Ergonomic Aspects of the Architectural Designing of the Stairs in the Spaces for the Great Public Gathering

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Abstract. Spaces designed for large public gatherings, arranged both inside buildings and outside them, need to take into account a number of specific conditions. Among them the most important are design issues related to stairs. In this case, the main problems arise from the need to ensure a smooth and safe movement of the human masses, while fulfilling the relevant conditions of mental and physical comfort for each of the individuals, which are part of the moving crowd. In this context, the most critical design issues relate to the evacuation, taking into account the specific behaviours during the panic, especially when the crowd moves down the stairs from the upper to the lower floors. The article presents considerations, research results and conclusions of the author, based on his own experience of many years of architectural practice in the design of stadiums.

Keywords: Ergonomic · Stairs · Architecture · Designing · Crowd movement

1 Introduction

Contemporary realities of urban development, responsible for organizing the functioning of huge human clusters, require the use of solutions enabling for spatial displacement of their inhabitants. The most difficult are the displacement resulting from the need to change the utility levels - so called vertical communication. Used since time immemorial stairs and ramps, serving this purpose, have been supplemented in our times by a new inventions, such as escalators, moving ramps and elevators. To the issues that require special attention in this regard are the problems associated with the movement of crowd - movement of the large, dense masses of people. A special consideration requires the behavior of the crowd during the evacuation in a state of panic. In this case, provided mechanically vertical transport means are useless. Their performance reliability and safety are much inadequate. The only solution to these problems can be properly designed escape routes, taking into account the specificity of the crowd movement and behavior (Fig. 1). The phenomena of this kind are encountered in modern cities, and are connected, inter alia, to the functioning of large stadiums. In the design of modern stadiums, there are two trends in solving the problem of

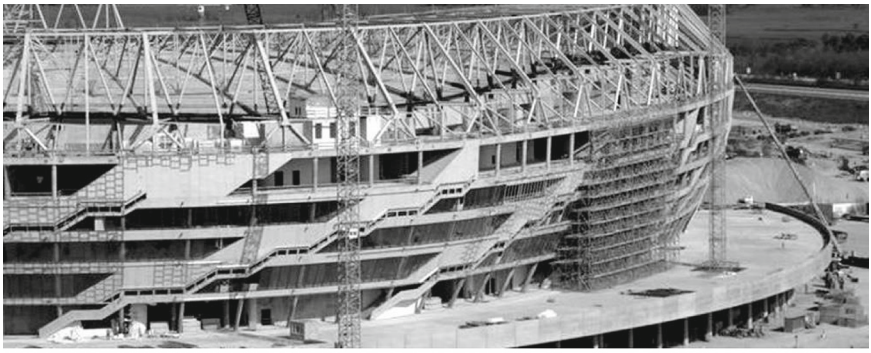
M. Antona and C. Stephanidis (Eds.): UAHCI 2015, Part IV, LNCS 9178, pp. 468–479, 2015.
DOI: 10.1007/978-3-319-20687-5_45

Fig. 1. Slaski Stadium in Chorzow, Poland. Dangerous situation when leaving the arena by thousands of fans after the rock concert. Excessive density of the crowd caused complete blockade of the movement inside 60 m long and 12 m wide output tunnel. As seen in the photo, the stands are empty at this time, thanks to an efficient circulation. (Photo: author).

collective escape routes from the interior of the stadium to the grounds surrounding it. One of them uses the stairs, the other relies on a ramps with a gentle slopes. Based on own practical experience in the design of the stadiums and own research methods author has conducted an analysis of the advantages and disadvantages of both solutions. In the presented paper particular attention is focused on the study of the legitimacy of the stairs application for the purpose of organizing the main channels of escape, especially in terms of ergonomics and safety issues.

2 Definition of the Research Problem

The subject of detailed research undertaken by the author are the main escape routes leading from the interior of the stadium to the external safety zones. Analyses of the large stadiums, implemented in recent years, show that the mentioned above escape routes are solved in two ways. One of them involves the use of different arrangements of stairs, the second based on the use of several varieties of ramps (Fig. 2). In both cases, the design task is to bring down thousands of spectators from the zones situated at high floors on the level of external terrain. It follows that research mainly should concern the movements of the crowd down the stairs or down the ramp. In order to clearly highlight the rank of problem to analyze have been selected the extreme cases. To such include, in author's opinion, the solutions adopted, inter alia at Allianz Arena stadium in Munich (Fig. 2A), and also at the Stade de France in Paris (Fig. 2B). Their length results from the fact that they run continuously down to the ground level from the stadium concourses situated at altitudes exceeding 30 m. In fact, they form a kind of



A).

B).

C).

Fig. 2. The examples of two different solutions of the major evacuation routes present in modern stadiums: - (A). *Allianz Arena* in Munich, (B). *Stade de France* in Paris (C). *The Stadio Giuseppe Meazza*, commonly known as *San Siro* in Milan (Sources: A.- http://www.silesiabl.pl/contents/02/img/027.jpg; B.- http://media.livenationinternational.com/lincsmedia/Media/x/g/s/0994544b-baa1-4c51-a3e8-8e7120d2314b.jpg; C.- http://www.came.com/fr/sites/default/files/1-san-siro.jpg ; admittance 2015-02-15).

linear staircase tunnels with a one-way up to down movement, inclined at an angle of approx. 30°. In extreme situations, during the hurried evacuation and panic, described inclined stair tunnel can be completely filled by moving down compact crowd. The possibility of occurrence of such a dangerous phenomenon has been the main motivation to undertake the research presented in the following parts of this paper.

3 Characteristics of Normal Movement Down the Stairs

The ability to move on the stairs is the result of biomechanical characteristic of human locomotive apparatus. The stairs have accompanied mankind since the dawn of history. However pioneering research on the geometry of comfortable stairs took place in the mid-17th century, and are attributed to Francois Blondel, the director of the Royal Academy of Architecture in Paris. Around the year 1672 Blondel had defined the algorithm, used to this day, enabling to set proper ergonomic relationship between height of rise and depth of tread, as depending on length of the human step. He discovered namely, that a comfortable stairway require to fulfil the condition according to

Fig. 3. Sensory role of the foot while walking up and down the stairs - overhanging heel or nose of the foot over the below tread of stairs enables to locate position edge of the step. (Photo: M. Pelczarski).

which: two risers + tread = step length. This principle results from the kinetic characteristic of the human body and as such is correct. The problem is, however, that for practical reasons the design of stairs is based on the average step length. Such stairs serve well only to part of the population.

Human gait, from the viewpoint of biomechanics is a spatial and cyclic mobility act, consisting in instantaneous change in center of gravity of the torso beyond the plane of the support leg, and then recovering the balance of the simultaneous implementation of the sliding movements on the ground. The above definition is correct also for a gait up the stairs. From the point of view of this research, the very essential fact is that while walking down the stairs each step has a long sequence of movement when the human body carries its weight on one leg only. This is the moment in which even a small impact of external horizontal force can lead to loss of body balance, and consequently to fall.

Long-term observations, conducted by the author and documented photographically shows, that the majority of people moving up the stairs behaves as shown on Fig. 3. It turns out that almost all people use just part of the foot while walking up or down the stairs. The sole of the shoe contacts the tread through some 75 % of its surface. Usually, while walking up the stairs the heels protrude outside the nose of tread, partially or completely. While moving down, the nose of the shoe extends beyond the edge of the stair tread.

On Figs. 4 and 5 have been presented comparative analysis of the human steps on a horizontal plane and on the stairs. The purpose of these studies is the definition of the differences in the two types of movement. It should be noted, when considering normal human step, the movement of the free of load leg in space, detached from the ground, from the rear to the front position is as long as about 4 treads of the stairs. The same kind of movement of the unloaded leg, while descending down the stairs reaches horizontal displacement distance equal to 3 treads of stairs. In the same time this leg lowers its location in space by 2 risers. On the stairs the muscles of both legs perform much more work than while walking on a flat surface. Especially the leg carrying the weight of whole body is very loaded. In sum it should be noted, that comparing to normal walking, descent down the stairs is for human much more complicated task

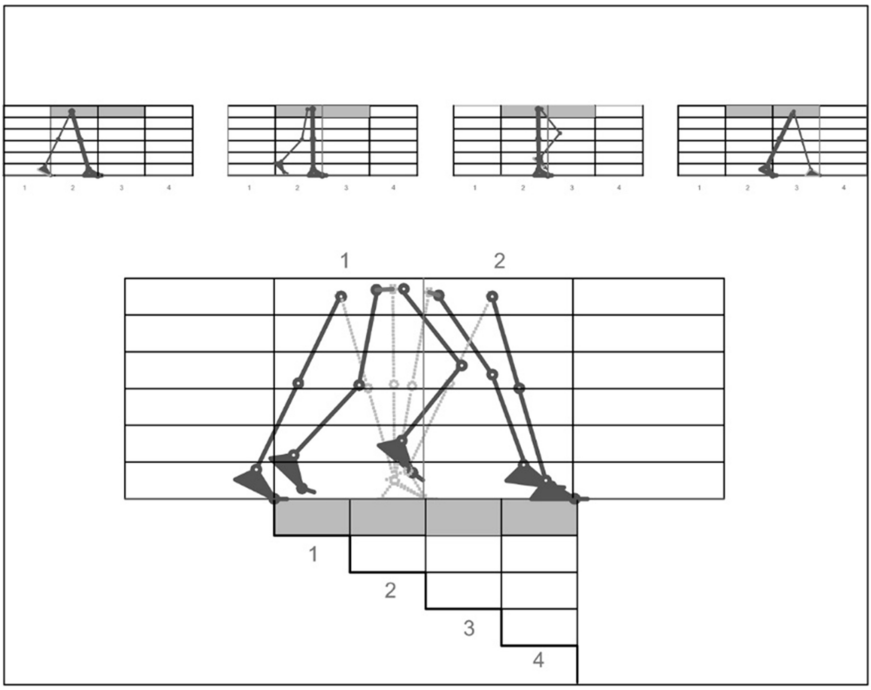


Fig. 4. The repeatable sequence of movement of both legs while walking on a horizontal surface (Source: author).

physically - very aggravating musculoskeletal system and carrying a significant risk of falling and getting hurt. Main safety limits of movement down the stairs arise due to the inability for support by the second leg on the middle level, when this leg is just above the third tread, in the last phase of its movement. This phenomenon is due to the fact that walking on the stairs is an automatic process that uses human psychomotor skills. The appropriate, subconscious placing the foot activate the sense of touch, allowing to locate the edge of the tread. It is well known that the easiest way to determine if the stairs were designed properly is to walk on them with closed eyes. Described above issues play an important role in the movement of large masses of people on the stairs. Moving in the crowd completely eliminates the possibility to control shape of the ground by the help of the sense of sight.

4 Issues of the Crowd Movement Down the Stairs

Crowd behaviors are not yet fully recognized and as such are still the subject of research undertaken by specialists in many fields. The greatest achievements in this area have been reached by psychologists, particularly with regard to an extensive knowledge on the psychology of the crowd. Rapidly develop new fields of science related to the management of the crowd. Among them there is also urban planning and

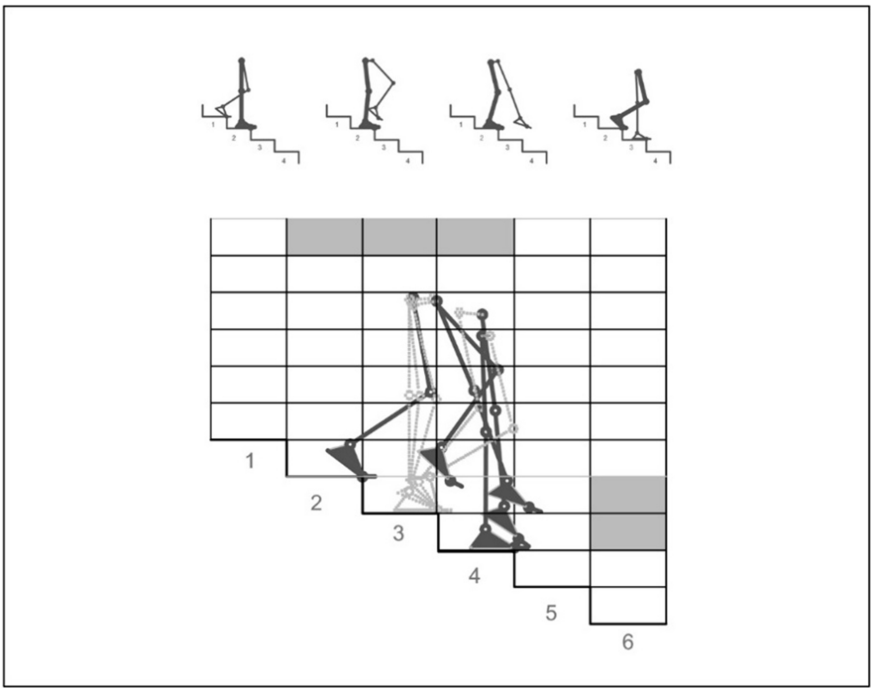


Fig. 5. The repeatable sequence of movement of both legs while normal walking down the stairs (Source: author).

the architecture Author's professional experience, related to the stadiums designing, indicates, that architects, undertaking such a tasks, ought to have deep knowledge concerning the mobility of crowd - particularly its spatial, dynamic, kinetic and bio-mechanic characteristics.

The scope of the analysis is limited to one exemplary case which is the most characteristic for defined earlier research problem. The object of the analysis is theoretical system of the main evacuation channels, modeled on the solution applied to the Allianz Arena in Munich. The system consist of the set of linear, long staircases with an one-way up to down movement, running continuously down to the ground level from the highest concourses, inclined at an angle of approx. 30°. It was assumed, for the purposes of analysis, the extreme situations, during the evacuation and panic. In such conditions, described above inclined stair tunnel could be completely filled by moving down compact crowd.

The configuration of the folded, falling down surface which is created by the treads arrangement determines dramatically location of individual persons creating the dense crowd (Fig. 6). Depth of stair tread is similar to a foot of the person standing on it. So, at every one tread can only stand as many people as number of lanes at the stair run. Some extreme cases, can lead to even greater density. This can occur when individual

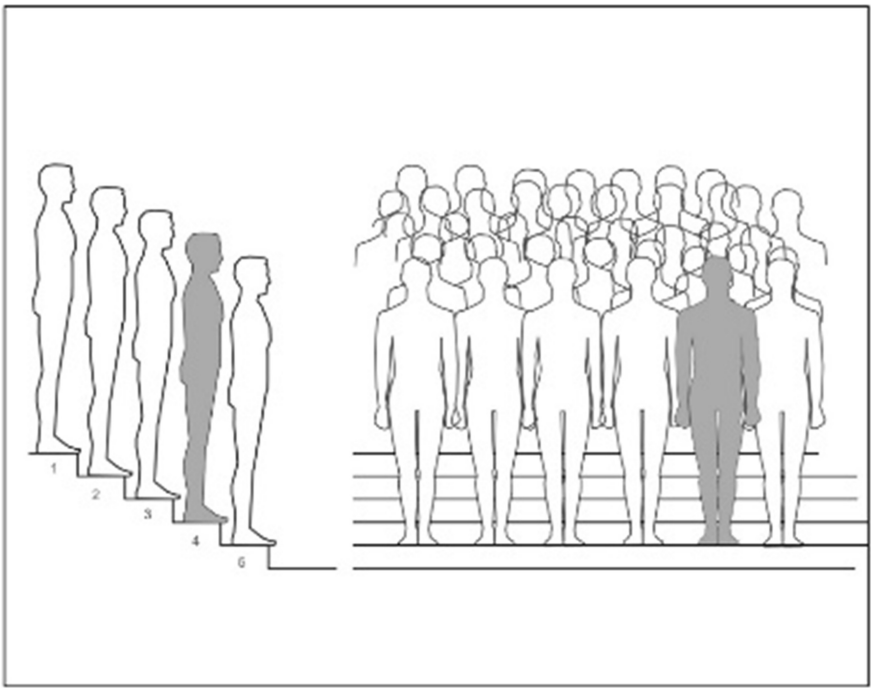


Fig. 6. The crowd of extremal density on the stairs - the downward movement (Source: author)

person adopt a lateral position relative to the axis of the run of stairs. In this case crowd density will double. Considering the general conditions of the human mass movement down the stairs it should be noted, firstly, that this movement will only be possible when individual pedestrians will have guaranteed free space in front of them (Fig. 7).

Smooth movement of many people down the stairs in one lane requires that the distance between them, measured by number of free treads between the treads carrying the body weight was equal to at least 2 (Fig. 8). When the interval described above is only one step of the stairs smooth descend of many people on one lane is possible provided however that all of these people will be traversed synchronously. Disruption of this synchronization will cause a lack of free space on the tread in front of a person coming down the stairs and, consequently, a collision in the form of stepping on the heel of predecessor. It can also leads to disruption of the body balance of one or both person, threatening collapse. The described collision will stop one of the links of the chain. The consequence of this stopping will be the occurrence of a domino effect in the upper part of this lane. It will cover all the above part of the lane, where will occur the disappearance of free treads what is equivalent to the stop of chain movement.

The deficit of free space for normal movement will initiate the next phase of this very dangerous process. The compacted mass of human bodies will act like volcanic lava or other fluid matter on the hillside. Acting down, parallel to the slope of stairs

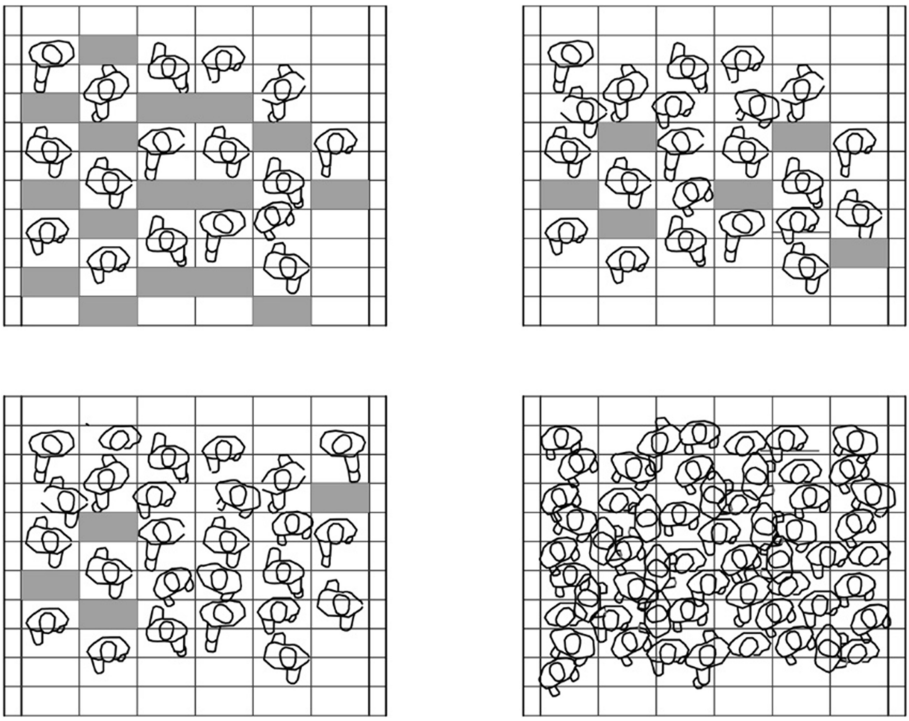


Fig. 7. The impact of the degree of compaction of the crowd on ease of the movement while descending the stairs (Source: author).

vector of force, derived from gravity will result in the flow of the crowd mass, leading to its further compaction with increasing internal destructive pressure. The history of disasters involving crowd proves that the described above situations often cause casualties, including death and serious injuries.

Figure 9 shows the analysis of the movement sequences while walking down the stairs in the conditions arising in the crowd. As has been previously demonstrated the lack of free tread in front of a person moving down the stairs causes stopping. Such an individual, standing on two legs, waits for a moment when the tread below will be released. Only then will be possible any movement in space, by lowering and horizontal shifting the position, equal to one rise and one tread of the stairs. The diagram shows that this locomotion activity requires the free space of motion greater than provided by the two treads. Lack of space hinders the proper body movements. It is rather a kind of sliding down the stairs than walking.

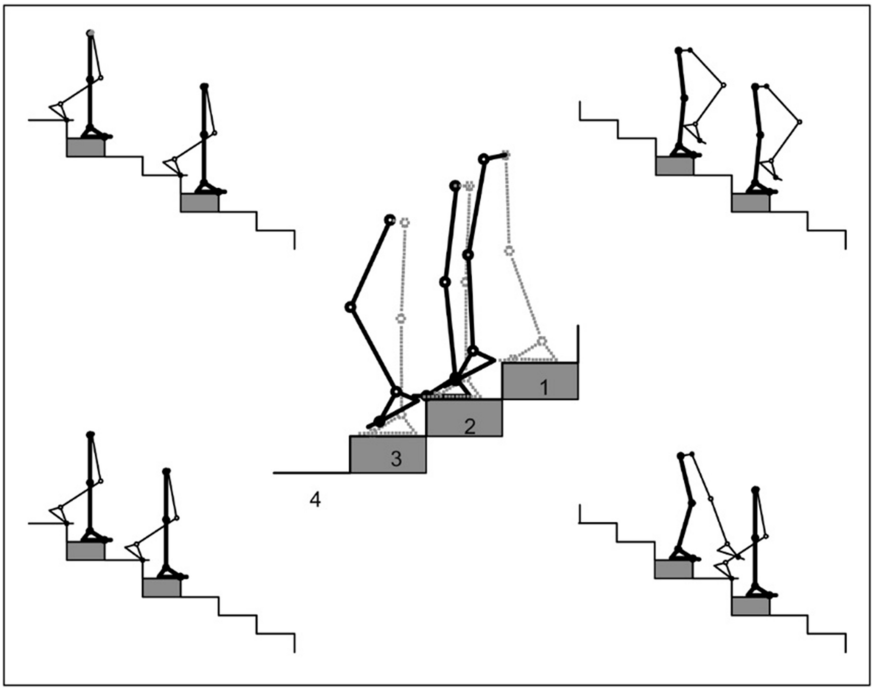


Fig. 8. The determinants of walking down the stairs many people in one lane of movement (Source: author).

5 The Use of Ramps for Escape Routes

As previously been found, an alternative way of providing to the masses of viewers an evacuation routs from the interior of the stadium leading to the external safe space could be based on the use of several varieties of ramps. One of the examples illustrating this is the system of escape routes serving the eastern stands at the *Silesian Stadium* in Chorzow (Fig. 10). Two pairs of wide ramps, North and South, in a much shorter time than 5 min, are able to lead all viewers from this part of stadium directly to the main exit gates [1]. Extremely interesting example, with regard of a sophisticated idea and the date of construction (1925) is the stadium designed as only of the for football, in the district of Milan, named San Siro (Figs. 2C, 11). Equally interesting are the effects of further renovations (1990) in the form of an extra tier being added to three sides of the

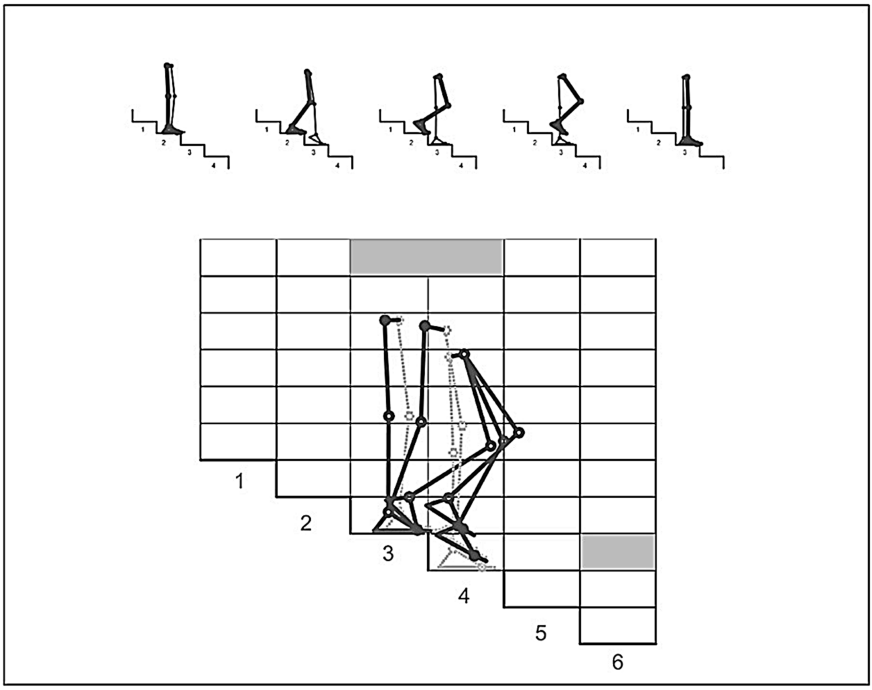


Fig. 9. The sequence of movement of both legs when moving by only one step of stairs down (Source: author).

pitch. This required the building of 11 concrete towers around the outside of the stadium, Four of them support a new roof. Around each of these columns wrap the spiral ramps, ensuring the evacuation of spectators from the highest parts of the stadium. In the United States and Australia have been built number of stadiums using the systems of ramps for the purpose of organizing the main roads of evacuation.

The most representative of these include among others: Melbourne Cricket Ground, Australia Stadium 2000 in Sydney, The Arrowhead and Royals Stadium at Kansas City, as well as Joe Robbie Stadium in Miami [2].

Fig. 10. Located in a 600 ha urban park, Silesian Stadium in Chorzow, Upper Silesia, Poland (the state after redevelopment 1994–2007). Two pairs of wide ramps, North and South, in time shorter than 5 min, are able to evacuate all viewers from this part of stadium directly to the main exit gates. (Source: Archives of WOSiR, photo - P. Oles).

6 Conclusions

Both the author's practical experience and research on architectural models of the main evacuation channels or, in other words, the main escape routes, leading from the interior of the stadium to the external safety zones show that solutions based on the use of stairs have a number of disadvantages.[1] These drawbacks do not occur in case of application for these purposes the solutions in the form of ramps, arranged in many ways. This general conclusion follows, in particular, the factors related to the efficiency and safety of spectators during extreme conditions of evacuation which accompany the movement of the crowd under the influence of panic. The most important of these are kinetic - motoric difficulties of a compact human masses in a movement down the stepped surface. Equally important problems are due to the relatively big steepness of the stair run. Declination of approximately 30° causes a formation of a downward force, acting in parallel to the run, being result of the gravity. This force depending on the mass of the crowd can reach very large, indeed destructive, values. It can lead to very dangerous situations that threaten the health and the lives of people. In this context, reported in the literature on the subject the advantages of the solutions of applying stairs, such as the construction economy, saving of the space and greater

[1] In the years 1994–2007 the author was the chief architect of the reconstruction of the *Silesian Stadium* in Chorzow, Poland.

Fig. 11. Efficient and spectacular spiral and peripheral ramps serving the circulation and evacuation movement at the *San Siro* stadium in Milan. (Photo: Timothee Nalet, http://www.timotheenalet.com/urban/milan-san-siro, admit. 2015-02-15).

speed of evacuation, should be taken with great care and restrain [3–6]. The safety and comfort of the users must be the primary criterion for choosing the solution. Both of these conditions are met completely only by the use of ramp systems of evacuation. Furthermore, an additional advantage of these structures is the attractiveness of their spatial forms, enriching the architectural values of the whole stadium.

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