A STUDY ON SAFE EVACUATION FROM INUNDATED UNDERGROUND MALL BY A MULTI-AGENT MODEL

YUTARO NAKASAKA
Graduate school student of Science and Engineering, Kansai University, 3-3-35 Yamate-cho, Suita-shi, Osaka, 564-8680, Japan, k192114@kansai-u.ac.jp

TAISUKE ISHIGAKI
Faculty of Environmental and Urban Engineering, Kansai University, 3-3-35 Yamate-cho, Suita-shi, Osaka, 564-8680, Japan, ishigaki@kansai-u.ac.jp

RYUJI KAWANAKA
Hydro Technology Institute Co.,Ltd., 3-3-23 Nakanoshima, Osaka-shi, Osaka, 530-6126, Japan, kawanakarj@hydrosoken.co.jp

ABSTRACT

In recent years, underground spaces have been used to make effective use of limited land in large cities. In particular, the convenience and comfort of living have been improved by using a large under-ground space where subways and underground malls have been connected each other. On the other hand, it is dangerous to stay there when a disaster occurs, and to do safe and quick evacuations is an important measure for disaster prevention. For example, in recent years, the number of heavy rainfalls has increased due to climate change, and in urban underground spaces, such as underground mall, subway stations and basements, are prone to inundations caused by pluvial and fluvial flood. The safe evacuation plan from the underground space is necessary to make in order to minimize flood damage. However, it is difficult to examine the evacuation behavior of people in a large enclosed space by experiments such as evacuation drills because of the huge cost. In this study, a multi-agent model was used to simulate the evacuation behavior of users in the underground space before an inundation occurs, and the evacuation time was figured out. Moreover, the critical lines of safe evacuation time are created by using the inundation data in the underground space when flooding occurs. This study also compared how long the evacuation time and the critical lines of safe evacuation time and found the factor to improve the success rate of evacuation. The results would be useful to make an evacuation plan.

Keywords: underground space, evacuation, inundation, pluvial flood, multi-agent model

1. INTRODUCTION

In Japan, underground spaces have been developed and used to make effective use of limited land. Especially, in urban areas, a large-scale pedestrian space network connecting buildings and stations has been constructed. But, in recent years, due to climate change, the number of heavy rainfalls has increased. Therefore, in urban areas underground spaces, such as underground mall, subway stations, are prone to inundations caused by pluvial flood. The underground space is closed and has a complicated structure, so it is difficult for users to obtain information from the outside and to grasp the current position. Therefore, it is very important to perform quick and safe evacuation in the event of a disaster. In this study, it is investigated how to improve the evacuation success rate in a city area, assuming the possibility of underground flooding caused by inland water flooding caused by short-term torrential rainfall that may occur in the future because of climate change. In this study, two study data were used to consider the success of evacuation of people in the underground mall when pluvial flooding occurred. Firstly, using the inundation analysis data of the underground shopping mall by inland flood simulation, the time from the start of rainfall until all the people could safely evacuate was calculated. Secondly, the time from the start of evacuation to the completion of evacuation was obtained by evacuation behavior simulation using a multi-agent model. By comparing these data, this study showed what improved the evacuation success rate in the event of pluvial flooding, considering the effects of climate change.

2. STUDY AREA

The study area has a large-scale underground mall in the Umeda area in Osaka, Japan. Figure 1 shows the location of Umeda. This area is very vulnerable to water disasters because of its low ground level and rivers and seas on all sides. In particular, if local torrential rain frequently occurs due to the effects of climate change, there is a risk of pluvial flooding. Figure 2 shows the mesh data and analysis range of the underground shopping mall. This mesh data was created in the past inundation research (Morikane et al., 2012; Hamaguchi et al., 2016). The size of the mesh is a 2m square grid. The objective of inundation analysis is a department store building that is connected to the passage section of a large-scale underground shopping mall, subway, ticket gate, store, and partly. In addition, evacuation behavior analysis was performed only for passages in large underground shopping malls.

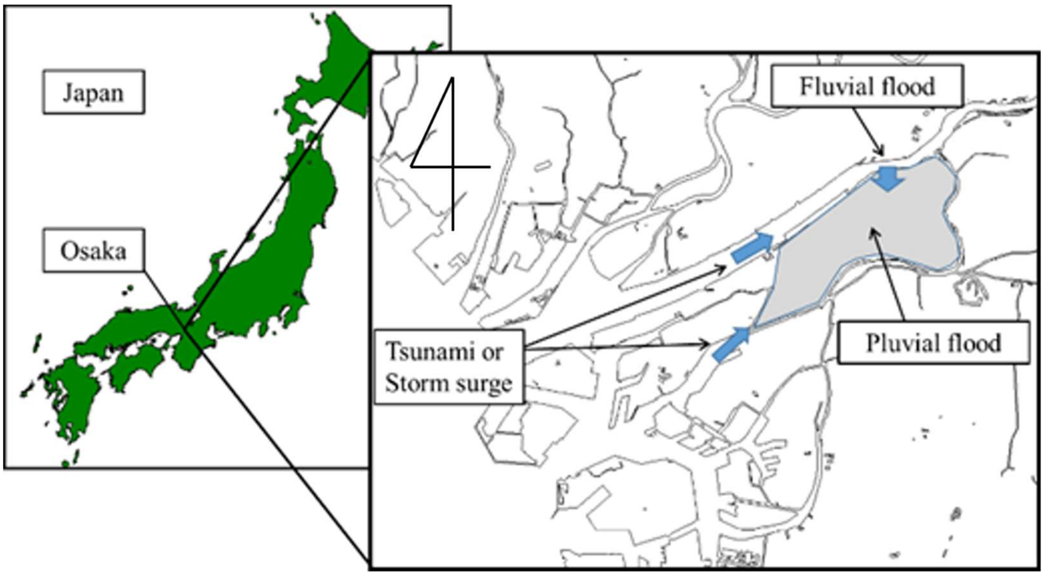

Figure 1. Umeda area, Osaka, Japan

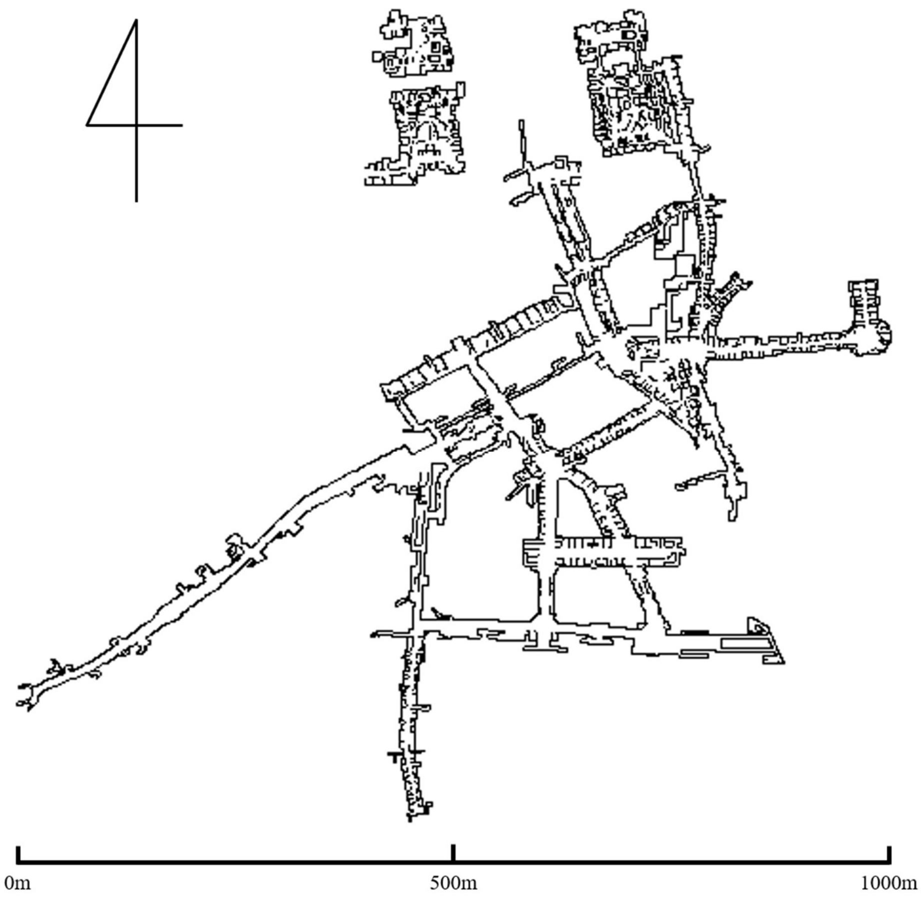

Figure 2. Study site (Umeda underground mall)

3. METHODOLOGY

3.1 Underground space inundation caused by extreme rainfalls

3.1.1 Analysis method and conditions

The analysis of inundation in the entire underground mall can be performed by creating rainfall data, simulating inland inundation on the ground surface, and calculating the inflow discharge to the underground mall. In this study, we use the numerical method and conditions in past studies (Morikane et al., 2011; Ishigaki et al., 2016). The inundation calculation was performed using InfoWorks CS, a software developed by Wallingford Software that can analyze ground inundation considering the sewer road network. The rainfall data are those created using three rainfalls of 60mm/hr, 120mm/hr and 180mm/hr. The rainfall of 120 mm/hr and 180mm/hr are twice and three times as large as the reference rainfall of 60 mm/hr, the design rainfall in Osaka City (Kho et al., 2018). Figure 3 shows hyetographs of these rainfalls. These data are centralized with a time interval of 5 minutes and a rainfall duration of 2 hours.

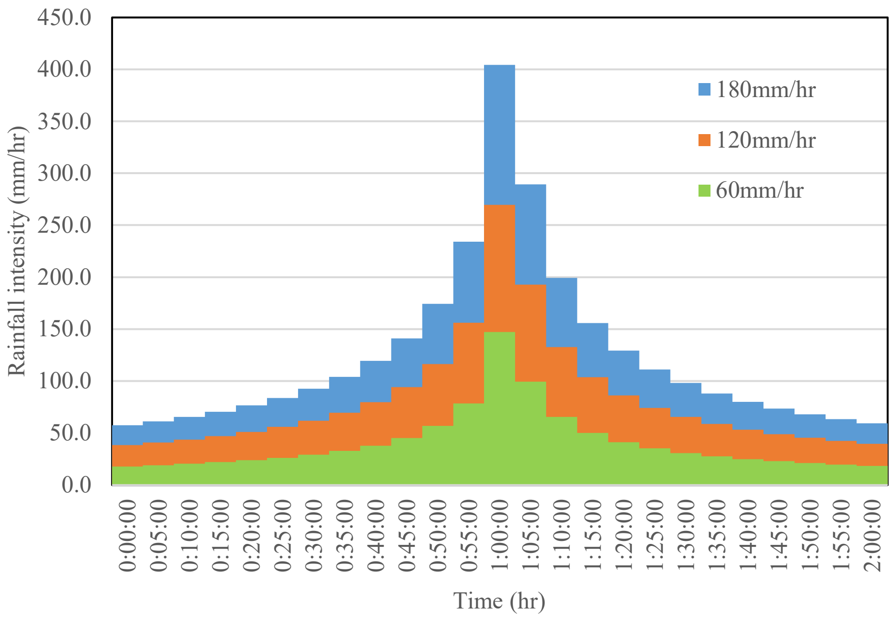

Figure 3. Rainfall hyetograph (three types) (Kho et al., 2018)

3.1.2 Safe evacuation criteria

In the underground space, the velocity is high at the stairs and the water depth is high at the passages. Therefore, the unit width specific force that can be considered by the flow velocity and water depth has been studied (Onishi et al., 2008; Asai et al., 2009). This is an index that can appropriately evaluate the degree of evacuation difficulty considering the effect of fluid force and hydrostatic pressure. Therefore, in this study, we used the specific force per unit width M_o to judge whether each grid in the underground shopping mall was able to evacuate. The formula for calculating the unit width specific force is shown in Eq. (1). Table 1 shows the evacuation difficulty criteria for the age group and gender using the unit width specific force.

$$M_0 = \frac{u^2 h}{g} + \frac{h^2}{2} \tag{1}$$

where, M_0 is the specific force per unit width (m^3/m), u is the flow velocity (m/s), h is the water depth (m), and g is the gravity acceleration (m/s^2).

Table 1. Criteria of safe evacuation presented by the specific force per unit width, M_0 (m^3/m) (Asai et al., 2009)

	Limit of safe evacuation	Difficult without any help
Male	0.125	0.250
Elderly male	0.100	0.200
Female	0.100	0.200
Elderly female	0.080	0.160

3.1.3 Evaluation of the degree of safety evacuation of the underground mall

From the inundation results, the safe evacuation time starting from the start of rainfall is calculated. The safe evacuation completion time is obtained by using a criteria based on the specific force per unit width for elderly female whose evacuation is difficult at the earliest time. Figure 4 shows the change over time in the proportion of the area that can be evacuated. In this study, the safety evacuation time is the time when the ratio of the safe evacuation area falls below 100%.

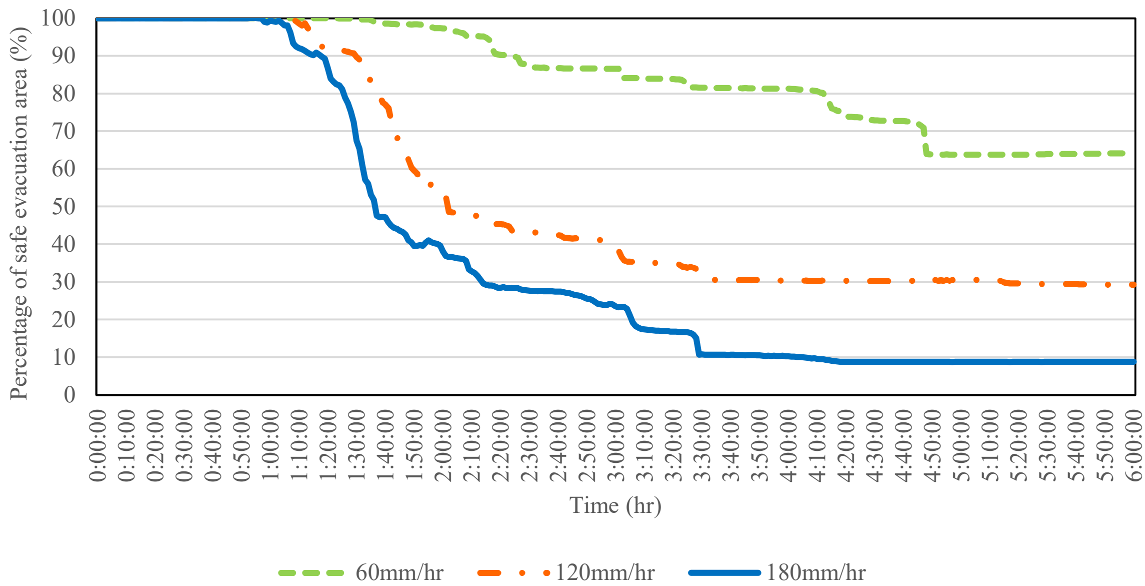

Figure 4. The time variation of safe evacuation area (elderly female)

3.2 Evacuation behavior simulation by a multi-agent model

3.2.1 The explanation of a multi-agent simulation

The multi-agent model is a model that can analyze human autonomous decision-making and crowd behavior by placing people in a virtual space, giving each one its own rules, and considering interactions. In this study, we use a multi-agent simulation platform “artisoc 4.2” developed by Kozo Keikaku Engineering Inc., to build a simulation model.

3.2.2 Walking network model

A walking network model was built on map data. The map data used was the same as that used in the inundation analysis. It is a space consisting of 1060m by 1020m, laid out by 2m square mesh. A network model is a model that is represented by a polygonal line (link) and an intersection (node). This model does not need to consider the two-dimensional position of the agent, so the computational load is light, and it is suitable when many agents move in a large space.

3.2.3 The basic data of agents (evacuees)

Table 2 shows the settings of the agents (evacuees). Age and gender ratios were set from the Ministry of Internal Affairs and Communications' 2018 population estimation data, and walking speed was set from past experimental results (Asai et al., 2009). In addition, in order to take individual differences in walking speed into account, random numbers that follow a normal distribution with an average value of 0 and a standard deviation of 0.1 are made and included in the walking speed.

Table 2. Agents’ data (Ministry of Internal Affairs and Communications, 2018; Asai et al., 2009)

	Percentage	Speed (m/s)	Notes
Male	30.2%	$1.40 + \sigma$	
Elderly male	29.5%	$1.30 + \sigma$	
Female	12.2%	$1.10 + \sigma$	
Elderly female	15.9%	$0.80 + \sigma$	
Young	12.2%	$0.80 + \sigma$	Considering as elderly female

where, σ is the random numbers that follow a normal distribution with an average value of 0 and a standard deviation of 0.1

3.2.4 Decreasing waking speed due to crowd density

The walking speed of agents decrease when there is a crowd ahead or when they are climbing the stairs. On the stairs, the walking speed is half of normal speed (Ishigaki et al, 2006). The crowd density was calculated by dividing the number of agents inside by the area multiplied by the distance in front of agents and the width of the link with agents. Eq. (2) shows the formula for calculating the crowd density. The walking speed was set so that the walking speed decreased from one or more people per square meter to a very low walking speed when the density became four or more (Architectural Institute of Japan, 2003). Eq. (3) shows the formula for calculating the walking speed when a crowd occurs.

$$\rho = \frac{n}{WL} \tag{2}$$

where, ρ is the crowd density, n is the number of agents, W is the width of the link with agents, and L is the distance in front of agents (in this study, 2.0m).

$$V = min\left(V_0, V_0\left(\frac{4-\rho}{3}\right)\right), \rho < 4$$
$$V = \varepsilon, \rho \geq 4 \tag{3}$$

where, V is the walking speed when congestion occurs, V_0 is the free walking speed, and ε is very low walking speed (in this study, 0.01m/s).

3.2.5 How to search the route to exits

The agents randomly select a node and moves on the network, except for specific conditions. When agents reach a dead end, they turn back to the previous node. Using the node adjacent to the staircase node as a guide point, the agents aim at that node. If the stairs are at a node adjacent to the agent, the agents aim at the stairs. If the exit is on a node adjacent to the agent, the agents aim at the exit. When moving in an underground passage, the agent that reaches the intersection selects the link that has the largest number of agents going forward as the next route. However, if the number of agents coming to this side is greater than the number of agents moving forward, it will stop for 1 step.

3.2.6 Analysis method

Figure 6 shows a flowchart of evacuation behavior. Time step is 1 second. In this study, evacuation behavior was simulated with six patterns of 10,000, 12000, 14000, 16000, 18000, and 20000 visitors. The simulation was performed 10 times for each pattern. It was assumed that the rain start time was the evacuation start time, and in this simulation the time which everyone took to evacuate was measured. After that, the average evacuation time for each pattern were calculated.

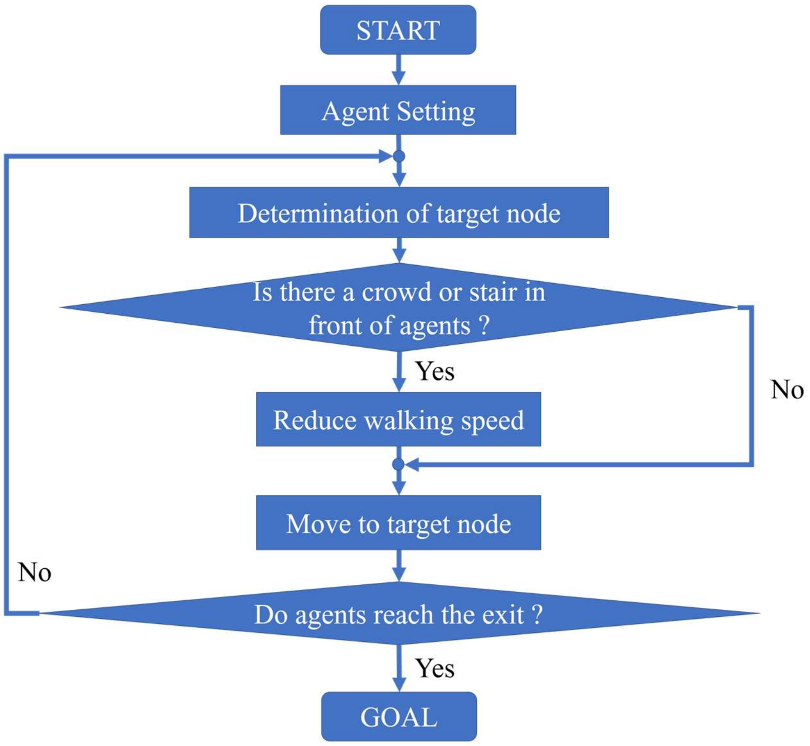

Figure 6. The flowchart of the evacuation behavior

4. RESULTS AND DISCUSSION

4.1 The results of multi-agent simulation

Figure 7 shows an example of the multi-agent simulation. The colors are divided according to the crowd density of 4 or less. From this figure, congestion is occurring at the exit and in the vicinity because the following behavior is considered for all the members. Figure 8 shows the results of the evacuation behavior simulation. The evacuation completion time increases as the number increases from 10,000 to 20,000. In this study, it was considered that the evacuation time increased because people settled at a specific exit because the following action was set in order to consider the synchronicity at the time of disaster. It would be possible to shorten the evacuation time if it could be set so that the route could be changed in the event of a guide or congestion.

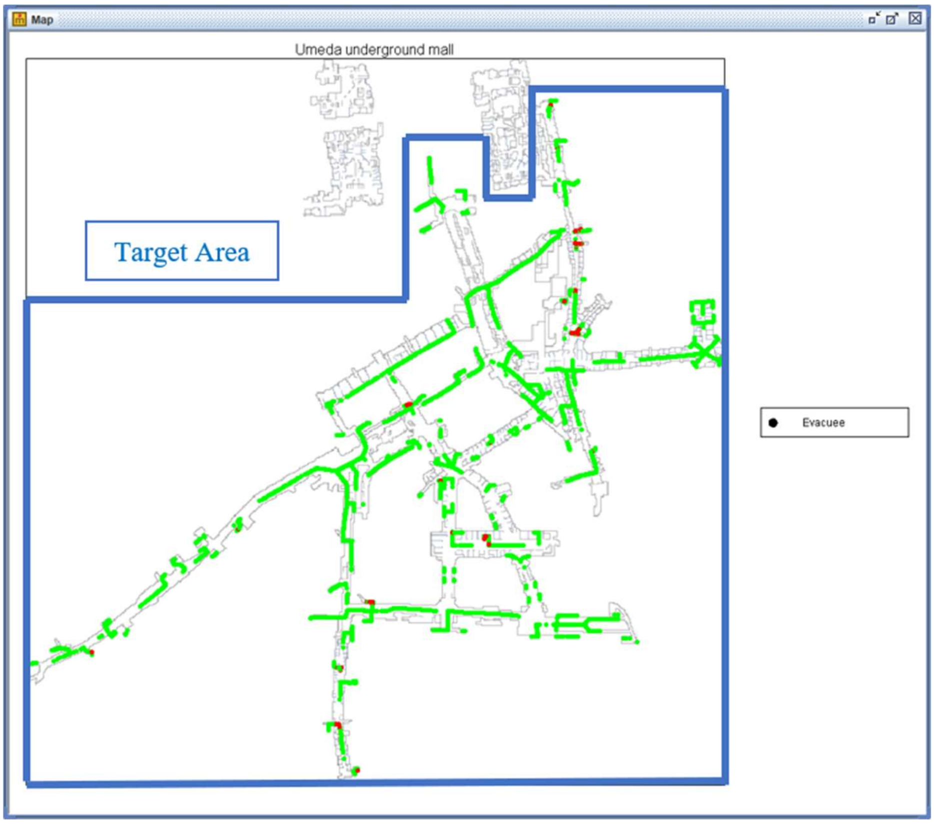

Figure 7. Evacuation simulation if 14000 agents are set (Red agents are crowded)

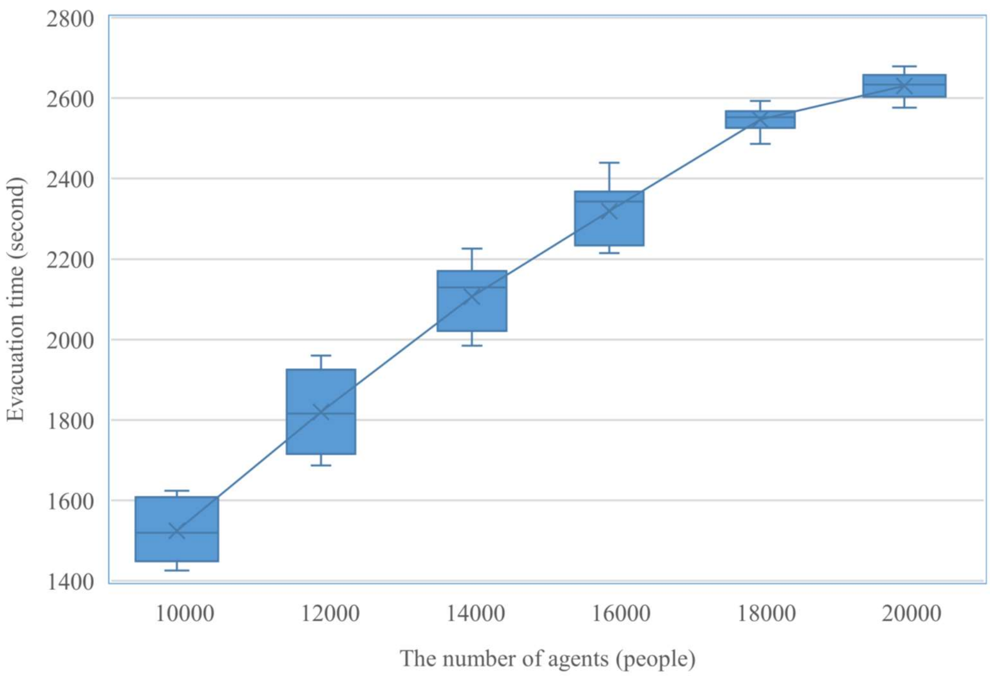

Figure 8. The box-plot of evacuation time (10 times for 6 patterns)

4.2 The factor improving the success rate of evacuation in the case of inundation

Figure 9 shows a comparison between the average of evacuation time and the critical lines of the safe evacuation time. In the case of 60 mm/hr, it can be seen that any pattern can be evacuated with almost no problem, but in the case of 120 mm/hr and 180 mm/hr, it can be seen that as the number of people increases the evacuation margin time decreases. In addition, even if you evacuate to the ground, it is conceivable that evacuation will be difficult on the way to the evacuation sites. In other words, it is dangerous to evacuate to the exit to the ground. It is important for people to evacuate to the building connected in the underground shopping mall and evacuate to the upper floor in order to improve the evacuation success rate.

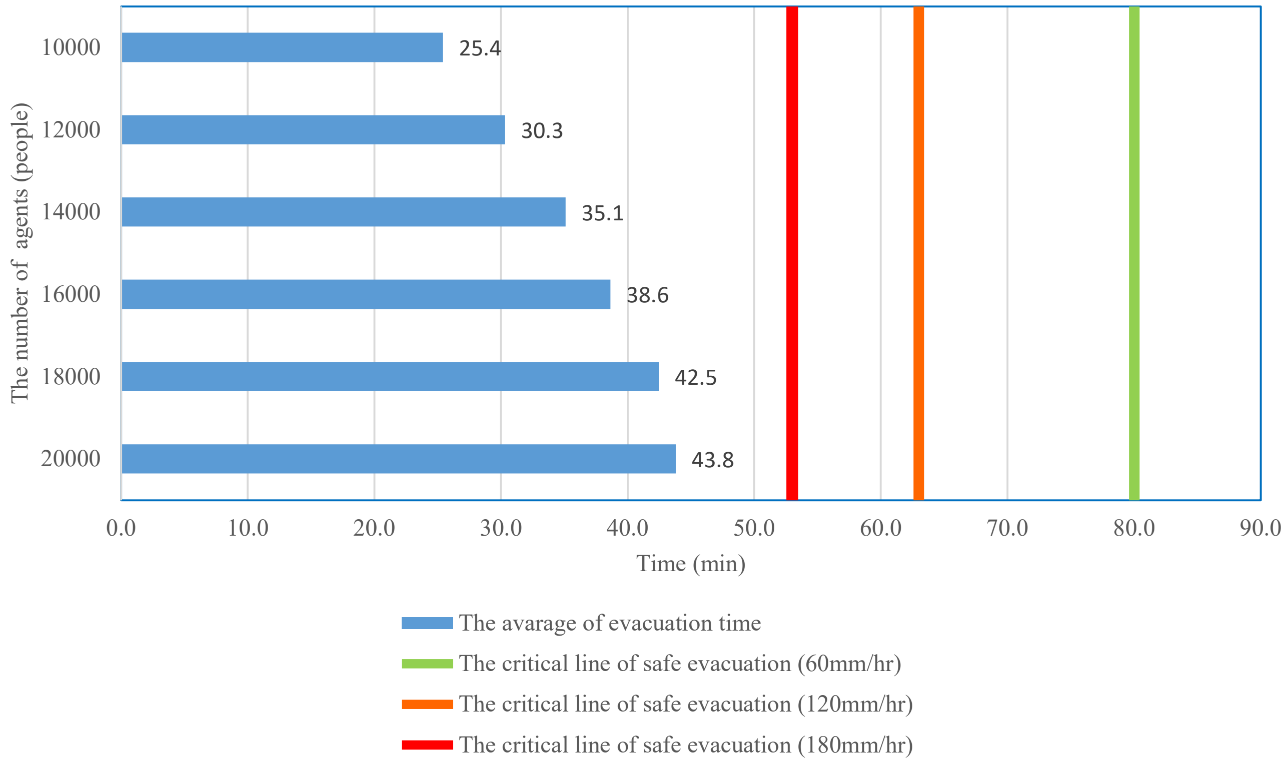

Figure 9. The evacuation time and critical lines of safe evacuation

5. CONCLUSIONS

In this study, we investigated how to improve the success rate of evacuation by comparing the results of inundation analysis with the results of evacuation simulation for an existing large-scale underground shopping mall. Although the evacuation simulation model has some improvements factor, it has been shown that the evacuation time decreases as the rainfall increases and the number of evacuees increases. It has also been shown that evacuation methods of getting out of the ground and going to evacuation shelters were not an effective means to safely evacuate all evacuees if the floods become severe. In the future, it will be possible to consider more specific evacuation success rates by considering when entering connected buildings and adding some guidance systems.

REFERENCES

Architectural Institute of Japan (AIJ) (2003). *Handbook of Environmental Design, Human Edition*, Japan, Maruzen, p.128. (in Japanese)

Asai, Y., Ishigaki, T., Baba, Y., and Toda, K. (2009). Safety analysis of evacuation routes considering aged persons during underground flooding, Annual Journal of Hydraulic Engineering, JSCE, Vol.53 pp.967-972, (in Japanese)

Hamaguchi, S., Ishigaki, T., Ozaki, T., and Toda, K. (2016). Study on vulnerability of mega-underground space to extreme flood, Journal of Japan Society of Civil Engineering, B1(Hydraulic Engineering), Vol.72, No.4, I_1363-I_1368. (in Japanese)

Ishigaki, T., Kawanaka, R., Ozaki, T., and Toda, K. (2016). Vulnerability to underground inundation and Evacuation in densely urbanized area, Journal of Disaster Research, Vol.11, No.2, pp.298-305.

Ishigaki, T., Toda, K., Baba, H., Inoue, K., and Nakagawa, H. (2006). Experimental study on evacuation from underground space by using real size models, Annual Journal of Hydraulic Engineering, JSCE, pp.583-588. (in Japanese)

Kho, H., Ishigaki, T., Ozaki, T., and Toda, K. (2018). Evacuation from inundated underground shopping mall under extreme weather condition, Proceedings of Symposium on Underground Space, JSCE, Vol.23, pp.103-108. (in Japanese)
Ministry of Internal Affairs and Communications. (2018). Current Population Estimates as of October 1, 2018 [Online], Accessed 10 February 2020. Available: http://www.stat.go.jp/english/data/jinsui/2018np/index.html.
Morikane, M., Ishigaki, T., Toda, K., Ozaki, T., and Baba, Y. (2011). Rainwater flooding and its counter measures in urban area of mega-underground mall, Journal of Japan Society of Civil Engineering, B1(Hydraulic Engineering), Vol.67, No.4, I_967-I_972. (in Japanese)
Morikane, M., Inoue, T., Ishigaki, T., Ozaki, T., and Toda, K., (2012). Effects of counter measures for reducing underground inundation caused by pluvial flooding, Journal of Japan Society of Civil Engineering, B1(Hydraulic Engineering), Vol.68, No.4, I_1003-I_1008. (in Japanese)
Onishi, M., Ishigaki, T., Toda, K., and Baba, Y. (2008). Criterion and its application for safety evacuation during underground flooding, Annual Journal of Hydraulic Engineering, JSCE, Vol.52, pp.841-846. (in Japanese)