A Safety Evaluation Method of Evacuation Routes in Urban Areas in Case of Earthquake Disasters Using Ant Colony Optimization and Geographic Information Systems

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Abstract

The present study aims to propose the method for the quantitative evaluation of safety concerning evacuation routes in case of earthquake disasters in urban areas using Ant Colony Optimization (ACO) algorithm and Geographic Information Systems (GIS). Regarding the safety evaluation method, firstly, the similarity in safety was focused on while taking into consideration road blockage probability, and after classifying roads by means of the hierarchical cluster analysis, the congestion rates of evacuation routes using ACO simulations were estimated. Based on these results, the multiple evacuation routes extracted were visualized on digital maps by means of GIS, and its safety was evaluated. Furthermore, the selection of safe evacuation routes between evacuation sites, for cases when the possibility of large-scale evacuation after an earthquake disaster is high, is made possible. As the safety evaluation method is based on public information, by obtaining the same geographic information as the present study, it is effective in other areas regardless of whether the information is of the past and future. Therefore, in addition to spatial reproducibility, the safety evaluation method also has high temporal reproducibility. Because safety evaluations are conducted on evacuation routes based on quantified data, highly safe evacuation routes that are selected have been quantitatively evaluated, and thus serve as an effective indicator when selecting evacuation routes.

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Category Short Paper

1 Introduction

From the experiences gained through the Great Hanshin earthquake (1995) as well as the Great East Japan earthquake (2011), in recent years, Japan has been focusing on disaster reduction by means of self and mutual help. In case of earthquake disasters, especially in crowded urban areas, many road blockages are likely to occur due to secondary disasters

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which include the collapse and combustion of buildings. Additionally, if an earthquake disaster occurs during a big event such as the Tokyo Olympics and Paralympics, which will be held in Japan in 2020, busy urban areas especially around the stadiums are expected to be crowded with evacuees. Therefore, in such cases, it is necessary to put emphasis on how to reduce damage for risk management in central Tokyo.

In order to make a quick and safe "escape" from disasters, a clear evacuation plan, or more specifically, an evacuation route must be developed. Current efforts to develop such evacuation plans by means of self and mutual help include activities such as walking the streets for disaster prevention in addition to disaster drills using maps, and an example of the latter is Disaster Imagination Game (DIG). However, as the main purpose to create evacuation routes using such activities is the promotion of disaster prevention awareness and disaster prevention education, they are not quantitatively evaluated. As a result, the evacuation plans developed in the way described may be influenced by the developers' subjective thinking, and its practicability is left uncertain.

Based on the backdrop mentioned before, assuming a large-scale evacuation in case of an earthquake disaster, the present study aims to propose the method for the quantitative evaluation of safety concerning evacuation routes in urban areas using Ant Colony Optimization (ACO) algorithm and Geographic Information Systems (GIS). More specifically, the multiple evacuation routes extracted using ACO algorithm will be visualized on digital maps by means of GIS, and its safety will be evaluated. Based on the evaluation results, the present study will provide effective information concerning disaster reduction through self and mutual help, namely, the development of evacuation plans by individuals and voluntary disaster prevention organizations in regional communities.

2 Related Work

The present study is related to (1) evacuation routes; (2) road blockages; (3) Spatial analysis using geographic information; and (4) application of ACO algorithm for route searches. The present study comes under the first category of studies, and proposes the safety evaluation method of evacuation routes referring to the results of studies related to (2), (3), and (4). In studies related to (1), though evacuation routes were extracted, its safety was not yet evaluated. Additionally, comparing the related studies, the present study particularly targets crowded urban areas as well as densely populated areas, and in order to provide effective information concerning the development of evacuation plans for earthquake disasters, originality and usefulness will be displayed when proposing the method for the quantitative evaluation of safety concerning evacuation routes. More specifically, assuming a large-scale evacuation in case of an earthquake disaster, the present study will propose the method for the quantitative evaluation of safety concerning evacuation routes in urban areas using ACO algorithm for risk management, in order to provide effective information for the development of evacuation plans using self-help and mutual help methods, which are more direct forms of natural disaster reduction help.

3 Safety Evaluation Method of Evacuation Routes

3.1 Evaluation Method and Framework

In the present study, firstly in this section, after selecting the evaluation target area, the evacuation rules, which is the most important factor for the safety evaluation method of evacuation routes, will be introduced. In Section 4, a road network data using GIS will be made. Additionally, Road blockage probability per road and the number of estimated populations of evacuees in roads will be calculated, and will be added to the road network data as attributes. A hierarchy cluster analysis using the above data will be conducted, and roads will be classified by focusing on the similarity in safety.

In Section 5, an evaluation experiment of ACO algorithm concerning the evaluation target area will be conducted. More specifically, a simulation of congestion conditions of evacuation routes in the target area will be conducted, the parameter of the most valid evaluation results will be applied to ACO, and the congestion rate of each evacuation route will be calculated. ACO is a search method which mimics the path generation process when the ant is on the hunt for food, and it has been applied to combinatorial optimization problems such as the Travelling Salesman Problem (TSP), and has had many effective research results. Ants use pheromones to communicate while they move as a group, resulting in a type of organized system. ACO uses this system formation process for searches.

As the present study assumes a large-scale evacuation, in section 6, evacuation routes with high congestion rates will be extracted and visualized on a digital map by means of GIS, and its safety will also be evaluated. In the present study, the ArcGIS Ver.10.1 of ESRI will be used as GIS, and making of road network data, spatial analysis and the visualization of evacuation route choices will be conducted.

3.2 Selection of Evaluation Target Area

Large-scale evacuations are when many people around venues of large events have to evacuate. As the Olympics and Paralympics will be held in Tokyo Metropolis in 2020, an increase in tourists around the stadiums and other venues is expected. Therefore, if an earthquake disaster occurs in such areas, the probability of a large-scale evacuation is high. Consequently, Hongo district of Bunkyo Ward, an area close to the Tokyo Dome Stadium where a lot of sports games and entertainment events are frequently held, is chosen as the evaluation target area.

3.3 Evacuation Rules in Evaluation Target Area

3.3.1 Order of Evacuation

If an earthquake disaster occurs in Tokyo Metropolis, especially in crowded urban areas, many road blockages are likely to occur due to secondary disasters which include the collapse and combustion of buildings. Therefore, in Tokyo Metropolis, the principal of a two-step evacuation on foot must be kept as an evacuation rule in case of an earthquake disaster. In this two-step evacuation, as a first step in the evacuation from the occurrence of a disaster, evacuees will evacuate to a temporary gathering sites and the damage situation will be confirmed. After checking the damage situation, if the temporary gathering site is seen as dangerous, an evacuation to a wide-area evacuation site (more than 10 hectares) will be made as part of the second step. On the other hand, if the damage caused by fires following the disaster extends significantly and the evacuation to temporary evacuation site is seen as dangerous, evacuees will be instructed to go directly to wide-area evacuation sites (direct evacuation). In the present study, in order to evaluate the safety of evacuation route assuming a large-scale evacuation, the travel between evacuation sites will be assumed and the safety of route between evacuation sites will be evaluated.

3.3.2 Assignment of Evacuation Sites

As with the target area in the present study, University of Tokyo and an open space near the Dome Stadium are assigned as a wide-area evacuation site by Bunkyo Ward. Additionally, nine locations are also assigned as temporary evacuation sites. Therefore, in the present study, a total of ten evacuation sites have been set as both the evacuation starting points as well as destination points, and searches for evacuation routes will be conducted.

3.3.3 Evacuation Distance and Time for Evacuation Routes

Based on material from the Urban Disaster Prevention Office of the City Bureau of the Ministry of Construction and the Director-General for Disaster Management in the Cabinet Office, taking into consideration walking speed and evacuation time in times of a disaster, locations that are within 2 km of walking distance are assigned as wide-area evacuation sites. Regarding walking speed, although it is generally said to be about 4 km/h, taking into consideration the elderly and children as well as the fact that this is in case of a disaster, walking speed is considered to be 2 km/h which is half the normal speed (speed can drop to 1 km/h if in the dark).

Regarding evacuation time, from the fatality occurrences according to the cause in the Great Kanto Earthquake in 1923, it became evident that the fatalities caused by fire rapidly increased 3 hours after the earthquake, and that the first hour after earthquake quickly passed by with the transportation of injured people, first-aid firefighting, and situation grasping. Therefore, although this leaves 2 hours for evacuation, if another hour is allowed as a margin, only an hour is left for the actual evacuation time. Hence, the evacuation distance for an hour of evacuation time is around 2 km.

This shows that for evacuation route in case of wide-area evacuation, the evacuation distance must be within 2 km and a route that is within an hour of evacuation time is desirable. As mentioned in the previous section, because the present study sets all evacuation sites including temporary evacuation sites as targets, evacuation routes within 1 km of evacuation distance and 0.5 hours of evacuation time are considered desirable.

4 Creation of Road Information and Road Classification

4.1 Creation of Road Information Using GIS

In the present study, using the land use data and building use data developed by the Tokyo Metropolitan Office, the road blockage probability will be calculated from the relationship between the debris width buffer of wooden buildings along the road and the road's centerline located in front of the buildings. Therefore, the road centerlines will be extracted from the above land use data to make the node data with intersection and junctions as well as link data with roads connecting the intersections and junctions. By integrating the node data and link data, a road network data will be made. The the road blockage probability was added to the road network data as an attribute. Additionally, using the population data provided by the Ministry of Internal Affairs and Communications, and the above building use data, the estimated populations of evacuees were calculated in roads at the time of a disaster outbreak in both cases of daytime (AM 7:00–PM 6:00) and nighttime (PM 6:00–AM 7:00). The estimated populations of evacuees were also added to the road network data as attributes, and were used in the ACO when calculating evacuation time for a route.

4.2 Road Classification

Focusing on the similarity in safety and setting the road blockage probability calculated on the basis of building collapse risk, all roads in the evaluation target area were classified by the hierarchy cluster analysis using MATLAB. The Euclidean distance as the distance between objectives, and Ward's method for calculation of the distance between clusters are used. Cluster 1 has the lowest safety, and safety levels are classified into 5 levels. The road classification results will be referred to when estimating the congestion rate using ACO.

5 Evaluation Experiment of the ACO Algorithm

5.1 Method

5.1.1 Congestion Estimation Using the Back-Track Method

In this section, an evaluation experiment will be conducted to demonstrate the effectiveness of the ACO algorithm. Using the information of large earthquakes obtained from a rescue simulator, the ever-changing disaster conditions will be replayed. Additionally, route searches using ACO, which is a crowd flow model and metaheuristic solution, will be conducted to reduce the amount of calculations and to estimate real-time congestion in evacuation routes. In the evaluation experiment in this section, evacuation starting points and destination points are all considered as evacuation sites, and the congestion condition of evacuation route between evacuation sites will be estimated.

In the present study, when trying to obtain the number of evacuation routes from geographical information, a simulation by the back-track method using MATLAB will be conducted. The back-track method is a type of search that prioritizes depth, and when searching for a solution using this method, a potential process will be tested according to order. If it becomes evident that a solution cannot be found in a certain process, it will go back to the previous step and a different process will be tested.

5.1.2 Simulation Process

According to the two-step procedures, the simulation will be conducted:

(1) 1st tour: 1. All ants will select an evacuation route at random with the same probability;
2. The evaluation function of the evacuation routes selected by each ant will be calculated;
3. Based on the evaluation function value selected in ii), pheromones will be attached to the evacuation routes;

(2) From the 2nd tour on: 4. All ants will select evacuation routes following the pheromones;
5. The evaluation function of the evacuation routes selected by each ant will be calculated;
6. Based on the evaluation function value of each ant, the pheromones on the evacuation routes will be updated.

5.2 Simulation and Evaluation Experiments Concerning the Target Area

In order to verify the effectiveness of the original simulation of the present study, a comparison of three different simulation results will be conducted, by changing the number of ants in correspondence with the number of evacuees and the amount of pheromones adjusted according to the process in the previous section. By doing these, the congestion rate of each road will be estimated. In order to compare the difference in results depending on the number of ants, all parameters except for the number of ants (100, 200, 300) is made the same, and simulations for three different cases were conducted. Because there are ten evacuation sites within the target area, the number of solutions where pheromones can be updated is also seven. Additionally, the number of evacuees is represented in the number of ants. Taking into consideration the daytime and nighttime populations within the target area, the number of ants is 300 for daytime population and 100 for nighttime population.

6 Safety Evaluation of Evacuation Routes Assuming a Large-scale Evacuation

In this section, the simulation results of the previous section will be applied to the evaluation target area, and evacuation routes with high congestion rates will be extracted. From these evacuation routes, those that meet the three conditions will be extracted with reference to section 3.3.2. The extracted route will be visualized on digital maps by means of GIS and its safety will be evaluated: (i) Distance between evacuation sites is less than 1 km; (ii) Evacuation time between evacuation sites is under 0.5 hours; (iii) Congestion rate is more than 80 percent. Considering the congestion rate that represents the difficulty in activity in times of a disaster, each evacuation site will be selected as evacuation starting points. In the present study, in order to estimate the congestion rate of evacuation route between evacuation sites, the closest evacuation site to each evacuation site will be selected as evacuation destinations.

The simulations are conducted, and ACO parameters set in the cases of daytime evacuation (300 ants) and nighttime evacuation (100 ants). Since two evacuation sites which are close to the Tokyo Dome Stadium, the areas around these sites require attention especially when large-scale events are being held. Additionally, it is evident that evacuation routes with high congestion rates differ according to whether it is daytime or nighttime.

7 Discussion and Conclusion

In the present study, the multiple evacuation routes extracted were visualized on digital maps by means of GIS, and its safety was evaluated. Furthermore, the selection of safe evacuation routes between evacuation sites, for cases when the possibility of large-scale evacuation after an earthquake disaster is high, is made possible. Additionally, using the safety evaluation method in the present study, if all data and research information is updated with the future technology developments and advances in related fields, it will be possible to update and provide even more accurate information.

From land use data and building data, road network information which would be an evacuation hindrance in disasters situations was created in the present study. Because the safety evaluation of evacuation routes based on current building and road layout conditions is made possible by estimating evacuation routes with high congestion rates based on such information, it can be said that the safety evaluation method has high spatial reproducibility. Furthermore, as the safety evaluation method is based on public information, by obtaining the same geographic information as the present study, it is effective in other areas regardless of whether the information is of the past and future. Therefore, in addition to spatial reproducibility, the safety evaluation method also has high temporal reproducibility.

However, regarding spatial reproducibility, it is essential to modify the safety evaluation method, paying attention to the differences concerning types of disasters and secondary disasters between regions. In the present study, assuming a large-scale evacuation in case of an earthquake disaster and targeting a fireproofed area to conduct the safety evaluation of evacuation routes, it is required to just consider building collapse risks. On the other hand, on the same assumption as the present study in the area has a high concentration of wooden dwellings, it is necessary to consider fire risk in addition to building collapse risk.