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Exhaustive analysis with a pedestrian simulation environment for assistant of evacuation planning

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Abstract

In this paper, we apply an exhaustive analysis to large-scale pedestrian flow in evacuating against tsunami. The exhaustive analysis is a method for understanding the tendency of behavior of a social system based on massive simulation scenarios. With the pedestrian simulation environment, we verify evacuation plan from the point of view of the number of the evacuees and overlapping of evacuation routes. As a result of our exhaustive analysis with 17,496 scenarios, especially in the case with many evacuees, an evacuation plan is required to guide evacuees to prevent from concentration rather than guide to nearby evacuation facilities.

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1. Introduction

Recently, although the clock rate of processors has not increased rapidly, calculation speed has been increasing owing to multiprocessor/multicore technology and GPU acceleration. Furthermore, rapid progress of cloud computing environments has afforded opportunities to deal with problems that require large-scale computational resources. Therefore, we can now treat social phenomena precisely without simplification and parameterization because we have enough computational power.

Conventionally, in modeling social phenomena, only essential parts are modeled, and the social behavior is simplified and parameterized as an environment. However, we have one problem: the number of simulation conditions increases exponentially. For example, in a model that consists of eight parameters, each having ten possible values, the number of combinations is 10^8(i.e., 100,000,000). To understand the response of this model to change in parameters, verifying an enormous simulation scenario, one that is a combination of all parameters, becomes necessary. Although we have sufficient computational resources, there is no established method to treat a massive number of simulation scenarios efficiently with parallel and distributed computing technology on a computer cluster environment.

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Based on this problem, we propose an exhaustive analysis as a method of using computing resources efficiently. This exhaustive analysis aims to understand the tendency of behavior of a social system under various conditions. The emphasis of the exhaustive analysis is not only on identifying optimal solutions but also revealing the stability of such optimal solutions and the difference between the optimal and worst cases.

In this paper, we simulate evacuation against tsunami. After the 2011 Great East Japan Earthquake, evacuation plans against tsunamis were made by local governments because the earthquake triggered powerful tsunami waves, and the tsunami caused extensive and severe damage. However, in the plans, only the locations of tsunami evacuation facilities are described. The plans do not consider congestion of vehicles and persons by overlapping evacuation routes and other realistic factors such as route choice mechanisms, physical ability of evacuees, and the degree of damage caused by the disaster. This is because there exists no reasonable technology to assist in creating and estimating evacuation plans. Therefore, as the first step in our research on exhaustive analysis within the pedestrian simulation environment, we verify the influence of overlapping evacuation routes on evacuation time under severe road conditions. In our simulation, for creating a realistic situation of tsunami evacuation, the position of evacuation facilities against tsunami and the road network pattern and size are based on actual data. Then, the number of the evacuees is calculated based on actual daytime population.

To apply exhaustive analysis to large-scale pedestrian flow, we implement the pedestrian simulator CrowdWalk and the simulation controller PRACTIS. CrowdWalk simulates pedestrian movement based on different granularities and calculation speeds. PRACTIS enables the automatic execution of CrowdWalk for exhaustive analysis.

In Section 2 and 3, we explain the characteristics of CrowdWalk and PRACTIS for exhaustive approach. In Section 4, we apply our exhaustive approach to verify a plan to evacuate 10,000 people against tsunami. Section 5 presents the conclusions.

2. CrowdWalk pedestrian simulator

2.1. Components of CrowdWalk

Our CrowdWalk pedestrian simulator is built around a one-dimensional space model and is composed of three parts: a Network Map Editor, a Simulation Engine, and a 3D Viewer. Using the Network Map Editor, CrowdWalk users can edit network map files to represent evacuation routes, including rooms, corridors, and emergency stairs in buildings and facilities. Network map files thus describe the area around which pedestrians can move. The Simulation Engine updates the position of all pedestrians at every time step according to the pedestrian movement models (Following model, Density model, and Expected Density model). There are three types of input files for the Simulation Engine: network map file, pedestrian data file, and simulation setting file. Network map files describe movable network structures with links and nodes. Pedestrian data files describe the time and link at which pedestrians are generated as well as their destinations. In simulation setting files, various parameters, such as the pedestrian movement model, update interval, simulation termination conditions, and required output data, are described.

Regardless of which pedestrian movement model is selected, the input and output data structure of the CrowdWalk Simulation Engine reamins the same. It is easy for a CrowdWalk user to apply multiple pedestrian movement models because there is no additional model calibration required. Both the network map file and pedestrian data file can be applied to multiple pedestrian movement models without modification. Furthermore, using gas diffusion files, the Simulation Engine can calculate the detriment to individual pedestrians.

2.2. Pedestrian model

2.2.1. Spatial representation

A number of evacuation simulators have been developed recently for various applications (Kuligowski and Peacock (2005)) [1,2,3]. Most pedestrian simulators use a two-dimensional continuous space model and a cellular automata

[1] A&A Co., Ltd. SimTread (online). http://www.aanda.co.jp/products/simtread/index.html.
[2] Legion International Limited. Legion studio (online). http://www.legion.com/.
[3] Savannah Simulations AG. SimTalk (online). http://www.savannah-simulations.com/simwalk/index.html.

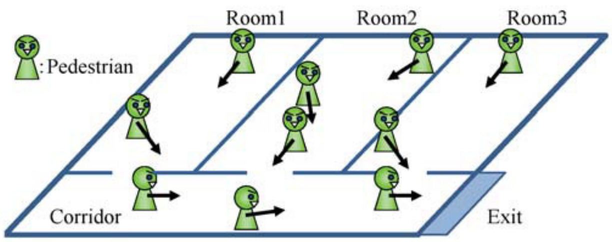

Fig. 1. Real situation.

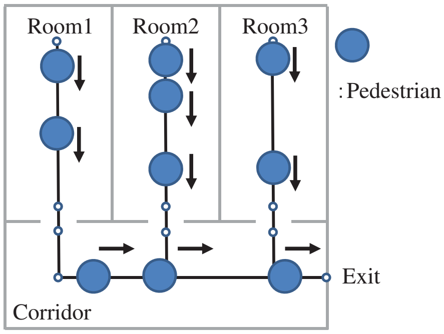

Fig. 2. One-dimensional continuous space model representing the situation shown in Fig. 1.

model to represent the space in which pedestrians move. In a two-dimensional continuous space model, pedestrians determine the direction, velocity, and/or acceleration of their movement based on the distance between neighbors and obstacles (Hoogendoorn et al. (2001), Helbing et al. (2001)). In a cellular automata model, pedestrians must decide at each time step to move to one of four cells (in a von Neumann neighborhood) or eight cells (in a Moore neighborhood) (Nishinari et al. (2003)).

However, to quickly calculate the movement of several tens of thousands of pedestrians, we use the one-dimensional space model for our simulator to realize high-speed calculations. Our one-dimensional space model simplifies the traffic flow by representing it with a graph model: a model with links and nodes. The paths along which pedestrians move are represented as links, and these are connected at nodes. Thus, in this model, corridors and rooms are treated as links, and connections between corridors and rooms (i.e., doors) are treated as nodes. Fig. 2 shows the one-dimensional space model representation of the situation in Fig. 1. At a relatively high density, pedestrians walking along corridors and rooms frequently form lines. We consider these lines as pseudo-lanes, and define a link to contain some lanes.

2.2.2. *Pedestrian velocity model*

To handle various scales of pedestrian flow, we propose three pedestrian movement models within the one-dimensional space model. We call these the Following model, the Density model, and the Expected Density model. Details of these models were described in our earlier paper (Yamashita et al. (2012)). Here, we explain only the Density model because we use CrowdWalk with the Density model in section 4.

In the Density model, a pedestrian's speed is determined by the density of other pedestrians within a certain range. We base the range of pedestrian i on the length l_{range}, which is the distance from pedestrian i in lane l_k of link L_m. The number of pedestrians within the range of pedestrian i at time t is defined as $n_i(t)$. We can then calculate the density $\rho_i(t)$ of pedestrian i at time t as

$$\rho_i(t) = n_i(t)/(w_{range} * l_{range}) \quad (1)$$

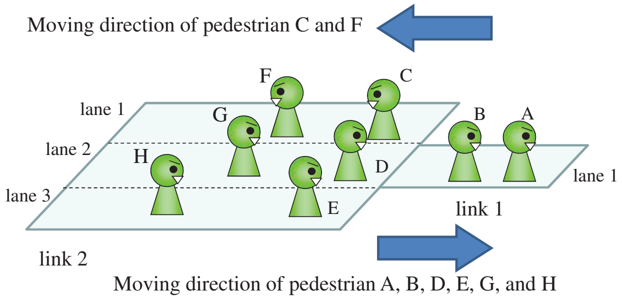

Fig. 3. Example of the Density model.

where w_{range} is the width of a lane. The speed function of pedestrian i at time t depends on the link status, whether one-way flow or counter flow. If the link is a one-way flow, the speed function (2) is applied to determine the speed of pedestrian i, and if the link has a counter flow, the speed function (3) is applied. The core idea of the speed function is based on Okada's equation (Okada (1977)).

$$v_i(t) = v^0_{oneway} - b_{oneway}\rho_i(t) \tag{2}$$

$$v_i(t) = v^0_{counter} - b_{counter}\rho_i(t) \tag{3}$$

Here, v^0_{oneway} and $v^0_{counter}$ are the free-flow speeds of the pedestrian in one-way and counter flow, and b_{oneway} and $b_{counter}$ are positive real numbers. The speed is set to a minimum v_{min}, if the distance between pedestrian i and and pedestrian i-1 falls below some minimum d_{min}. In the Density model, the speed of pedestrian i at time t does not depend on that at time t-1.

Fig. 3 shows an example of the density model with a counter flow in link 2. Pedestrians A and B in link 1, and D, E, G, and H in link 2, move from left to right, whereas pedestrians C and F in link 2 move from right to left. Therefore, to calculate the speed of pedestrians A and B in link 1, the speed function (2) is applied. For pedestrians C–H in link 2, we use speed function (3).

2.2.3. Pedestrian route choice model

CrowdWalk has a simple and static route choice model. At simulation setting, a CrowdWalk user sets the origin, via-points, and destination of a pedestrian. The origins belongs to a link, and the via-point and destinations belong to a node. In the simulation, at first, a pedestrian takes the shortest path from the origin to the first via-point. After passing all via-points in the assigned order, a pedestrian moves along the shortest path to the destination. With this model, it is difficult to simulate the behaviors of a pedestrian who changes the route based on congestion on a road network and a pedestrian who follows others going the opposite way. However, the advantage of this model is that overlapping of routes can be set easily.

For example, to analyze the relationship between the passage number of pedestrians and passage time, we just need to control the number of the pedestrians passing the link and measure the passage time. If a pedestrian has a dynamic route choice mechanism, controlling the route choice of pedestrians is difficult; that is, some pedestrians will avoid the crowded link. However, with this model, we can control the route choice of pedestrians completely.

3. PRACTIS simulation controller

3.1. Functionalities for exhaustive analysis

To support effective planning for the evacuation in various scenarios, we use the PRACTIS simulation controller. PRACTIS enables an exhaustive analysis to be performed efficiently in a cluster environment. Fig. 4 illustrates the

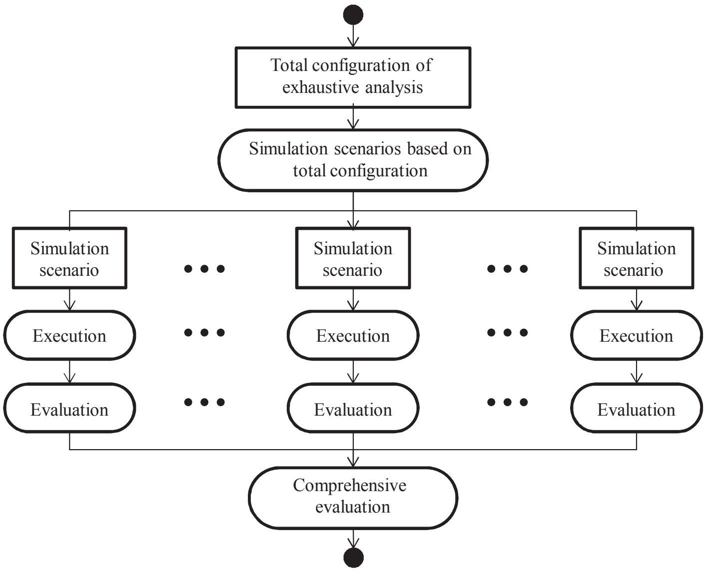

Fig. 4. Overview of exhaustive analysis procedure.

process of exhaustive analysis. First, the target parameters and their ranges within the simulation settings are described to allow a total configuration of the exhaustive analysis. Next, each simulation scenario is generated based on the total configuration. The generated simulation scenarios are automatically executed. Finally, the results of the simulation scenarios are statistically evaluated.

3.2. Components of PRACTIS

To realize the three functionalities identified in the previous subsection, we develop the simulation controller PRACTIS. Fig. 5 gives an overview of PRACTIS, and shows the components of functionality distributed by cluster node in a server cluster. PRACTIS consists of four components: a Scenario Generator, an Execution Controller, a Resource Manager, and a Simulation Analyzer.

The Scenario Generator formulates simulation scenarios from the total configuration of the exhaustive analysis. Here, a simulation scenario consists of a network map file, a pedestrian data file, and a simulation setting file. The Scenario Generator sends all scenarios to the Execution Controller, which distributes simulation executables and simulation scenarios to the cluster nodes. This distribution is determined by the calculation volume of each scenario and the resources available to the server cluster environment. When a cluster node completes a simulation scenario, it reports its status and the simulation result to the Resource Manager. The Resource Manager sends notification of that cluster node's availability, and the Execution Controller then distributes the next executable and simulation scenario. Finally, the Simulation Analyzer evaluates the simulation results.

4. Exhaustive analysis

In this section, we apply our pedestrian simulation environment with CrowdWalk and PRACTIS for verifying evacuation plan against tsunami. Once a tsunami wave is generated, the best way to alleviate human suffering is to move to higher grounds. Further, many Japanese local governments deem schools and condominiums in such places as evacuation facilities. In evacuation plans, the distance to an evacuation facility is considered, but the congestion caused by the concentration of evacuees rarely is. Therefore, we verify with exhaustive analysis the influence of the number of the evacuees and overlapping of evacuation routes on evacuation time. Here, our purpose is not to search the optimal combination of evacuation routes from city blocks to evacuation facilities. Our purpose is to understand

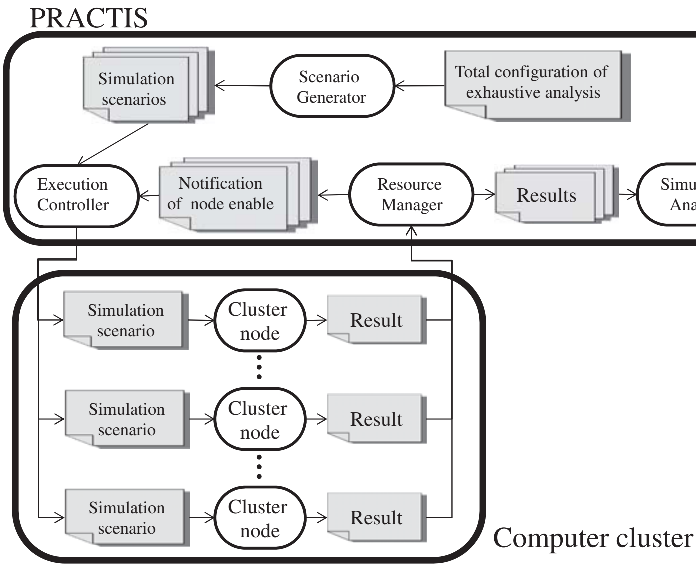

Fig. 5. Architecture of PRACTIS in a cluster environment.

the tendency of the evacuation time to be influenced by the number of evacuees and the combination of evacuation routes. The exhaustive analysis is expected to reveal the difference and distribution between the optimal and worst cases.

4.1. Simulation settings

4.1.1. Map data

We simulate the road structure (1.4 km × 1.3 km) shown in Fig. 6, which is in a part of Kamakura city that faces the Pacific Ocean. In this network map, there are 5,286 nodes (intersections) and 6,530 links. There are seven city blocks (B1,. . . ,B7) (origins) and three evacuation facilities (F1, F2, and F3) (destinations). The width of a sidewalk of a general road and a main road are set as 2.0 m and 4.0 m, respectively.

4.1.2. Number of evacuees

Table 1 shows the number of pedestrians generated in city blocks under cases 1 through 8. We prepare eight conditions for the total number of evacuees: 70, 1,000, 2,000, 3,000, 4,000, 5,000, 7,500, and 10,000. The actual nighttime population of this area is 7,500, i.e., case 7. The actual nighttime populations of city block B1,. . . , B7 are also used in case 7. Other cases have the same population ratio as case 7. The aim of case 1 is to estimate the evacuation time based on distance because there are only a few pedestrians in this scenario. The evacuation time under case 1 depends only on the distance from city blocks to evacuation facilities.

4.1.3. Route choice

As for route choice, the evacuees generated in each city block have three candidate destinations, i.e., the three evacuation facilities (F1, F2, and F3), as shown in Fig. 6. In this simulation, we set a precondition of route choice: the evacuees generated in a particular city block have the same destination. Under this precondition, we obtain 2,187 ($=3^7$) scenarios based on all combinations of evacuation routes. Here, a scenario is defined as a set of parameters used for simulation.

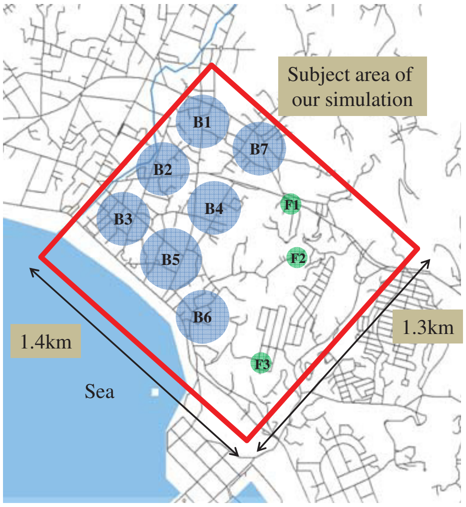

Fig. 6. Road network of a part of Kamakura city.

4.1.4. Scenario generation

Using 2,187 scenarios and six cases of the number of evacuees as the total configuration of exhaustive analysis, the Scenario Generator in PRACTIS generates 17,496 pedestrian data files (= 2,187 scenarios × 8 cases). In this simulation, the differences in the conditions are the number of evacuees and destinations of each city block. The same network map file and simulation setting file are used for all scenarios.

Our cluster environment has 4 compute nodes, and each node has 32 cores (i.e., 128 cores in total). Each node uses four AMD Opteron 6282 SE (2.6 GHz) processors and 128 GB RAM. The Execution Controller assigns scenarios to the 128 cores.

Table 1. Number of pedestrians generated in city blocks.

Ctiy block	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8
B1	10	137	274	412	549	686	1028	1371
B2	10	131	261	392	523	653	980	1306
B3	10	202	404	605	807	1009	1514	2019
B4	10	87	175	263	350	438	657	876
B5	10	189	378	567	756	945	1418	1891
B6	10	157	314	470	627	784	1176	1567
B7	10	97	194	291	388	485	727	970
Total	70	1000	2000	3000	4000	5000	7500	10000

4.2. Simulation result

4.2.1. Evacuation time

Fig. 7 shows the evacuation time of 2,187 scenarios of cases 1 to 8. The horizontal axis represents the scenario of route choice, and the vertical axis represents the evacuation time of each scenario. The left edge of the horizontal axis represents the minimum evacuation time of all 2,187 scenarios in each case, and the right edge represents the maximum evacuation time. In case 1, the movement of the evacuees is not influenced by congestion. The minimum evacuation time is 18 minutes and the maximum is 29 minutes. This extension of evacuation time depends on the

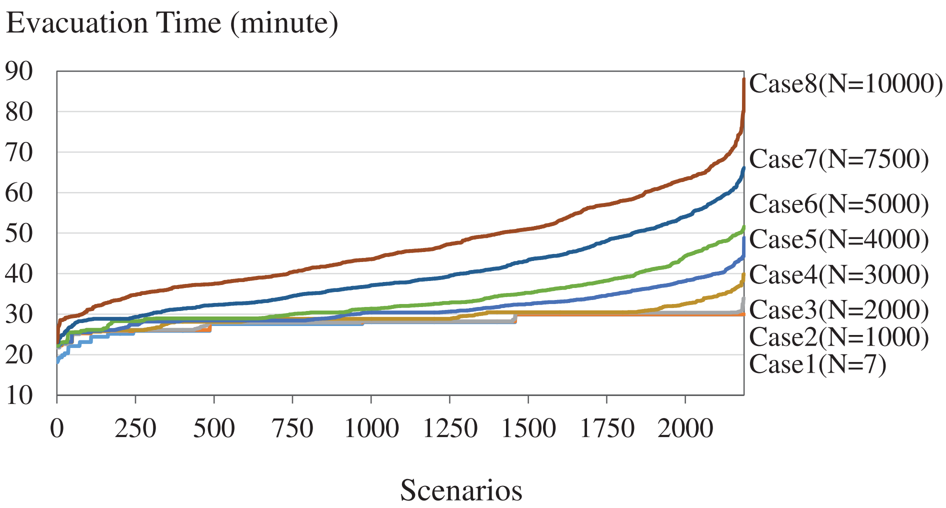

Fig. 7. Evacuation time for 2,187 scenarios of cases 1 to 8 in ascending order.

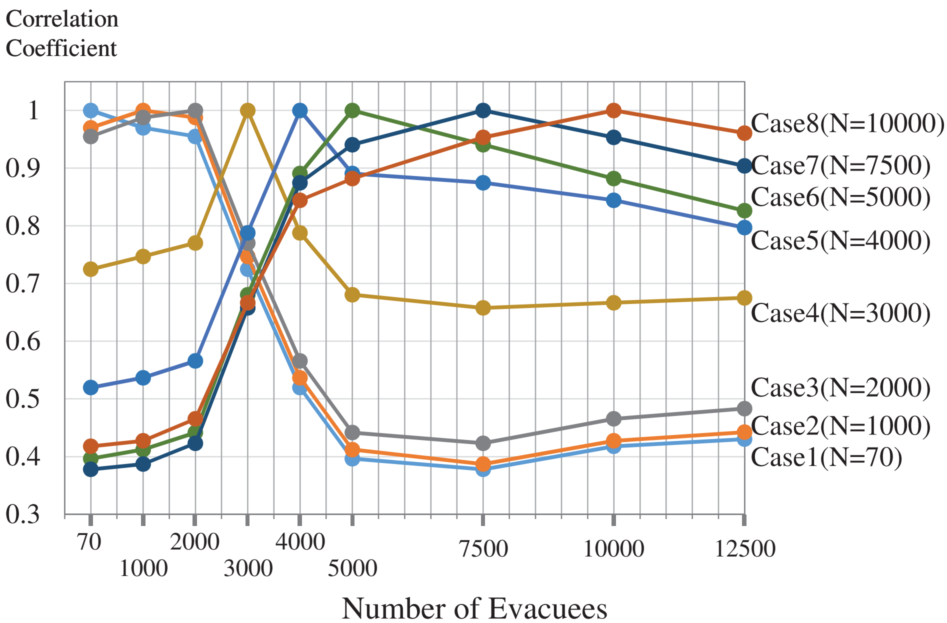

Fig. 8. Correlation of the evacuation time of case 1 to 8.

distance from the origin to the destination. The evacuation time is extended by 11 minutes with the increase in distance. The evacuation times of case 2 and 3 are similar to those of case 1. As the number of evacuees increases in cases 4 to 8, the evacuation time grows.

This is especially true for case 8, in which the minimum evacuation time is 23 minutes and the maximum is 88 minutes. As the number of evacuee increases from case 1 to case 8, the shortest evacuation time is extended by 5 minutes (=23-18). Furthermore, as a result of the comparison between the left edge of case 1 and the left edge of case 8, the largest influence of the increase of the evacuees and the overlapping route extends the evacuation time by 70 minutes (= 88-18). The influence of the route overlapping in each case is represented as the difference between the right and left edge. As the number of the evacuees increases, this difference becomes larger, and the influence of the route overlapping increases. This result means that an evacuation plan is required to guide evacuees to prevent congestion rather than to only guide them to nearby evacuation facilities.

4.2.2. Correlation between cases

Next, to reveal the influence of the number of the evacuees quantitatively, we perform correlation among the evacuation time of all cases. Fig. 8 shows the correlation among the evacuation time of cases 1 to 8. The horizontal axis represents the number of the evacuees and the vertical axis represents the correlation of the evacuation time. In this graph, the correlation coefficients of cases 1, 2, and 3 are each more than 0.9. The correlation coefficient of case 4 is moderate, hovering around 0.7. The correlation coefficient of cases 5, 6, 7, and 8 are each more than 0.8.

The results of cases 1 to 3 have similar evacuation times because the evacuation time depends only on distance to the evacuation facilities and not the number of evacuees; the number of the evacuees are not so large compared to the size of network. Case 4 has no similar cases. Case 4 has more evacuees than cases 1 to 3, where there is no congestion, and has fewer evacuees than cases 5 to 8, where congestion always occurs. Therefore, case 4 lies on the dividing line between light congestion scenarios (cases 1 to 3) and heavy congestion scenarios (cases 5 to 8). In cases 5 to 8, the number of evacuees are enough to cause congestion. The evacuation times of cases 5 to 8 differ, but the tendencies of these cases are similar.

Based on this result, we propose that when there are more than 3,000 evacuees in the area, the local government needs to pay special attention to guide evacuees. To decrease the evacuation time, an evacuation plan should focus on guiding evacuees to prevent congestion, because the dividing line of constant congestion is 3,000 evacuees.

5. Conclusion

In this paper, we proposed an exhaustive analysis as a method for understanding the tendency of behavior of a social system under various conditions. For the implementation of the exhaustive analysis, we used the CrowdWalk pedestrian simulator and the PRACTIS simulation controller. The pedestrian simulation environment using CrowdWalk and PRACTIS was confirmed to be suitable for the exhaustive analysis of large-scale pedestrian flows in a cluster environment. We applied this pedestrian simulation environment to verify the evacuation plan of 10,000 people against tsunami from the viewpoint of overlapping of evacuation routes. As a result of our exhaustive analysis, we demonstrated that especially in the case of a large number of evacuees, disaster prevention agencies and local governments need to not only guide them to nearby evacuation facilities but also guide evacuees in order to prevent congestion.

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