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Paper:

Analysis of Evacuation Time for Vulnerable Individuals During Inundation of Lowland Areas

Chang Yeon Bae† **and Kenichiro Kobayashi**

Department of Urban Management, Kobe University
1-1 Rokkodai-cho, Nada-ku, Kobe, Hyogo 657-8501, Japan
†Corresponding author, E-mail: 01088771539@hanmail.net
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There is an increasing demand for establishing pre-emptive measures for disaster management. However, there is a lack of support systems available for vulnerable individuals living in disaster-prone regions in Korea. This study constructs a multi-agent simulation model to analyze the evacuation time for Dongnae district and Yeonje district in Busan, Korea. In disaster-prone regions, vulnerable people experience difficulties, such as, obtaining updated information about the disaster situation, and this reduces their evacuation speed. Additionally, there is a possibility that the evacuation speed, while evacuating vulnerable people, may decrease due to environmental and geographic factors, including the slope and elevation of the areas. Therefore, this section of the society requires special attention and policies that are different from those made for people who may not face such calamities and are physically abled. An analysis based on factors such as road slopes and delays in evacuation due to flooding, was conducted to formulate realistic evacuation plans for people who are vulnerable. The location of shelters in the case of flooding in Dongnae and Yeonje district, have been better identified. Furthermore, it was confirmed that the evacuation time could be reduced if wide-area evacuation is implemented. This study provides a base for developing suitable shelters and evacuation plans for disaster-prone regions.

Keywords: multi-agent simulation, optimum route, flood disaster, wide-area evacuation

1. Introduction

1.1. Background and Purpose of the Research

Implementing necessary actions before a disaster occurs is the most important way to prevent damage to lives and property. However, the damage to human lives can be further reduced if evacuation behavior is optimized even after inundation occurs. According to several surveys [1, 2], the flood damage in Korea is concentrated in the lower elevation areas around rivers. Consequently, the government has introduced regulations [3] related to evacuation of lowland areas to prevent damage to life and property. However, the guidelines are not adequate for establishing comprehensive evacuation measures. Flooding can be extensive when there is excessive rainfall, and evacuation based on the measures taken by the local government may be difficult. At such times, evacuation creates unusual traffic demands which result in traffic conditions that are not normal. Consequently, evacuees cannot utilize their past experiences to gauge which routes may minimize evacuation time [4]. Therefore, comprehensive evacuation measures must be introduced by the combined efforts of the state and various local governments [5]. While selecting an evacuation route, it is necessary to consider the environmental and geographical factors, including the slope and elevation of the areas. In Korea, installation and construction standards for evacuation shelters have not been specified. In some cases, by overlapping the geographic information system (GIS) data of the shelters with the existing inundation maps, some evacuation shelters have been designated in areas that have suffered inundation previously. However, clear guidelines, for the action to be taken in the event of flood damage, are yet to be established. Hazard maps for urban flooding, in Korea, do not provide sufficient information that is necessary for evacuation largely because disclosure of disaster risk is not mandatory. Seo et al. [6] stated that information on disaster risk is often not disclosed as residents are concerned that real estate prices of an area would fall if it is declared as a flood hazard zone. Therefore, it is important to distribute urban inundation hazard maps that show areas that face flooding risks and evacuation routes to enable evacuation when required. According to Japan's disaster prevention policy, the government provides disaster prevention services, especially for people over 65 years of age [7]. Therefore, when considering the adequacy of evacuation sites and the time required to evacuate, evacuation speed of vulnerable individuals must be considered. This study investigates the validity of the location of the shelters that are operational in the study area and analyzes the evacuation time in case of a wide-area evacuation.

1.2. Review of Extant Evacuation Models

In the event of a tsunami caused by a flood or an earthquake, evacuation by car is prohibited in principle, and evacuation on foot is recommended [8]. The primary reason for this is to avoid congestion and prioritize the smooth movement of emergency and rescue vehicles. Therefore, the most effective way of determining the time required is by an evacuation simulation with the assumption that people will be walking. The usage of evacuation simulations [9–12] has rapidly increased in the last years as these are used to predict various disasters. Research about using a multi-agent model to analyze flood evacuation behavior was first conducted by Takasao et al. [13]. Kobayashi et al. [14] constructed a multi-agent evacuation model for tsunamis and applied it to an evacuation drill of around 1000 people in Ashiya High School, Hyogo, Japan. Saito and Kagami [15] built a tsunami evacuation model based on the Aonae district of Okushiri Island in Hokkaido and verified the validity of the model by comparing it with the survey of actual evacuation conditions. At the time of a tsunami evacuation, the direction of evacuation is clear. However, in urban inundation, the evacuation route may vary based on the level of precipitation and the drainage capacity. For this study, the analysis has been conducted with the assumption of sporadic flooding in an urban area. In Korea, studies to determine the location of shelters through geographic information system service area analysis [16, 17] have been performed. However, the slope of the evacuation area is not considered and analysis has been based on the evacuation speed only. Therefore, the analysis may not be accurate. Lee et al. [18] stated that the elderly in Tokyo's 23 districts prefer walking when they have to travel for a short distance, such as, while going to hospitals, shopping, and banking, and the proportion of people who prefer walking increases as the age group increases. In addition, it is reported that when the elderly going out, they are much more likely to move to the stairs or slope. Therefore, the road and terrain have to be taken into consideration. In Korea, the civil defense shelters that were created for war have been designated as flood shelters [19]. However, these are located underground, therefore are not appropriate. This study evaluates the inundation of urban areas during evacuation by calculating the three-dimensional distance with the uphill and downhill road slopes. Administrative boundaries have not been considered when evacuating to the nearest shelter.

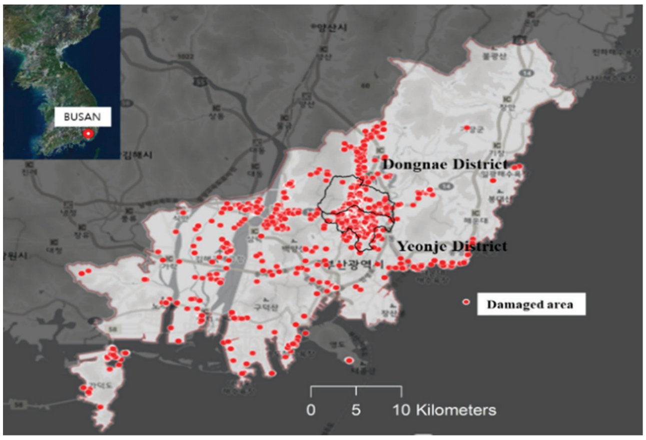


Fig. 1. History of damage in the study area.

Fig. 2. Sensors and speakers in Dongnae district (left) and Yeonje district (right).

2. Methods

2.1. Selection of Research Area

To identify the areas that require assistance due to flooding, a meeting was conducted with the public officials of the Busan Metropolitan City in April 2018. As shown in **Fig. 1**, the historical data on flood damage, over the past five years, is visualized as dots. The damage points in the comprehensive plan for the reduction of damage from storms and floods published by Busan Metropolitan City, have been identified as well. Dongnae and Yeonje districts in Busan Metropolitan City, where flooding occurs frequently, are areas where inland drainage becomes a disadvantage when the water level of the adjacent Oncheon river increases. As shown in **Fig. 2**, the local government has installed an inundation detection water level sensor and a broadcasting speaker to create a system that can be used in real time to prepare for such eventualities. Despite this, heavy rains in August 2020 led to flood damage. Additionally, these districts have a high percentage of vulnerable individuals. Thus, soft measures, such as, arrangements for these individuals, which includes the elderly and children, during evacuation are important.

Table 1. Status of inundation response with time in Busan metropolitan city [20].

Time	Status of inundation response
09:10	Operation of the city, county, and district central disaster relief centers with the issuance of heavy rain warnings
13:00	Heavy rain warning
13:20	Consultation on the disaster situation by the deputy mayor of the administration
14:22	Emergency working of 1/4 of all employees and 13 consultation teams
14:32	400 people evacuated because of inundation in Gupo neighborhood, North district
16:00	All clear of heavy rain warning
16:00	Two people dead because of flooding in Ujangchun Road, Oncheon-dong, Dongnae district
16:12	Inundation of subway line 4
18:40	Damage situation countermeasure meeting by the mayor
22:30	Inspection of damage situation and restoration measure meeting by the deputy mayor of the administration

2.2. Analysis of Status of Damage and Evacuation Response

On August 25, 2014, inundation damage occurred in the entire Busan area it recorded the highest rainfall in the last 200 years. As shown in **Table 1**, Busan Metropolitan City took an emergency guard according to the weather report. However, the information in the evacuation manual was insufficient, there were too many emergency calls that could not be handled, the situation was not fully understood, and communication with citizens was insufficient, thus, the damage was severe. In Dongnae district, where the rainfall increased rapidly, two people died on Ujangchun road and four people were isolated. This district reported the largest amount of damage to private facilities (home or agricultural land) in Busan.

2.3. Methodology

OpenStreetMap [21] and digital elevation model (DEM) [22] data by advanced land observing satellite (ALOS) World 3D were used to identify road networks and slopes in Dongnae and Yeonje district. For the evacuation shelters [23] in preparation for inundation, the buildings classified as public facilities from the public data portal were selected, and the coordinates were geocoded. Additionally, to factor the decrease in walking speed during flooding, the flooding mark information [23] was analyzed based on data from the public data portal.

2.4. Calculation of Road Slope

Satoh et al.'s [24] proposed formula as seen in **Fig. 3** and Eq. (1) that expresses the distance by the degree of inclination, is applied.

Figure 3 shows a schematic diagram by Satoh et al. [24] to show the horizontal and slope distance and the possible resistance when a person moves on a slope. The actual slope distance L is expressed using the horizontal distance d and slope angle θ as:

$$L = \frac{d}{\cos\theta}. \qquad (1)$$

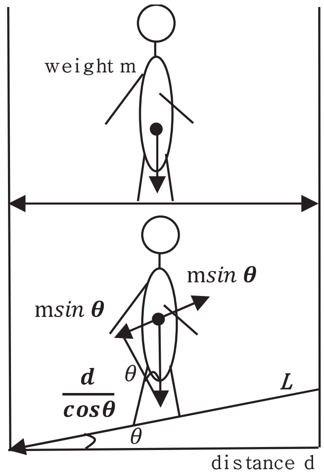


Fig. 3. Calculation of inclined road distance (L) using the values of horizontal distance (d) (Source: Satoh et al. [24]).

According to Satoh et al. [24], for weight m, while walking on a slope, a resistance of $m\sin\theta$ occurs on the slope opposite to the travel direction. The total weight in the case of a slope is set to $m + m\sin\theta = m(1+\sin\theta)$. Based on this assumption, the pseudo-distance L_{sim}, has been calculated as:

$$L_{sim} = \frac{d}{\cos\theta}(1+\sin\theta), \qquad (2)$$

which shows the actual slope distance $d/\cos\theta$ multiplied by $(1+\sin\theta)$, representing the effect of the velocity change while moving on a slope.

In this study, the pseudo-distance considering the slope was calculated as follows:

1. The road data was subdivided into unit links and the road distance (d) was calculated. The "unit links" refer to the links between the vertex and the vertex.
2. Convert vertices of each unit road to points.
3. Enter the corresponding elevation value (Z) for each point.
4. The pseudo-distance L_{sim} by slope was obtained using the formula $L_{sim} = (d/\cos\theta)(1+\sin\theta)$ consid-

Table 2. Simulation results according to the proposed equation.

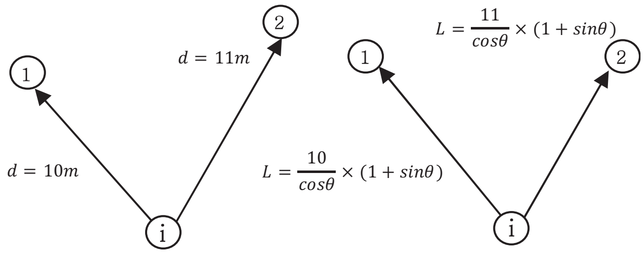
Choi				Proposed			
Slope (θ)	Time taken	Slope (θ)	Time taken	Slope (θ)	Time taken	Slope (θ)	Time taken
+4.8°	6.24 s	−4.8°	5.76 s	+4.8°	7.89 s	−4.8°	7.71 s
+5.7°	6.37 s	−5.7°	5.79 s	+5.7°	7.96 s	−5.7°	7.10 s
+7.1°	6.57 s	−7.1°	5.95 s	+7.1°	8.07 s	−7.1°	7.00 s
+9.5°	6.68 s	−9.5°	6.06 s	+9.5°	8.27 s	−9.5°	6.84 s

ering the speed reduction by $(1+\sin\theta)$.

Choi and Choi [25] made a 10 m slope, walked on it and measured the time required by changing the slope angle. This is shown in **Table 2**. **Table 2** also shows the time calculated by the simulation model that has been used for this study. The comparison between the simulation and observation indicates an error of about 1.58 s+ in the uphill and 1.13 s+ in the downhill movement, on an average. Choi and Choi [25] elaborated that while walking downhill, the walking time increases as the slope angle increases. This could be because people walk slowly while walking downhill to avoid falling, especially if the slope is steep. The concept proposed in this study allows the evacuee to increase speed while walking downhill and this is an essential difference. The psychological factor should be taken into consideration in future studies. However, the time difference calculated while walking uphill and downhill in this study is small, and most of the area in the simulation is uphill. Thus, the simulation is carried out as it is in the following.

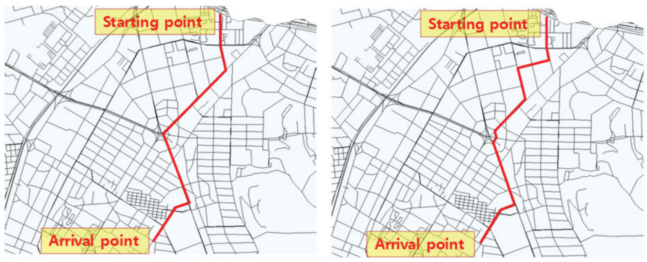
2.5. Calculation of Evacuation Time to Evacuation Shelter and Selection of Route

In this study, algorithms to express the change in evacuation speed due to inundation and slope are added to a multi-agent system in C++ language [14], and the shortest route is selected by the Dijkstra algorithm, an optimization algorithm that is primarily used for determining the shortest paths. The Dijkstra algorithm is an uninformed search algorithm to identify the shortest paths that rely purely on local path cost. This algorithm offers the advantage of identifying the shortest path between the first starting point and the directly connected point, then expanding the node, estimating the best path from the first point to the target point, and accurately deriving the results. Based on the previous section, the new shortest distance was searched considering the slope effect, and the evacuation route was calculated as shown in **Fig. 4**. **Fig. 5** shows the results of the simulation using a part of the new Dijkstra algorithm in the study area. In the figure, the line represents the agent's evacuation route. For example, if this is calculated using the existing method as shown in **Fig. 5(a)**, the agent moved by selecting route (a) with the shortest distance. However, the method applied in this study changes the path as shown in **Fig. 5(b)**. Thus, it was confirmed that the walking path can change if the slope effect is considered.



(a) Existing method (b) Proposed method

Fig. 4. Shortest evacuation route calculated by the Dijkstra algorithm.



(a) Existing method (b) Proposed method

Fig. 5. Evacuation route simulated by the Dijkstra algorithm in the study area using (a) existing method and (b) proposed method.

2.6. Calculation of Walking Speed by Age

The walking speed during evacuation depends on the physical ability of the individual and the conditions of the evacuation route. Therefore, in the evacuation speeds by age used in [26], the evacuation speed of the elderly (0.93 m/s) and children (1.06 m/s), was considered. Additionally, information on the reduction in speed [27] due to flooding was also used. Lee et al. [27] conducted an experiment to study the change in the speed of evacuation based on the depth of water in the case of flooding, and reported that for the inundation depth of 20 cm, the speed reduces by 25%, for 30 cm by 32%, for 40 cm by 36%, and for 50 cm by 41%. Furthermore, if the inundation depth exceeds 55 cm, the area is classified as dangerous, and it is assumed that evacuation is not possible. Therefore, in this study, the agent moves in the simulation by applying a speed reduction rate below 50 cm flood depth. Above 50 cm, the agent chooses another route to avoid the inundation place.

Table 3. Number of vulnerable people per household in Dongnae and Yeonje districts.

District	Number of vulnerable people	Number of households	Number of vulnerable people per household
Dongnae	98,774	100,613	0.988 (about 1)
Yeonje	76,317	88,104	0.952 (about 1)

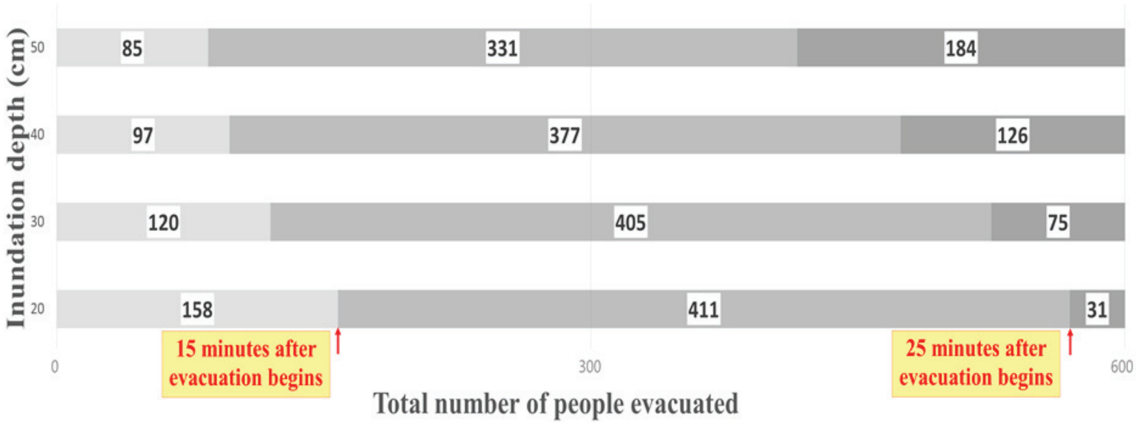


Fig. 6. Number of people evacuated with time by inundation depth.

3. Results and Discussion

3.1. Calculation of the Number People to be Evacuated

As shown in **Table 3**, the population classified as vulnerable individuals is children under 15 years of age and people over 60 years of age, based on the number of people per household [28]. The vulnerable population in the study areas was calculated using the information about buildings that are classified as residences in Dongnae and Yeonje district. The number of residential buildings near the Oncheon river was approximately 400 in Dongnae district and approximately 200 in Yeonje district. The number of vulnerable people was estimated as one per household. Therefore, about 400 people had to be evacuated in Dongnae district and about 200 in Yeonje district.

3.2. Results of Simulation

The simulation was conducted using the method described. **Fig. 6** shows the results of simulating the movement of 600 people in Dongnae and Yeonje districts. A sensitivity analysis was carried out assuming a uniform flooding depth, as the actual inundation depth is unclear. The results indicated that the number of people who finished evacuating can change according to the inundation depth. It was observed that when the inundation depth increased from 20 to 50 cm, the speed of evacuation reduced, and the number of evacuees decreased. Thus, the effect of increasing or decreasing the inundation depth has been appropriately considered in this method.

3.3. Evacuation Time Considering Road Slope and Walking Speed

In this study, road slope and flooding were considered during the simulation, and evacuation time was investigated by conducting a wide-area evacuation simulation. The multi-agent model begins with reading the road and building data as input files, then chooses the evacuation routes by calculating the pseudo-distance from each agent's current position to the shelter using the proposed method. The agents are generated on the road node nearest to the building polygon and immediately move to the shelter after the evacuation begins. The initial time of the evacuation is not changed at this time to observe the general tendency according to the changes of the evacuation distance based on the proposed method. Additionally, in case of wide-area evacuations, evacuation beyond the boundary of the district is considered as a viable option if the route is the shortest. **Fig. 7** shows the locations of evacuation shelters in Dongnae and Yeonje district and areas that have flooded in the past. Currently, there are 12 shelters in Dongnae district and 17 shelters in Yeonje district, which implies that there is a total of 29 shelters in Busan which are designated as evacuation shelters. The shelters numbered 1 to 5 were found difficult to evacuate because these were located near or in flooded areas, hence they were excluded from the study. The simulation results are shown in **Tables 4** and **5**. In Dongnae district, it was confirmed that it would take 33 minutes for the elderly and 29 minutes for children when evacuating using the proposed shortest route. In Yeonje district, it was confirmed that it would take 43 minutes for the elderly and 38 minutes for the evacuation of children. Considering the decrease in the speed of evacuation because of inundation, it was found that it would take 35 minutes for

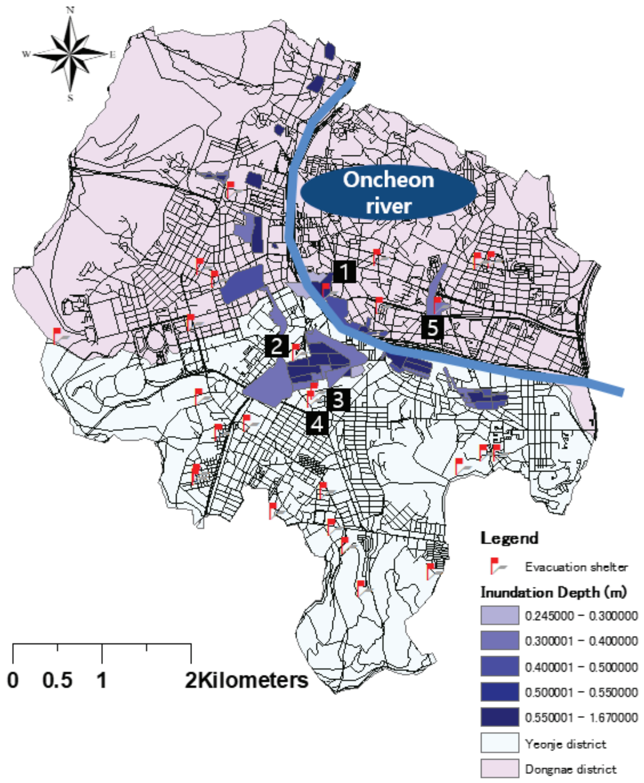


Fig. 7. Shelter location and past inundation areas.

Table 4. Evacuation completion time in Dongnae district.

Class	Time taken for proposed route	Time taken for flooded route	Rate of increase [%]
Older adults	33 min	35 min	6.1
Children	29 min	31 min	6.9

Table 5. Evacuation completion time in Yeonje district.

Class	Time taken for proposed route	Time taken for flooded route	Rate of increase [%]
Older adults	43 min	63 min	46.5
Children	38 min	55 min	44.7

the elderly and 31 minutes for the evacuation of children in Dongnae district, whereas for Yeonje district, it would be 63 and 55 minutes, respectively. The area of Dongnae and Yeonje districts is 16.64 km^2 and 12.08 km^2, respectively, however, despite the relatively smaller area of Yeonje district, the evacuation time is longer. According to the analysis result from **Fig. 8**, people in the Yeonje district have to pass through the flooded area within 30 minutes, therefore, it is believed that their speed reduced. As shown in **Fig. 9**, Yeonje district can be evacuated within 21 minutes if there is no flooding. However, the number of people evacuating through the flooded area is seen to increase after 35 minutes. Thus, Yeonje district needs to reduce the evacuation time as compared to Dongnae district or the shelters need to be relocated for successful evacuation. As shown in **Table 6**, the examination with the assumption of wide-area evacuation, established that the evacuation time for the elderly was 33 minutes and that for children was 29 minutes. For evacuating through the flooded area, the elderly and children required 42 and 37 minutes, respectively. While evacuating Yeonje district, the elderly took 43 minutes to evacuate through the proposed shortest route and 63 minutes through flooded areas, however, it took 33 and 42 minutes, respectively for wide-area evacuation. Thus, it was possible to reduce the evacuation time by 10 minutes for the proposed shortest route, and 21 minutes for evacuation through the flooded area, reducing the evacuation time by 23% and 33%, respectively, only in Yeonje district. Therefore, when evacuating from within Yeonje district as a starting point, considering the flooding situation and the location of the evacuation shelter, it has been determined that evacuation time can be shortened by evacuating not only to Yeonje district, but also to an evacuation center in the neighboring Dongnae district. It is therefore, necessary for local governments to identify evacuation sites and routes crossing the administrative boundaries, and flood prone areas in advance, and these should be reflected in the arrangement of new shelters or while setting a bypass evacuation route.

4. Conclusion

In this study, evacuation simulations were conducted for the elderly and children in the Dongnae and Yeonje districts, which face a high risk of inundation. In addition, a new route selection method was introduced considering the slope of the road, and the change in the speed of evacuation caused by inundation was also considered. The evacuation time considering the road slope and inundation depth was examined using a multi-agent model. Many of the evacuation shelters in Dongnae and Yeonje district were confirmed to be located in or near the inundation area. This highlights the importance of establishing evacuation shelters considering the past inundation conditions. The study states that evacuation shelters should be relocated if necessary. Evacuation of vulnerable people in Yeonje district required over 75% more time on average than that in Dongnae district when evacuating through the flooded station in the proposed route. Thus, it is found that the time of evacuation in Yeonje district needs to be reduced as compared to that of Dongnae district or the shelter need to be relocated for successful evacuation. Additionally, when a wide-area evacuation was carried out, the evacuation time in Yeonje district reduced by an average of 33%. Therefore, it is stated that local governments would be able to implement a more effective evacuation plan if the evacuation route is selected based on comprehensive topographical information and past flooding. The results of analyzing the evacuation time in this study can be used as a basis for the establishment of stan-

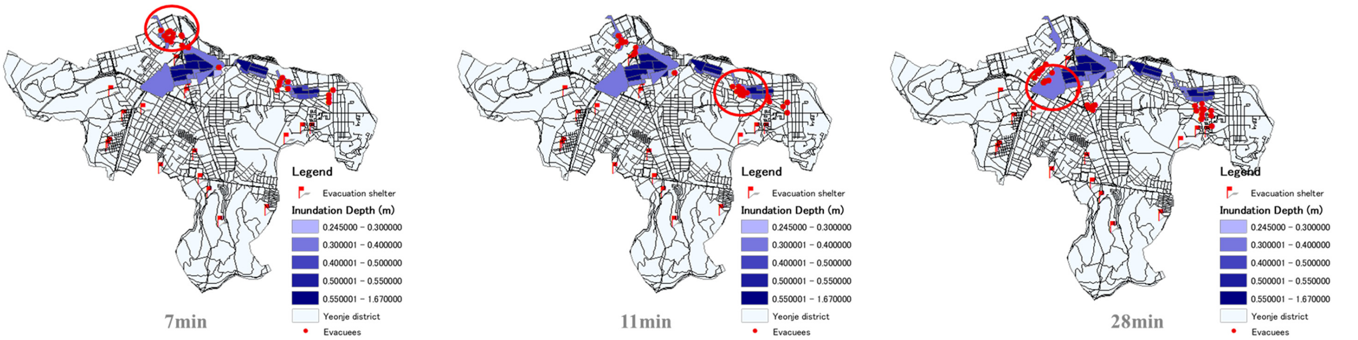


Fig. 8. Evacuation routes in Yeonje.

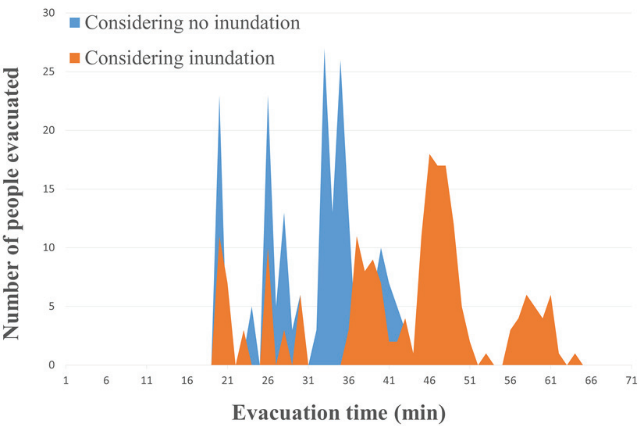


Fig. 9. Number of people evacuated with time considering inundation and no inundation in Yeonje.

Table 6. Evacuation completion time for wide-area evacuation.

Class	Time taken for proposed route	Time taken for flooded route
Older adults	33 min	42 min
Children	29 min	37 min

dards for safe evacuation on foot for flood control purposes. However, this study does not consider other factors such as wind speed, flow velocity, etc. Likewise, the fear of falling and the degree of fatigue due to the degree of inclination has not been considered. This implies that the actual evacuation time may be slower than observed in this study, which should be regarded as the upper limit of evacuation time. Further research on the limitations of this study will provide a useful tool to reduce the loss of life of the elderly due to natural disasters.

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Name:
Chang Yeon Bae

Affiliation:
Graduate Student, Research Center for Urban Safety and Security (RCUSS), Kobe University

Address:
1-1 Rokkodai-cho, Nada-ku, Kobe, Hyogo 657-8501, Japan

Brief Career:
2019- RCUSS/Department of Civil Engineering, Kobe University

Academic Societies & Scientific Organizations:
- Japan Society of Civil Engineers (JSCE)

Name:
Kenichiro Kobayashi

Affiliation:
Research Center for Urban Safety and Security (RCUSS), Kobe University

Address:
1-1 Rokkodai-cho, Nada-ku, Kobe, Hyogo 657-8501, Japan

Brief Career:
2006-2010 Institute of Sustainable Science, Kyoto University
2010-2012 Educational Unit for Adaptation and Resilience for a Sustainable Society, Kyoto University
2012- RCUSS/Department of Civil Engineering, Kobe University

Selected Publications:
- K. Kobayashi, L. Duc, Apip, T. Oizumi, and K. Saito, "Ensemble flood simulation for a small dam catchment in Japan using nonhydrostatic model rainfalls – Part 2: Flood forecasting using 1600-member 4D-EnVar-predicted rainfalls," Natural Hazards and Earth System Sciences, Vol.20, No.3, pp. 755-770, doi: 10.5194/nhess-20-755-2020, 2020.
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Academic Societies & Scientific Organizations:
- Japan Society of Civil Engineers (JSCE)
- Japan Society of Hydrology and Water Resources (JSHWR)
- International Association for Hydro-Environment Engineering and Research (IAHR)