, D_0, a and to establish empirical dependences between each of these parameters on the share of visually impaired participants in the flow.

Disclosure of the influence of factors on the speed of movement of evacuation flows, which include students with visual impairments, becomes possible thanks to the obtained results. They indicate that the speed of movement during evacuation from institutions of higher education with inclusive education significantly affects the duration of the process. This impact depends on the density of the flow and the percentage of participants with special educational needs. In all sections, where the flow density exceeds the critical value D_0, the speed decreases. Until the critical density is reached, the velocity remains constant. This explains the presence of horizontal sections in the graphs in Fig. 3. The results of speed measurements (Fig. 2) and their analysis (Fig. 3) together with the parameters (Table 2) make it possible to determine the influence of the percentage of visually impaired participants on the change in flow speed. Since the dependence of speed on density is mathematically described using equation (1), the main numerical parameters of which are V_0, D_0, a, the dependence of these parameters on the increase in the percentage of participants with visual impairments in the flow ω is established in the work. Dependencies are represented by formulas (6)–(14) for different types of escape routes (horizontal sections and stairs). Evacuation flows in institutions with inclusive education have a peculiarity: participants with visual impairments, guided by a scientific and pedagogical worker or an assistant, move with the general flow, which reduces its speed. According to the results of the work, it was established that with the increase in the percentage of visually impaired participants, these parameters decrease linearly.

The obtained results make it possible to improve the methodology for calculating the duration of evacuation from educational institutions with inclusive education, taking into account the percentage of visually impaired evacuation participants as initial data. Also, the research results can be used to develop architectural solutions aimed at creating safer and more accessible spaces for people with visual impairments. In addition, the results can serve to develop new technological solutions aimed at improving the control and management of evacuation processes, taking into account the needs of this population group. Incorporating these findings into curricula can improve the skills of students and professionals in the field of safety and emergency situations. The research findings will contribute to the social integration of people with visual impairments and to ensure their safety in various public spaces. Taking into account the received data will contribute to increasing the efficiency and safety of evacuation measures for all participants, in particular for people with visual impairments.

Developed models for calculating evacuation (6)–(14) are divided into flow (for homogeneous flows with constant mobility) and individual (with individual motion simulation, often used in computer programs). It is individual models that must be used for flows that include participants with different mobility. Institutions with inclusive education need a unique approach to evacuation: individual models for people with reduced mobility and adaptation of the flow taking into account group evacuation. The results of this work make it possible to formally reduce such a heterogeneous evacuation flow to a homogeneous one with defined parameters. This is confirmed by the results of the calculations given in the Table 3. The use of the proposed model makes it possible to obtain significantly smaller discrepancies with the results obtained in real conditions (for different areas, such discrepancies are 3.4–25 %), in comparison with the use of an individual model (35.5–52.3 %).

The conditions for using the results of this study are that the established empirical dependencies are characteristic exclusively for flows in which the number of visually impaired evacuation participants is in the range from 0 to 10 %.

This study does not take into account the presence of students with musculoskeletal disorders. Therefore, the object of further research will be to determine similar parameters for evacuation flows, which include not only students with visual impairments, but also persons with musculoskeletal disorders.

This requires the use of auxiliary supports or wheelchairs. The study of such flows is the object of further investigations, which requires the involvement of a larger number of persons and measurements in the experiments. This will make it possible to expand empirical databases on the movement parameters of mixed evacuation flows of people of different mobility groups. This will contribute to the improvement of the method of calculating the duration of the evacuation of flows taking into account people with reduced mobility of different groups and to the improvement of the existing planning and management procedures in evacuation scenarios.

However, research and implementation of the results of parameters of evacuation flows, which include students with musculoskeletal disorders, may face a number of difficulties. One of these challenges is the limited availability of data needed for analysis due to the difficulties in gathering information about the movement and behavior of this audience during evacuation. In addition, it is important to consider the representativeness of the sample of persons with musculoskeletal disorders and to conduct the study in accordance with ethical standards, as this may be the subject of special attention due to the sensitivity of the topic. Additional challenges include technical limitations associated with measurements and observations, as well as interpretation of results, which requires attention to differences in behavior and needs of individuals with different musculoskeletal disorders. Taking into account these difficulties in the planning and implementation of the study will help to ensure the accuracy and significance of the obtained results.

The research results can be used in calculations of the duration of evacuation from the buildings of educational institutions with inclusive education for groups that include participants with visual impairments.

7. Conclusions

1. A full-scale experiment was conducted with participants imitating the behavior of visually impaired people while receiving assistance. 241 speed measurements were made on horizontal sections, 204 – during moving down the stairs and 206 – during moving up the stairs. The obtained results made it possible to carry out a regression analysis and establish the main parameters: the initial speed V_0, the critical value of the density D_0, and the coefficient a for flows with a different proportion of visually impaired evacuation participants ω (the proportions were 0, 2.5 %, 5 %, 7, 5 % and 10 %).

2. The values of V_0, D_0, a, obtained at different values of ω, made it possible to establish the empirical dependence of each of these parameters on the share of visually impaired participants in the flow. This result is of applied importance, as it allows to obtain more accurate results of calculating the duration of evacuation from the buildings of educational institutions with inclusive education for flows, which include students with visual impairments. For each specific case, it is necessary to calculate the value of ω and set the corresponding values of V_0, D_0, a, which are then substituted into the averaged equation of the value of the flow density, which describes the dependence of the speed of the human flow on its density.

3. The effectiveness of the proposed solution was verified by computer simulation using the dependencies obtained in the work, which describe the dependence of the speed of the human flow and its density on the increase in the percentage of visually impaired traffic participants in the flow. The use of these dependencies made it possible to obtain results with smaller deviations (3.4–25 %) compared to the individual model (35.5–52.3 %).

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship, or any other nature that could affect the research and its results presented in this article.

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Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence tools

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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