Evaluating the Effectiveness of Staged Evacuation in Radiological Emergencies using Agent-Based Modeling

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Abstract: The evacuation of residents during a radiological emergency is a crucial response measure. Staged evacuation is mentioned as an effective evacuation strategy. However, a method is needed to confirm the effectiveness of staged evacuation and to optimize the strategy. This study evaluates the performance of staged evacuation with more realistic factors which are implementable in a simulation platform. Evacuation simulation was conducted utilizing the PRISM (Platform for Radiological Emergency Integrated Simulation Model), developed by Kyung Hee University. Using GIS data, a fictitious nuclear power plant site was modeled, resembling the Precautionary Action Zone (PAZ) in South Korea and the evacuation simulation was conducted there. The results provided the following insights: (1) Certain staged evacuation strategies were effective in reducing evacuation times within the 5 km radius of the nuclear power plant. (2) Strategies that prioritized evacuating areas farther from the nuclear plant had shorter evacuation times. (3) Changes in the evacuation interval times did not proportionally affect evacuation times. This means that evacuation interval times can be adjusted according to the objective without significantly increasing evacuation time. We expect that this study will contribute to the measurement of evacuation time in Level 3 PSA.

Keywords: Staged evacuation, Agent-based-modeling, Radiological emergency

1. INTRODUCTION

The evacuation of residents during a radiological emergency is a crucial response measure. The shorter the evacuation time, the lower the risk of radiation exposure. Staged evacuation has been studied as an evacuation strategy to reduce evacuation time. Staged evacuation is a strategy where evacuees are evacuated in a sequential manner by varying their evacuation order.

When an evacuation order is issued, vehicles will flow onto the roads to evacuate. If a large number of vehicles enter the limited roads, severe traffic congestion can occur. This can delay the completion of the evacuation and increase the time vehicles spend on the roads. If radioactive materials have been released, this can increase the risk of exposure. Implementing staged evacuation is expected to alleviate such congestion [1].

Many researchers have studied the effects of staged evacuation [2-5]. However, the results of simulations conducted under theoretical conditions cannot guarantee the same effects in reality. Real cities are composed of very complex road networks, and the population distribution is highly uneven. Furthermore, evacuation areas cannot be simply divided theoretically. In this study, we aim to measure evacuation time by applying staged evacuation as if measuring actual evacuation time. We will analyze the results to evaluate the effectiveness of staged evacuation.

2. Simulation Setting

2.1. Introduction to PRISM

In this study, the evacuation simulation was conducted using PRISM (Platform for Radiological Emergency Integrated Simulation Model) developed by Kyung Hee University [6, 7]. PRISM was created using the NetLogo language. NetLogo not only helps understand complex phenomena using ABM (Agent-Based Modeling) but also allows for easy integration of GIS (Geographic Information Systems) data, enabling more realistic simulations. The figure 1 shows a flowchart of the algorithm for staged evacuation running in PRISM.

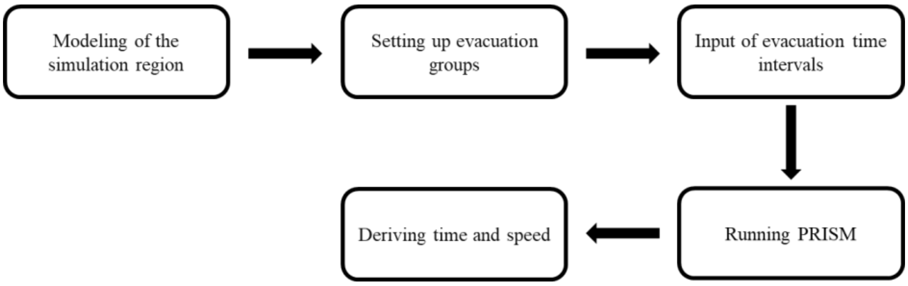

Figure 1. Flowchart of the algorithm for staged evacuation running in PRISM

2.2. Simulation Region

To model the simulation region, an arbitrary coastal area in South Korea was selected, and GIS data of roads, buildings, and administrative boundaries of that area were applied. The GIS data was downloaded from V-World [8], an open spatial information platform. The GIS data used for roads, buildings, and administrative districts are road centerlines [9], (Continuous Cadastral Map) buildings [10], and legal boundaries (Village unit) [11], respectively. Using this data, a fictitious nuclear power plant site was modeled, resembling the Precautionary Action Zone (PAZ) in South Korea. Figure 2 illustrates the modeled city.

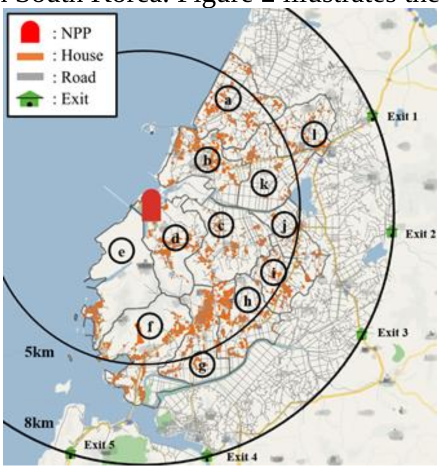

Figure 2. Map of modeled city

The modeled city consists of 12 villages. Evacuees were initially programmed to be located in buildings classified as residential in the building data. This approach was used to implement an uneven population distribution. Among the major roads leading from the modeled city to external areas, five locations within an 8km radius of the nuclear power plant were arbitrarily selected as exits. Evacuees evacuate towards the nearest exit.

3. Evacuation Simulation

To focus on evaluating the effectiveness of staged evacuation, the following assumptions were made:

- The release of radioactive materials and the resulting radiation exposure during the evacuation process are not considered.
- All residents wait at home before starting the evacuation and the evacuation is considered complete when they reach the designated exits.
- All residents have completed their evacuation preparations before the evacuation order is issued and start evacuating immediately once the order is given.
- A town has 5,000 households, each with 2 individuals, and each household owns one vehicle.
- All residents evacuate using vehicles only.

There are many possible ways to divide the villages into evacuation groups. However, in this study, the villages were divided into two evacuation groups, with 6 villages in each group. The 6 villages closest to the nuclear power plant were assigned to one group, and the remaining 6 villages were assigned to the other group. Figure

3 shows the evacuation groups and the villages assigned to them. The time intervals between the evacuations of the two groups were set at 5 minutes, 10 minutes, and 15 minutes. Considering the evacuation order and the time intervals between the evacuations of the two groups, there are a total of 6 staged evacuation strategies. Including the simultaneous evacuation strategy, there are a total of 7 evacuation strategies. Table 1 shows each of the evacuation strategies.

The formula for the evacuation time of each strategy is expressed as shown in Equation 1.

$$T_{evac} = T_{simul} - T_E(o, T_{interval}) \quad (1)$$

where
T_{evac} : Evacuation time
T_{simul} : Evacuation time for simultaneous evacuation
$T_E(o, d)$: Time reduced due to the effect of staged evacuation
o : Evacuation order
$T_{interval}$: Interval time

Measure the evacuation time for each evacuation strategy to determine the time reduction effect of staged evacuation strategies based on the evacuation order and time interval. Compare the evacuation times of each strategy to evaluate the effectiveness of staged evacuation.

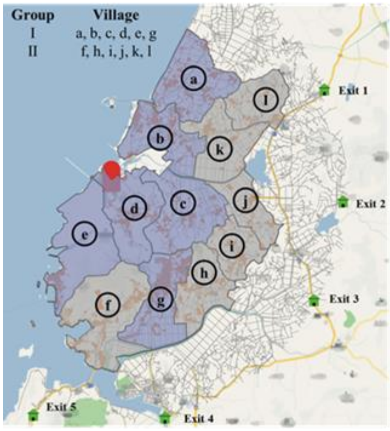

Figure 3. Map of evacuation groups and villages assigned to them

Table 1. The evacuation strategies

Strategy	Interval time	Order
1	-	-
2	5 min	I - II
3		II - I
4	10 min	I - II
5		II - I
6	15 min	I - II
7		II - I

4. Results

Figure 4 and Table 2 show the simulation results for each strategy. Among all staged evacuation strategies, the strategies with shorter evacuation times than simultaneous evacuation are Strategy 3 and Strategy 5, both of which follow the evacuation order Ⅱ - Ⅰ. For strategies with the evacuation order Ⅱ - Ⅰ, the evacuation time increased as the evacuation interval time increased. However, for strategies with the evacuation order Ⅰ - Ⅱ, the evacuation time was the longest when the evacuation interval time was 10 minutes. Regardless of the evacuation interval time, the evacuation time was shorter when the evacuation order was Ⅱ - Ⅰ compared to when it was Ⅰ - Ⅱ.

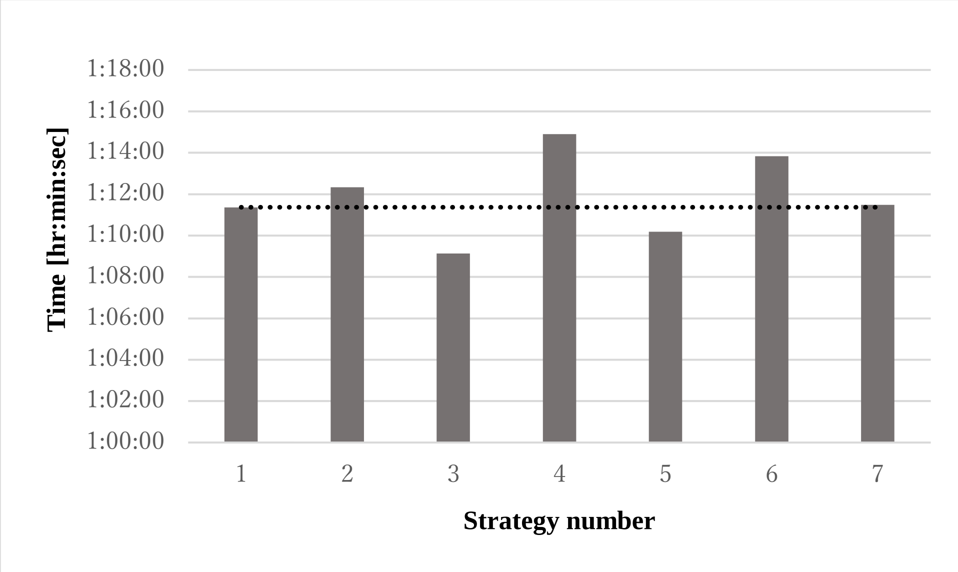

Figure 4. The evacuation times for each strategy

Table 2. The evacuation times and effect of staged evacuation for each strategy

Strategy	1	2	3	4	5	6	7
T_{evac}	1:11:22	1:12:20	1:09:08	1:14:54	1:10:11	1:13:50	1:11:29
T_E	0:00:00	-0:00:58	0:02:14	-0:03:32	0:01:11	-0:02:28	-0:00:07

5. CONCLUSIONS

This study aimed to evaluate the effectiveness of staged evacuation by applying more realistic elements. Evacuation simulations were conducted with varying evacuation interval times and orders, and the evacuation times and speeds of each strategy were compared.

The results provided the following insights: (1) Certain staged evacuation strategies were effective in reducing evacuation times within the 5 km radius of the nuclear power plant. (2) Strategies that prioritized evacuating areas farther from the nuclear plant had shorter evacuation times. (3) Changes in the evacuation interval times did not proportionally affect evacuation times. This means that evacuation interval times can be adjusted according to the objective without significantly increasing evacuation time.

We expect that this study will contribute to the prediction of evacuation time or its case study in Level 3 PSA.

Acknowledgements

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