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Tsunami evacuation simulation considering road congestion and difference in evacuation means depending on household composition

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Abstract

In the Great East Japan Earthquake, over 90% of the deaths were due to the tsunami, and many of the dead were the elderly. Old people who do not drive, have to either be evacuated on foot, or ride in a family member's car, which means that the evacuation speed of the elderly depends on the composition of their household. In addition, although evacuation by car has become acceptable following the Great East Japan Earthquake, there is a possibility that the evacuation does not run smoothly when there is road congestion, especially since evacuation traffic may build up on roads with small traffic capacity in urban areas. In this study, a tsunami evacuation simulation method considering evacuation means and speed, which depend on the composition of the household, is presented. The simulation is applied to the case of Toyohashi City, Aichi, Japan, in order to assess the simulation's performance in the presence of congestion, and to obtain a better understanding of the regional problems concerning the evacuation. It was found that congestion was indeed built up in the simulation, and the necessity of adding evacuation shelters and imposing rules to enable safe evacuation of the elderly was suggested.

Keywords: Tsunami evacuation simulation; Evacuation mean; Road congestion; Household micro-data

1. Introduction

Japan is a country prone to many natural disasters. Large-scale earthquakes have occurred frequently in the recent years, and have caused major damage. In the 2011 Great East Japan Earthquake, the tsunami caused great devastation; over 90% of the deaths were due to the tsunami. The proportion of the death toll for those aged 60 and over was more than twice the proportion of people aged 60 and over to the population composition (Cabinet Office, 2011). Evacuation using cars is unavoidable and has become acceptable following the Great East Japan Earthquake (National Public

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Safety Commission, 2017). However, when many people evacuate by car, there is a possibility that the evacuation does not run smoothly due to road congestion since evacuation traffic may build up on roads with small traffic capacity in urban areas. Besides, when the elderly who find it difficult to drive are evacuated, the evacuation needs to be either on foot or in a family member’s car. In cases where the evacuation means are constrained, it is difficult to complete safe evacuation. The evacuation speed of the elderly depends on the composition of their household which they belong to, since the possibility of riding in their family member’s car is different.

The scale of the damage varies considerably depending on which evacuation means people choose and whether they know the route to safe places. The minimum requirement for tsunami evacuation is that people evacuate to safe places before the arrival of the tsunami. Therefore, it is important to comprehend the problem and consider countermeasures beforehand through tsunami evacuation simulations, which express people's choices of evacuation means and places. Furthermore, in the simulation, it is necessary to take into consideration the possibility that the elderly ride in their family’s car.

This study aims to develop a tsunami evacuation simulation method by considering the evacuation means and speed which depend on the composition of the household to which the evacuees belong. Thus, the distribution of households with individual and household attributes are created using the microdata estimation method, and evacuation behaviors which differ depending on the evacuee’s household composition are simulated based on this distribution, while considering the possible road congestions caused by the evacuating cars. The tsunami evacuation simulation is conducted in Toyohashi City, Aichi, Japan, where the occurrence of tsunami damage is predicted in the event of a Nankai Trough Earthquake. The study will assess the simulation’s performance in predicting road congestion, and will be used to grasp a better understanding of the regional problems concerning evacuation in the event of the predicted tsunami.

2. Literature review

Extensive research has been conducted on the simulation of post- and pre-disaster evacuation under various conditions. Katada et al. (2008) developed a scenario simulator that comprehensively represents the regional situation from the earthquake occurrence to the tsunami arrival. This makes it possible to estimate more realistic human damage following a tsunami disaster by considering the road blockage due to house collapse. Koyanagi et al. (2016) developed an evacuation simulator integrated with tsunami simulation and examined the effect of human tsunami evacuation tower on human damage and evacuation behaviors. As a result, it was concluded that a tsunami evacuation tower can significantly reduce the mortality rate. Fan et al. (2015) modeled changes of evacuation demand and passable network with time lapse, and used dynamic simulation to represent the evacuation behaviors and their interactions through multiple means such as walking, car, and public transportation. The simulation results provided answers to problems such as traffic network blockage and delay due to traffic congestion. Joel et al. (2015) incorporated infrastructure, which was defined as information flow from the government to people and among people, into an agent based evacuation simulation model. It was shown that the evacuation rate is improved if the government prepares evacuation guidelines and provides information to evacuees with lessons from past disasters.

In these existing studies, conditions of emergency, changes in situation after disaster occurrence, and differences in evacuation means on an individual basis are considered, but differences in evacuation measures depending on the type of household to which evacuees belong, are not considered. Since evacuation plans that enable safe evacuation of the elderly are needed based on the fact that many were sacrificed in the Great East Japan Earthquake, it is necessary to develop a simulation method capable of representing the elderly who cannot drive or be driven by non-elderly household members. The tsunami evacuation simulation developed in the present study can be regarded as a novel simulation compared to the existing research in that it takes into account the riding of the elderly in a car driven by their household member using the estimated household micro data.

3. Estimation of household micro data

3.1. Estimation method of household micro data

In order to conduct the tsunami evacuation simulation using the households’ attributes, it is necessary to obtain data on the household units of the target area. However, it is difficult to obtain data which has all the attributes, from aggregated data such as a census. Therefore, it is necessary to estimate household micro data using population synthesis. The household micro-dataset estimation system composed of generalized attributes for the base year was developed (Sugiki et al., 2012), and rebuilt to adapt to a real city (Sugiki et al., 2015). In this study, household micro data is created using this estimation system. Then, a tsunami evacuation simulation that considers age, household composition, and evacuation means is conducted.

Fig. 1 shows the flowchart of the estimation procedure for the household composition attributes. The most characteristic point of this estimation method is the processing of relationships between continuous attributes. First, the original attribute variables $X_{is} = (x_{1s}, \cdots, x_{ms})$ (i.e., age of household members) for sample households composed of m members are converted into the non-correlated variables $P_{is} = (p_{1s}, \cdots, p_{ms})$ using a principal component analysis:

$$p_i = \sum_k^m v_{ik} x_k \, , \tag{1}$$

where p_i is a non-correlated variable for member i, x_k is the age of household member k, and v_{ik} is the principal component of i for household member k. Written in matrix form, we have:

$$\mathbf{p} = \mathbf{V}\mathbf{x} \, . \tag{2}$$

Then, based on the sample values, the cumulative frequency curve of p_i is drawn for m principal component variables as shown in Fig. 2. From equation (1) and (2), we have:

$$\mathbf{x} = \mathbf{V}^{-1}\mathbf{p} = \mathbf{W}\mathbf{p} \, , \tag{3}$$

$$x_i = \sum_k^m W_{ik} p_k \, . \tag{4}$$

To generate a synthetic household, a random number ran_{is} is generated for member i of household s. Then, p_{is} is obtained from Fig. 2, and the principal component variable x_{is} (or age) is obtained for member i of household s from equation (4). If a member composition is rare, it is obtained for member i of household s from equation (4). If a member composition is rare in the sample data set, the age composition is taken to be the same as that of the sample. The procedure is repeated to generate further synthetic households until the total number of households in the study area is attained. Therefore, by introducing the independent variables as intervening variables, the relationships between attributes are easily dealt with and the system becomes straightforward to operate.

The synthetic population is adjusted to fit the marginal conditions (e.g., population by age band by gender). Each estimation or synthesis and adjustment is probabilistic and uses the Monte Carlo approach.

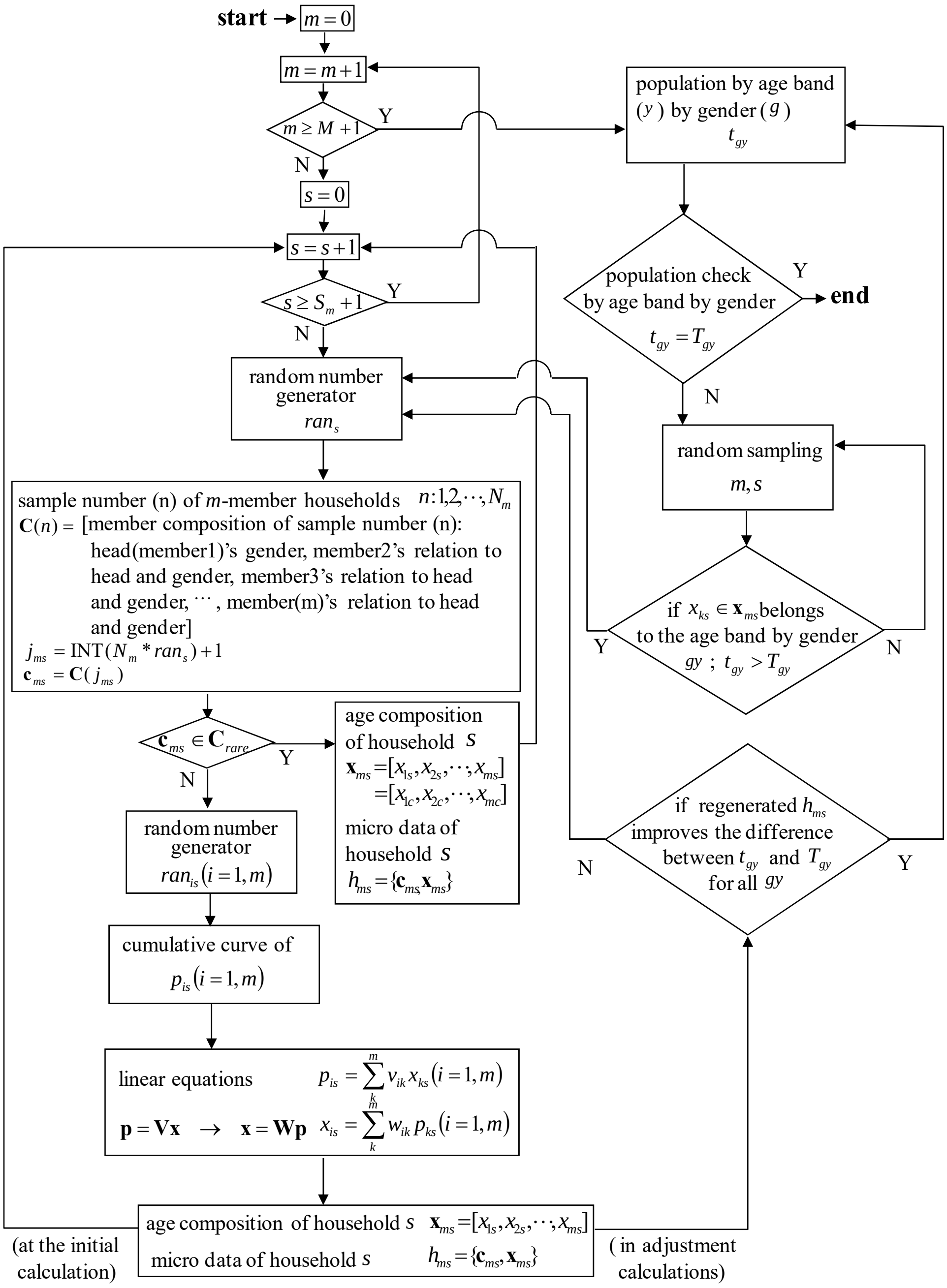
3.2. Target area and data

The target area in this study is the census zones area of Toyohashi City, Aichi, Japan, where tsunami inundation is predicted. The area is in the western district of Toyohashi City, facing Mikawa Bay, which was extracted from the Nankai Trough Earthquake damage prediction survey in Toyohashi city (2014) and Chizu Miru Toyohashi (2014). Although there is also a district facing the Pacific Ocean in the south, it is not targeted because an elevation in the district rises sharply from the coast to the inland and a tsunami would not flood the residential areas.

The marginal condition data and household sample data are required for household micro data estimation. As the marginal condition data, the population by gender and age group and the number of households by household size of the 2010 census were used. Household and members attribute data obtained from the 5th Chukyo metropolitan area person trip survey in 2011 were used as samples for household micro data estimation.

3.3. Estimation result and data allocation to mesh

Estimation of household micro data was conducted for each census zone. Household micro data was estimated as a set of household members. The overall average of the ratio of the elderly by census zones was 14.6% with the elderly being defined as persons aged over 65 years old. Based on the age of the members, households were classified into three types: households consisting of only the elderly, only the non-elderly, and the elderly and the non-elderly.



$m = [1, \cdots, M]$: number of household members

$s = [1, \cdots, S_m]$: household which has m members

S_m : number of households which has m members (Exogenous as the control total of the study area)

ran : random number $0 \le ran \le 1$

C_{rare} : rare household composition

$y = [1, \cdots, Y]$: age class

T_{gy} : total number of observed individuals belonging to g y (Exogenous as the control total of the study area)

$$\sum_m (m * S_m) = \sum_{gy} T_{gy}$$

t_{gy} : total number of estimated individuals belonging to g y

Fig. 1. Estimation procedures of household composition attributes.

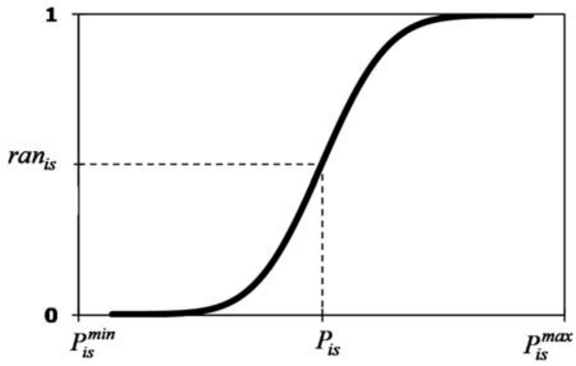


Fig. 2. Integration of correlations using uncorrelated variables.

Since the household distribution in census zone is too large for spatial aggregation to conduct the tsunami evacuation simulation, the number of evacuees by attribute in mesh units, which is a smaller spatial aggregation, was created. The number of the elderly and the non-elderly, which were obtained by aggregating household micro data-set in each census zone, were distributed to 100 m mesh units using the residential area data defined by Urban Area Land Use Subdivision Mesh Data of National Land Numeral Information in 2014.

4. Tsunami evacuation simulation

4.1. Overview

The evacuation route from each start point to the nearest evacuation shelter is obtained by searching the shortest path. The evacuees move along the route and it is judged that the evacuation is completed when they reach the evacuation shelter.

Walking and driving are considered as evacuation means. Evacuation on foot is simulated as moving at a constant speed along the evacuation route. Evacuation by car is represented using a multi-agent simulation where evacuees change their behavior depending on whether there is a car in front. Fig. 3 shows a flowchart of evacuation by car. Although the driving evacuees move along the same evacuation route as those on foot, if there is a car in front, they wait, otherwise, they move ahead.

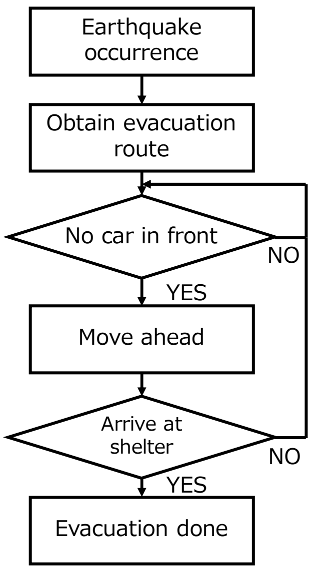


Fig. 3. Flowchart of evacuation by car.

As for evacuation start time, preparation time for the evacuation is taken into consideration. Therefore, not all evacuees start evacuation with the occurrence of an earthquake, but the start time of each evacuee is different. The evacuation start time distribution used in the simulation, which was the survey result on evacuation start time in the Tsunami disaster state survey of the Great East Japan Earthquake (2011), is shown in Fig. 4.

4.2. Data

A centroid of 100 m mesh was used as the start point of the evacuation. Fig. 5 shows the distribution of start points. Tsunami evacuation buildings, which are temporal evacuation facilities for tsunami disaster designated by Toyohashi City, were used as evacuation shelters. Fig. 6 shows the distribution of tsunami evacuation buildings. Road network data was obtained from Zmap-AREA II (Zenrin Co., Ltd.).

4.3. Simulation conditions

The elderly was defined as over 65 years old and the household microdata was classified into three household types: (a) households with only the elderly, (b) households with only the non-elderly, (c) households composed of both the elderly and the non-elderly. Two simulation cases were set up: in Case 1, (a) evacuate on foot, and (b) and (c) evacuate by car; in Case 2, (a) and (b) evacuate on foot and (c) evacuate by car.

Tsunami evacuation buildings include private facilities represented by black dots in Fig. 6. These are apartments or condominiums that do not have enough parking lots. Since these are not appropriate as evacuation places by car, the destination of evacuation by car was limited only to public facilities. Also, it was assumed that there was no restriction on the capacity of each evacuation shelter.

Each household evacuating by car uses one car. The evacuation speed by car without traffic was set to 30 km/h. Each vehicle waited if there was a vehicle within 0.5 m ahead. The evacuation speed on foot was set to 15.6 m/min for the elderly and 39.0 m/min for the non-elderly based on the Tsunami disaster state survey of the Great East Japan Earthquake (2011).

The completion of evacuation was judged by whether the evacuation completion time was earlier than the arrival time of the tsunami. The arrival time of the tsunami was set as 77 min which is calculated as the shortest time for the tsunami to reach the Mikawa bay after the predicted earthquake in the Nankai Trough Earthquake damage prediction survey in Toyohashi city (2014).

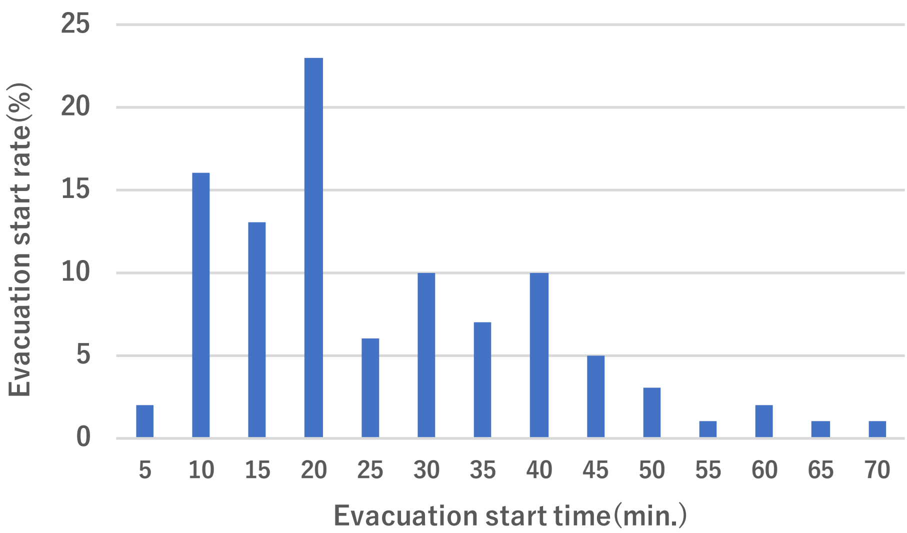


Fig. 4. Evacuation start time distribution.

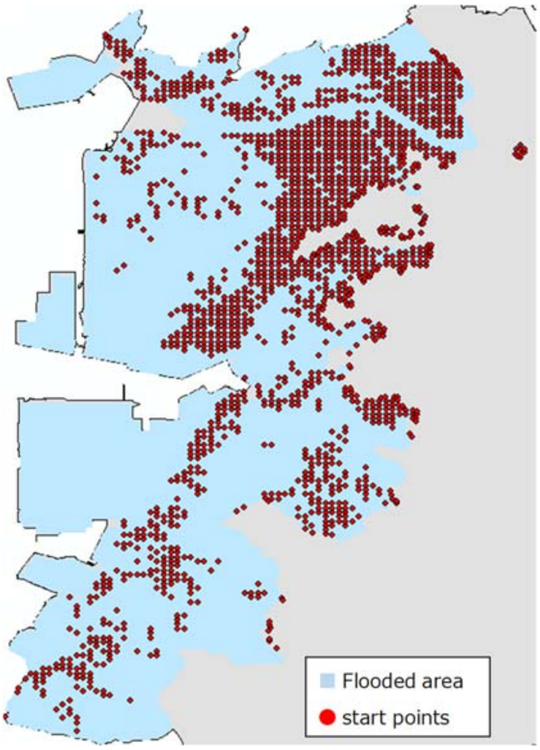


Fig. 5. Evacuation start point.

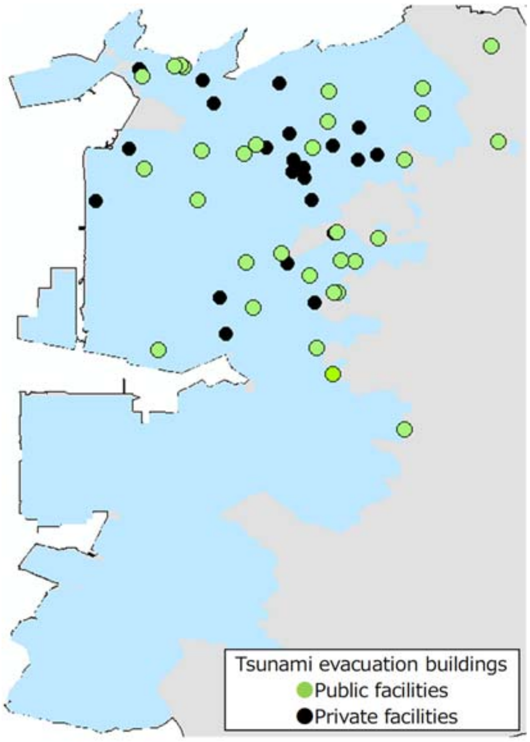


Fig. 6. Tsunami Evacuation Building.

5. Verification of adequacy of car evacuation

Here, the reproducibility of congestion in the car evacuation simulation is verified by a simple simulation. The verification targets are meshes where the evacuation destinations are Yoshidagata Elementary School, Shiota Elementary School, and Isobe Elementary School, which were randomly extracted from the tsunami evacuation buildings for car evacuation. Fig. 7 shows the tsunami evacuation buildings and the targeted meshes.

The verification result is shown in Fig. 8. In the graphs of Yoshidagata Elementary School and Isobe Elementary School, over 60% are vehicles with an average evacuation rate of 5.0 km/h or less. Since the average evacuation speed of the vehicle in the case of the Great East Japan Earthquake was 9.0 km/h, it was confirmed that road congestion was reproduced in the simulation. Furthermore, in the graph of Shiota Elementary School, since many vehicles are evacuating at a speed close to 30 km/h, which is the normal speed, it can be seen that there are areas where road congestion does not occur. The occurrence of traffic depends on the distribution of households and whether an evacuation shelter is located nearby.

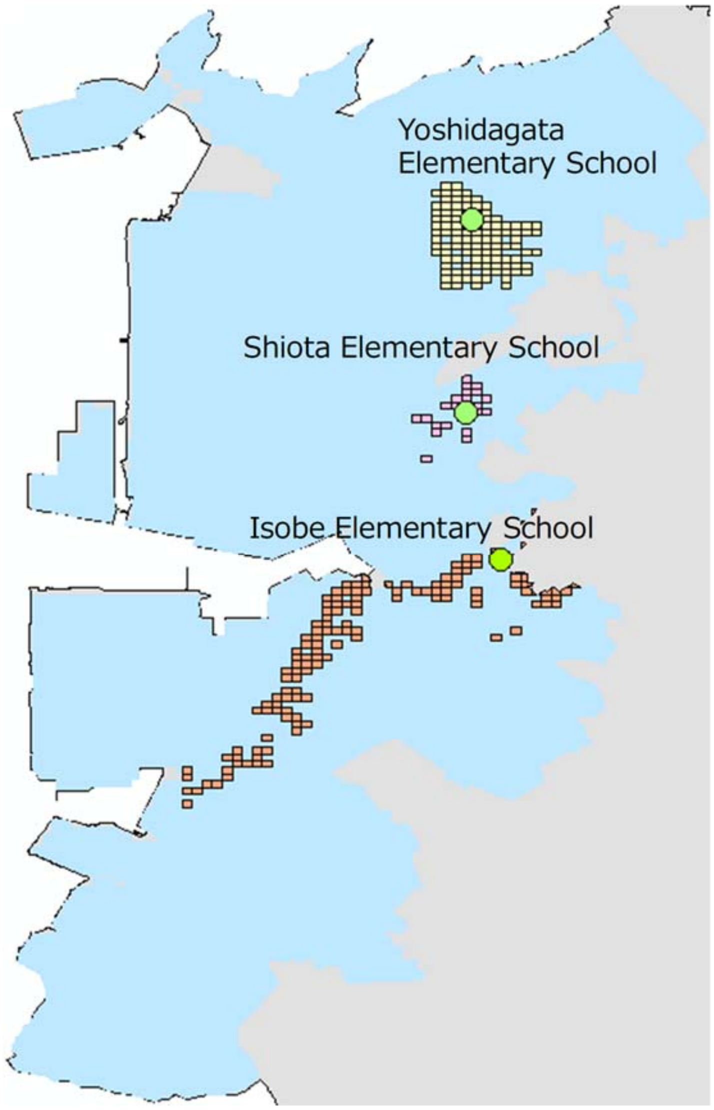


Fig. 7. Tsunami evacuation building and mesh targeted for verification

Next, assuming that car evacuation starts within a shorter time, the change in the congestion situation in the simulation is verified. Specifically, the interval of the evacuation start time distribution shown in Fig. 6 is reduced to half, and the simulation is conducted for the same three evacuation shelters.

The results are shown in Fig. 9. In comparison with Fig. 8, the average evacuation speed is slow in all evacuation shelters. It is important to start evacuation quickly in an actual disaster situation, but when many households start evacuation by car at the same time, evacuation becomes difficult due to road congestion. Thus, it was confirmed that simulation can represent traffic under various conditions.

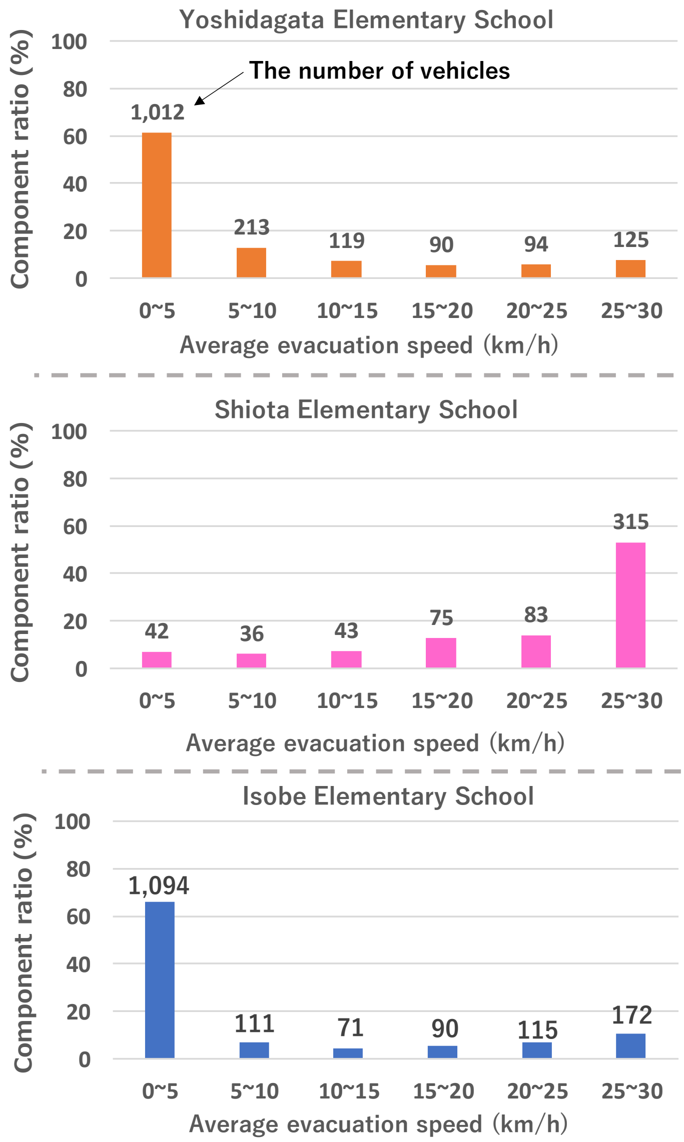


Fig. 8. Average evacuation speed in normal case

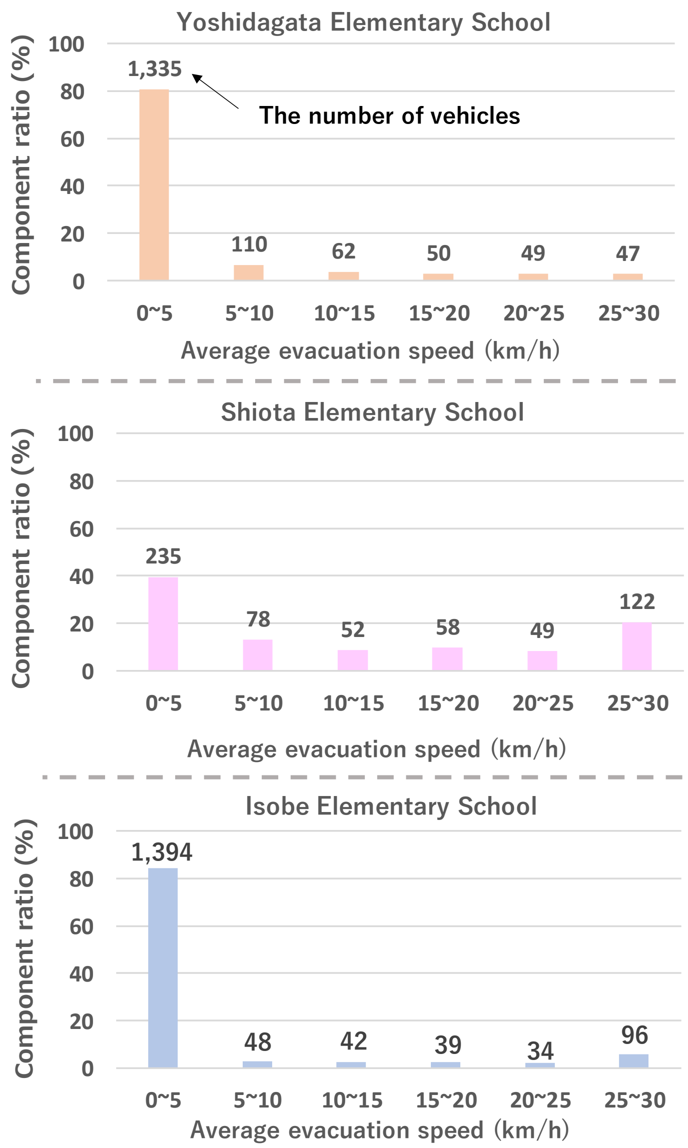


Fig. 9. Average evacuation speed in evacuation concentrated case

6. Analysis of evacuation completion status by tsunami evacuation simulation

6.1. Evacuation completion by car

Fig. 10 shows the number of evacuations completed by vehicle, and the time taken, after a disaster. The fact that there is a drastic decrease in the number of cars which, completed evacuations in 20 min compared to the number which completed it in 25 min, indicates that road congestion has occurred. Although the number of evacuation vehicles in Case 1 is about twice that of Case 2, these distributions are almost the same. Therefore, in both cases, congestion is considered to be occurring at a specific place or elapsed time. Furthermore, the evacuation completion number of households consisting of the elderly and the non-elderly in Case 2 is 1,715 more than that in Case 1. In order to increase the rate of evacuated households in the whole area, households that can evacuate on foot should do so as far as possible in order to alleviate congestion.

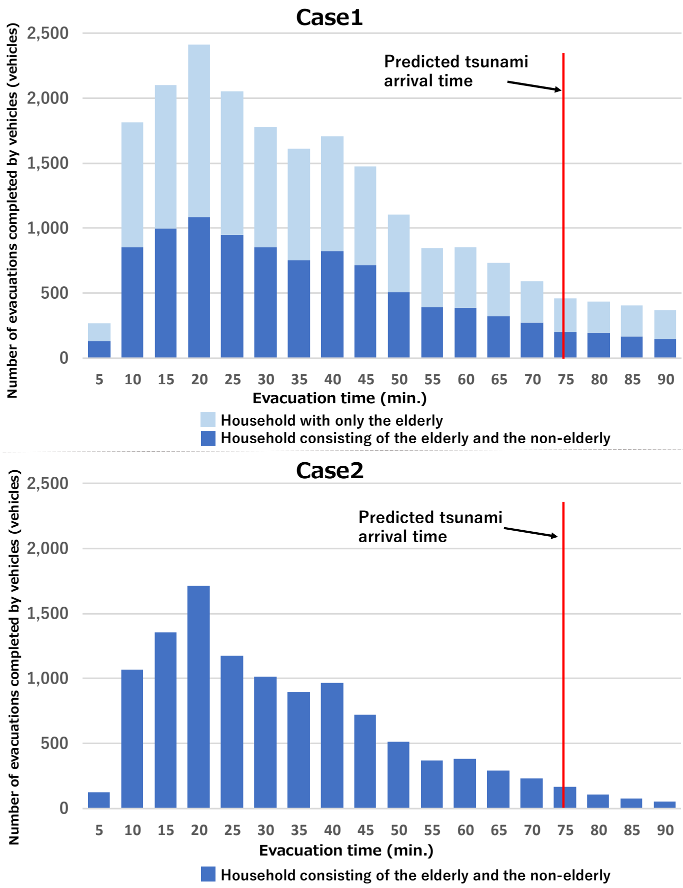


Fig. 10. Number of evacuation completed vehicles

6.2. Evacuation completion ratio

Fig. 11 shows the evacuation completion ratio for each mesh. A comparison between the two cases reveals that the evacuation completion rate in Case 2 is generally higher than that in Case 1. In both cases, the evacuation completion rate is extremely low in the southern area. This is because road congestion occurs since there is no shelter nearby, and the tsunami reaches the area before the evacuation is completed. This indicates that additional shelters are needed in the southern area. In Case 1, the area with a low evacuation completion ratio is also in the northern area. This is because this area is in the center of Toyohashi city, which is densely populated, and congestion is likely to occur. Even in areas with relatively numerous evacuation centers, one finds that evacuation cannot be completed due to traffic.

6.3. Cumulative evacuation completion rate by case

Fig. 12 shows the cumulative evacuation completion ratio of the elderly and the non-elderly over time after disaster. In both cases, the evacuation completion ratio of the elderly at the predicted tsunami arrival time is around 40%, so evacuation on foot is not realistic. Therefore, it is necessary to create rules at the community level, such that the non-elderly living near the elderly drive the elderly, with the incentive being that cars with the elderly people on board are given priority evacuation.

There is no significant difference in the evacuation completion ratio of the two cases near the predicted tsunami arrival time. Therefore, traffic will be alleviated and the evacuation completion rate in the whole area will rise by evacuating households that can evacuate on foot. However, if the capacity of evacuation shelters and road blockage are taken into account, then more serious congestion may occur. Countermeasures to alleviate congestion have a major impact on the success of tsunami evacuation.

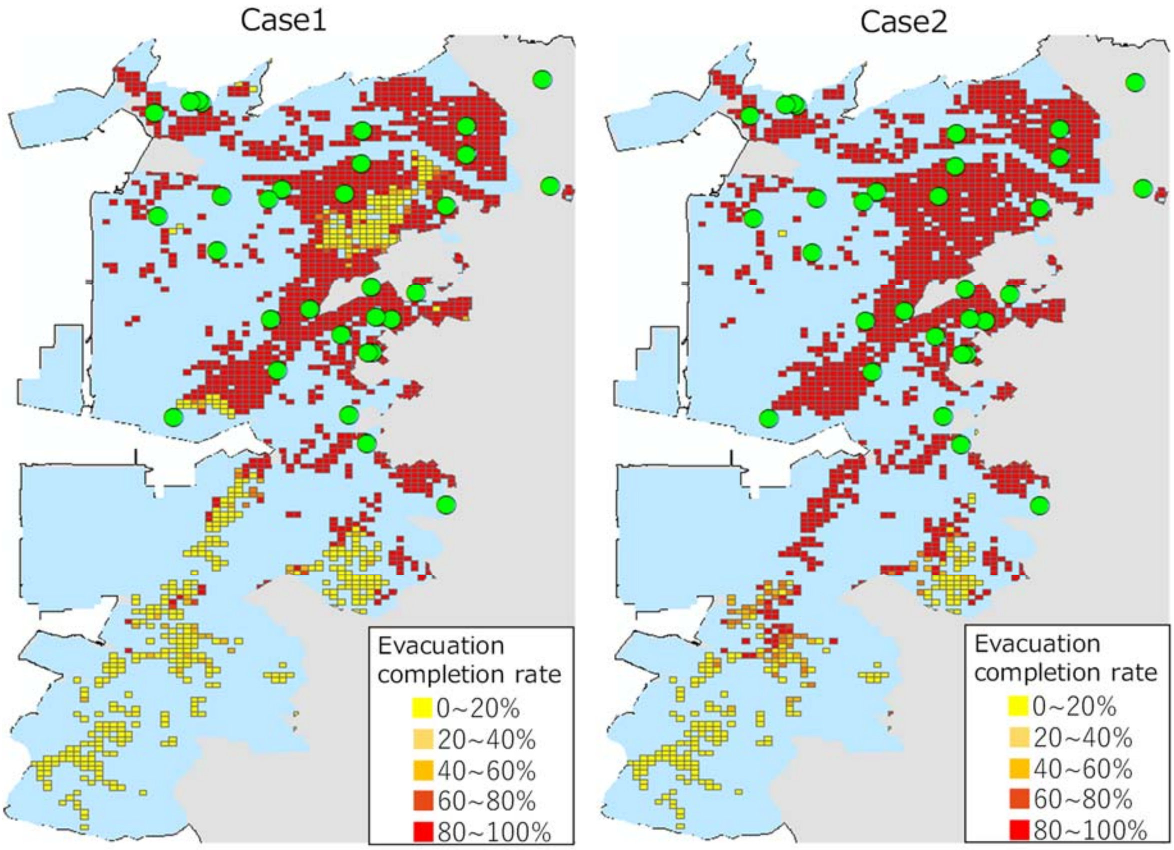


Fig 11. Evacuation completion rate for each mesh

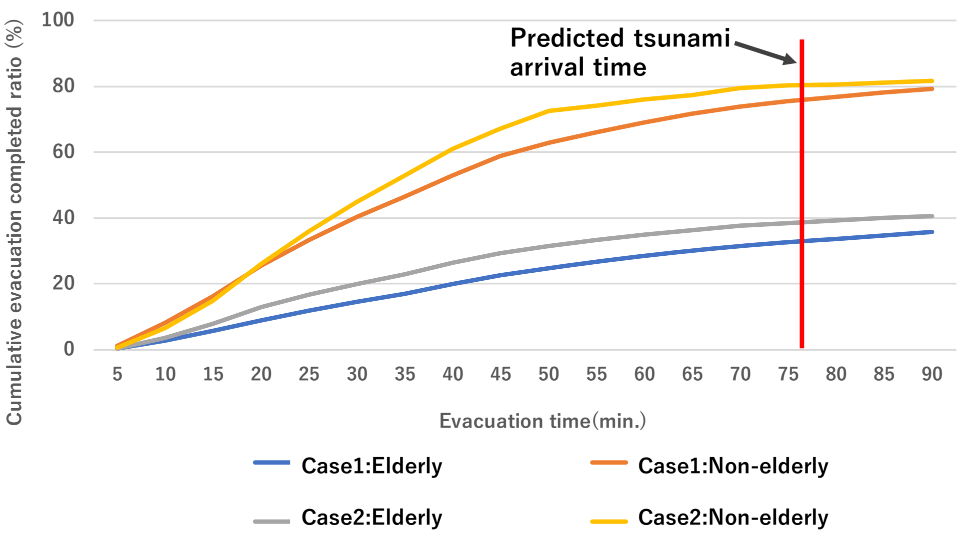


Fig. 12. Cumulative evacuation completion rate

7. Conclusion

In this study, a tsunami evacuation simulation considering road congestion and evacuation means, which depends on the composition of the household, was developed and conducted. As a result, it was found that, in some areas, traffic may result in households not being completely evacuated before a predicted tsunami arrival time. There are areas with remarkably low evacuation completion ratio in the southern region, because there are only a few evacuation shelters and congestion is likely to occur. In addition, as a result of comparing evacuation completion ratios of the elderly people and the non-elderly people in the two cases: one is households with only the non-elderly evacuated by car, and the other is households with composed of both the elderly and the non-elderly evacuated by car, it was found that the cumulative evacuation ratio of the two cases was not considerably different. In both cases, the evacuation completion ratio of the elderly at the predicted tsunami arrival time is around 40%, so evacuation on foot is not realistic. Therefore, it is necessary to add shelters and create rules at the community level.

As a further study, the simulation should be improved in order to conduct more realistic analyses. Although this study does not consider the capacity of evacuation shelters, it is paramount that these are taken into account, and express action is taken to change the evacuation destination in case evacuation centers are full. This study uses the night-time population distribution and assumes that all household members are at home. Because the production-age member is away from the residential area for work, even if a household consists of the non-elderly and the elderly, the elderly may not be able to evacuate by car driven by other household members. Therefore, it is necessary to conduct a simulation that takes into consideration different population distributions depending on the time of the earthquake's occurrence.

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