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Agent-Based Tsunami Crowd Evacuation Simulation for Analysis of Evacuation Start Time and Disaster Rate in Zushi City

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Abstract. In this study, we developed a tsunami crowd evacuation simulation system that can be operated by local governments using a game engine and open data. The purpose of this system is to visualize the evacuation behaviours of agents and obtain data for the disaster prevention planning of local governments, such as the locations of tsunami evacuation buildings and evacuation routes. The simulation results for Zushi City showed that the disaster rate increases rapidly with tsunami height and the time margin for tsunami evacuation has a significant impact on damage reduction. The locations where agents were affected revealed that there are insufficient evacuation sites, such as tsunami evacuation buildings, along inland rivers. However, Zushi City has a maximum height limit for buildings set by its landscape ordinance, so the local government and residents must work together to develop a town that balances disaster prevention and landscape.

Keywords: Tsunami Evacuation, Game Engine, Open Data, Agent, Simulation.

1 Introduction

A tsunami is a large-scale wave propagation phenomenon in the ocean caused by the rapid deformation of the topography due to an earthquake. Large tsunamis are natural disasters with very long wavelengths and large wave heights, which can penetrate deep inland from the coast and cause serious damage [1]. As a result of the 2004 Sumatra Earthquake, more than 220,000 lives were lost due to tsunamis with wave heights of up to 34 m [2,3]. As a result of the 2011 Great East Japan Earthquake, a tsunami with wave heights of up to 40.1 m resulted in more than 18,000 deaths and serious damage to the Fukushima Daiichi Nuclear Power Plant [4,5]. In Japan, earthquakes in Tokai, Tonankai, and Nankai are predicted to occur in the first half of the 21st century [6,7]. Such earthquakes have caused major earthquakes and tsunami damage in the past. It has been noted that when these earthquakes occur, large tsunamis may be generated over a wide area of the Japanese archipelago.

Previous tsunami simulations have mainly been conducted by numerical calculations [8,9]. These numerical tsunami simulations are based on the initial tsunami waveforms estimated from the seismic waves as the earthquake occurs. This method can predict the behaviour of tsunamis from the source area to the coast of the bay. These have been

used to predict tsunamis at the national level because they require large-scale calculations.

However, the hazard maps of local evacuation routes and tsunami evacuation buildings that residents of coastal areas refer to in the event of a disaster are produced by local governments based on the large-scale simulation results of inundation areas, tsunami arrival times, and tsunami heights. Because these hazard maps are developed using the data provided, they are subject to significant revision by local authorities when the original simulation results change. Since the Great East Japan Earthquake, many local governments have redesigned their hazard maps due to the large-scale risk review and data updates.

Agent-based simulations have been conducted in the past. Mas et al. proposed an evacuation model for the Great East Japan Earthquake that integrates numerical tsunami simulation and casualty estimation assessment [10]. Wang et al. studied a multi-modal evacuation simulation for a short-range tsunami on the Oregon coast using Netlogo, an agent-based modelling framework [11]. Mostafizi et al. evaluated nearby vertical evacuation behaviour and evacuation sites using agent-based modelling because vertical evacuation is an alternative protective measure to horizontal evacuation in the event of a near-field tsunami [12]. There have also been studies on tsunami evacuation simulation using cellular automata [13,14] and tsunami flow calculation using flow-based models [15,16]. However, these approaches require specialist knowledge to operate and discuss the results. At the local government level, it is not possible to build and operate conventional tsunami simulations, which makes it difficult to conduct independent trials of detailed simulations under various conditions.

In this study, we developed a tsunami crowd evacuation simulation system that can be operated by local governments using a game engine and open data. This system focuses on the evacuation behaviour of agents, visualizes the predicted disaster areas, and obtains data for disaster prevention planning of local governments, such as the layout of tsunami evacuation buildings and evacuation routes.

2 Methods

2.1 Modelling of Target Areas

The study area was Zushi City, Kanagawa Prefecture, which is an urban area on the coast of Sagami Bay, facing the Pacific Ocean. Due to the existence of the Sagami Trough in Sagami Bay, which has a water depth of over 1000 m, this area has been repeatedly affected by tsunamis caused by earthquakes off Sagami Bay in the past. In the 1923 Taisho Kanto Earthquake Tsunami, a tsunami wave height of up to 9 m was recorded. Zushi City is located in the north-western part of the Miura peninsula, facing Sagami Bay, and is a bedroom town for Tokyo and Yokohama, with many residential buildings and a tourist resort with swimming beaches. Because of the large number of people living there and visiting, there is a need for proper disaster management planning in the area.

The geographic model of the target area was made using the Basic Map Information download service [17]. The Geospatial Information Authority of Japan (GSI) has taken the lead in the development of this system, and the basic map information is provided free of charge online. The geospatial information of the Basic Map Information is used as the basis for the development and publication of a wide range of data by local governments and private businesses, enabling them to correctly link and superimpose data from different sources. The XML data downloaded from this service can be read by the Basic Map Information Viewer [18] display software, which converts it into Shape format data and exports it (see Figure 1).

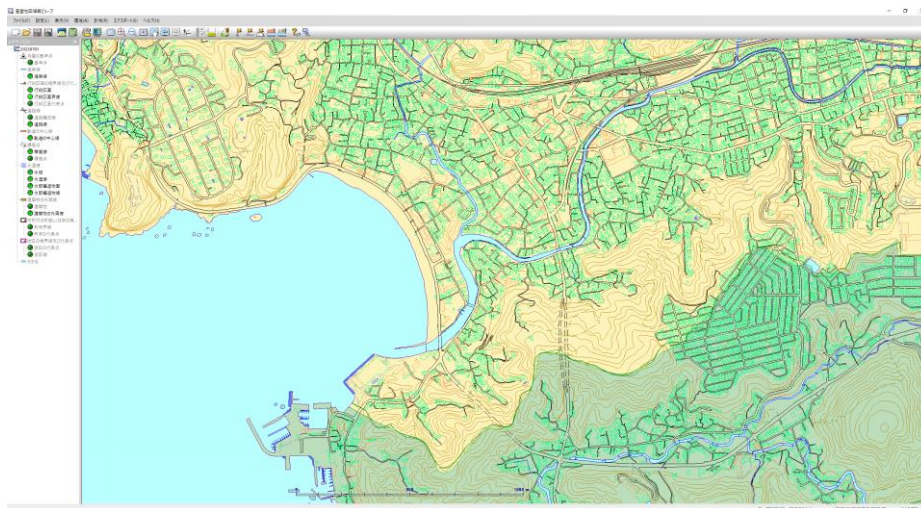


Fig. 1. Geographical information of Zushi City and its surroundings in Basic Map Information Viewer.

Next, the converted Shapefile can be loaded and displayed as a new vector layer in QGIS [19], a cross-platform open-source geographic information system (GIS) with browsing, editing, and analysis functions (see Fig. 2). In QGIS, we used TileLayer-Plugin [20], a plugin for adding tilemaps to the map canvas, and Qgis2threejs [21], a three-dimensional (3D) visualization plugin using WebGL. The three.js JavaScript library was used to create 3D geographical information data with height information. The 3D data processed in QGIS was exported in STL format data as three layers: terrain, roads, and buildings.

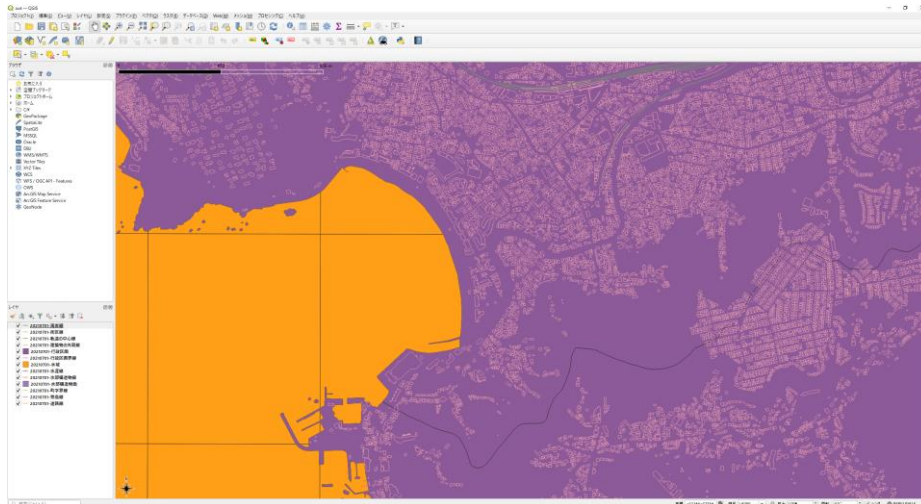


Fig. 2. Geographical information of Zushi City and its surroundings in QGIS.

The data in STL format was loaded into Blender, an open-source integrated 3D computer graphics software [22]. The road surface of the urban area was created by generating polygons on the surface corresponding to the road surface from the road edge data. The buildings were created from the perimeter lines of the buildings, and the assumed building heights were input from the floor–area ratios of the zoning districts on the city planning map of the target area. The 3D model data created in Blender was exported in FBX format after organizing polygons and reducing the weight of the model (see Fig. 3).

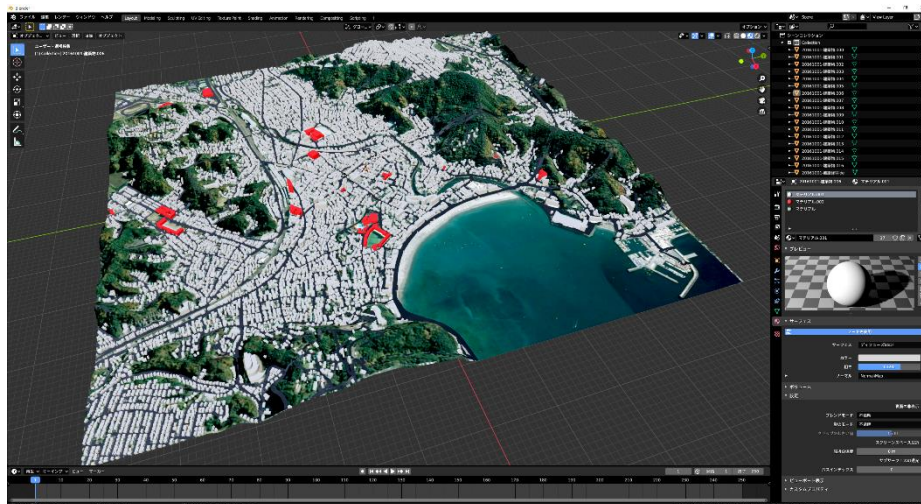


Fig. 3. 3D models of terrain, buildings, and roads in Blender.

These geographic data were imported into the UNITY game engine [23], an integrated development environment, to represent the tsunami and evacuation behaviour of agents.

2.2 Tsunami Model and Evacuation Behaviour of Agents

According to the Manual on Tsunami and Storm Surge Hazard Map prepared by the Ministry of Land, Infrastructure, Transport and Tourism in Japan [24], the choice of inundation forecasting method should be accurate according to the purpose of preparation and target of evaluation. It is said that setting the numerical simulation considering the time series can obtain the high-accuracy data necessary for the preparation of a hazard map, such as data on the time course of inundation and inundation depth data of each point. However, the number of trials is limited due to the high computational cost. In contrast, a simple method is to set the tsunami run-up based on the ground height. This can be achieved with simple calculations, but it does not predict the exact flow velocity, inundation start time, and time-series effect of tsunami run-up due to topography.

This system is based on the inundation prediction method based on ground height, and the tsunami model is moved at a specified speed to partially account for the time series, such as the inundation start time. In this study, a sloping plane rotated by 0.1 degrees was prepared as a tsunami model and inserted into the 3D terrain model to reproduce the time-series inundation according to elevation. This is a lightweight tsunami model because it does not provide for changes in flow velocities due to topography and buildings but can be represented by simple calculations (see Fig. 4).

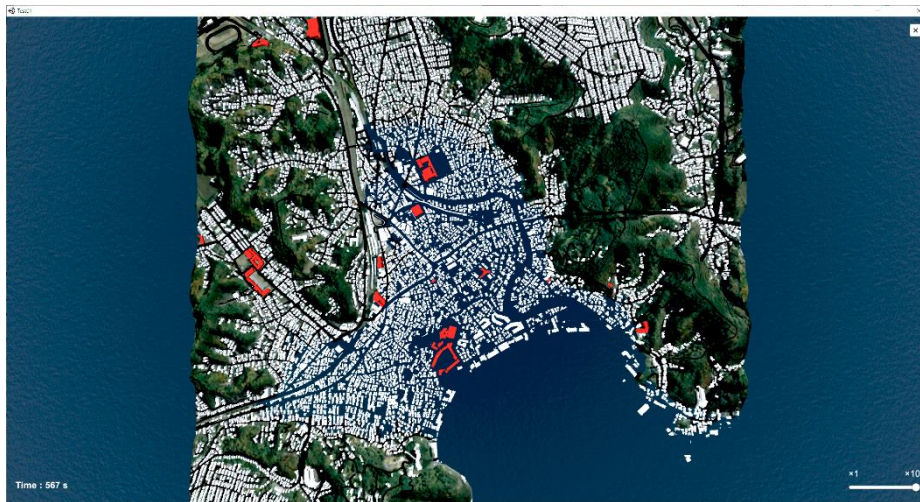


Fig. 4. Maximum inundation area in Zushi City for a 12 m high tsunami.

In this system, we created agents to autonomously evacuate from the tsunami. Each agent acted according to a given condition, and 10,000 agents were set to evacuate at the same time. After the tsunami, the agents evacuated to the nearest high ground or tsunami evacuation building from their coordinates at a predetermined speed. Each tsunami evacuation building has a fixed capacity. Therefore, when an evacuated agent arrives at a tsunami evacuation building, if the building is over capacity, the agent cannot enter the building. After confirming that the building capacity has been exceeded, the agent searches for the nearest evacuation site from the current coordinates and starts evacuating again.

The agents prepared for this system had three age attributes: children (5–14 years old), adults (15–64 years old), and elderly (65+ years old). The moving speed of a child agent was 1.2 m/s, and the depth of the affected tsunami was 0.3 m. The moving speed of an adult agent was 1.5 m/s, and the depth of the affected tsunami was 0.6 m. The moving speed of an elderly agent was 1.0 m/s, and the depth of the affected tsunami was 0.6 m. Children under 4 years of age were assumed to be evacuated alongside adult agents. Each agent was color-coded according to its type (see Fig. 5).



Fig. 5. Agents color-coded by age group.

The tsunami height and arrival time are registered in the configuration screen of the system. The agents with the numbers and characteristics registered in the configuration screen at the same time are randomly placed on the road surface in the target area after the simulation starts. The agents move to the nearest high ground or tsunami evacuation building, indicated in red, from their coordinates (see Fig. 6). The agents who were evacuated to high ground above the set tsunami height or to the tsunami evacuation building are represented by an orange bar to indicate where the agent evacuated to. Conversely, when the sloping plane representing the tsunami is greater than the affected tsunami height set for an agent, the agent is identified as a damaged agent. Damaged agents turn into pink bars on the spot and stay in the affected location. The areas where the pink bars are concentrated are considered to be the locations where most people are affected (see Fig. 7).

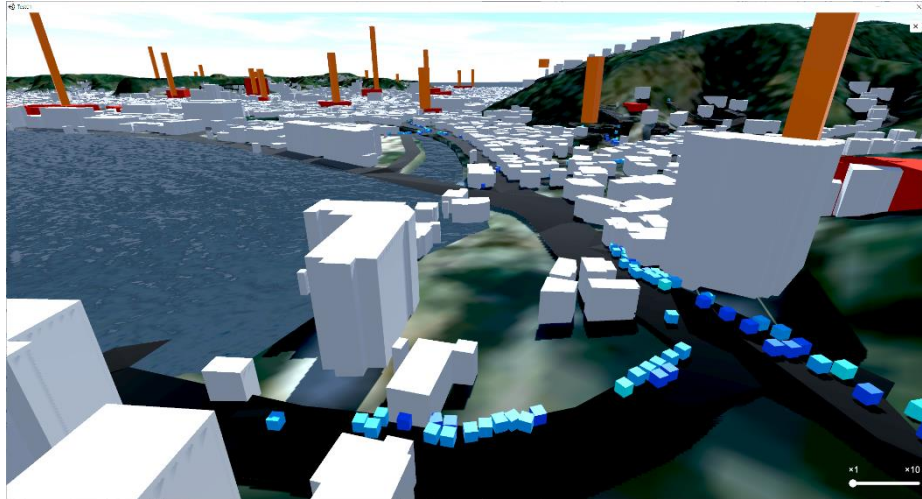


Fig. 6. Agents evacuating to nearest high ground or tsunami evacuation building.

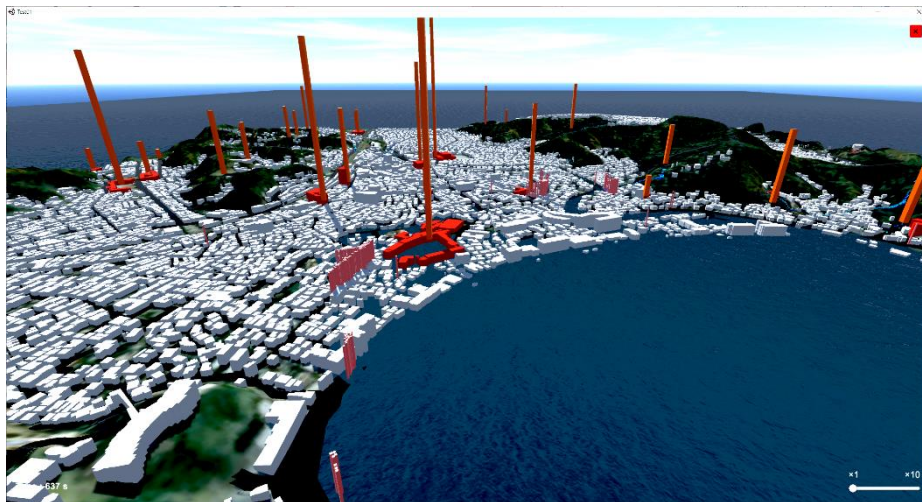


Fig. 7. Tsunami evacuation buildings (red), number of agents evacuated (orange), and affected agents (pink).

At the end of the simulation, a results screen is displayed, showing the number of affected people in each age group, and the results are exported as a CSV file. Because the agents are randomly placed on the roads, the results will vary depending on the initial conditions of the simulation. Therefore, it is possible to collect and analyse the data by repeated trials under different initial conditions.

3 Results and Discussion

Using this system, a crowd evacuation simulation was conducted for Zushi City. According to the statistics of Zushi City, there are 4787 households and 10729 inhabitants in the target area of this system, so we prepared 10000 agents for this simulation [25]. From the same statistical data, the age structure of the residents was also set in the same proportions as in the real city: 8% child agents, 60% adult agents, and 32% elderly agents. According to the Zushi City Tsunami Hazard Map, the maximum estimated tsunami height is 12.8 m, and the minimum tsunami arrival time is 9 min [26]. Therefore, in this simulation, six patterns of tsunami heights of 4–14 m (in 2 m intervals) at the time of arrival at the coast were prepared as tsunami conditions. In addition, we prepared three evacuation start times for the agents: after the tsunami reaches the coast (9 min after the earthquake), 5 minutes after the earthquake, and immediately after the earthquake. Because the agents were randomly placed on the road surface in the target area, we conducted 20 trials for each pattern.

First, the pattern in which agents start evacuating after the tsunami reaches the coast is examined (see Fig. 8). When the tsunami height was 4 m, the total damage rate was 0.14%, but the rate increased exponentially with height: 0.78% at 6 m, 2.56% at 8 m, and 4.85% at 10 m. When the tsunami height was 12 m, the disaster rate was 5.97%, and when it was 14 m, the rate was 9.06%, which indicates that the tsunami could cause severe damage. In the case of a tsunami height of 12 m, 4.66% of adult agents were affected, while 8.51% of child agents were affected due to their low water level to determine damage, and 7.80% of elderly agents were affected due to their low walking speed. At a tsunami height of 14 m, the disaster rate of adult agents was 7.39%, while those for child and elderly agents were 13.65% and 11.06%, respectively. Therefore, probability that children and elderly agents are affected is higher than that of adult agents.

Next, we examine the change in disaster rate according to the start time of evacuation (see Figs. 9 and 10 and Table 1). The overall disaster rate was 5.97% for the 12 m height and 9.06% for the 14 m height when the evacuation started after the tsunami arrived at the shore, whereas it was 3.32% and 5.27%, respectively, when the evacuation started 5 minutes after the earthquake (4 min before the tsunami arrived at the shore). In the case of evacuation immediately after the earthquake (9 min before the tsunami arrived at the coast), 2.43% of the evacuees evacuated when the tsunami height was 12 m and 2.29% when the tsunami height was 14 m. When the tsunami height was 4 m, the overall disaster rate was 0.14% when the evacuation started after the arrival of the tsunami, while the disaster rate was 0% when the evacuation started 5 min or immediately after the earthquake. Although the time between the earthquake and tsunami arrival varies greatly depending on the epicentre of the earthquake, a difference of a few minutes in the evacuation start time has a significant impact on the reduction of damage.

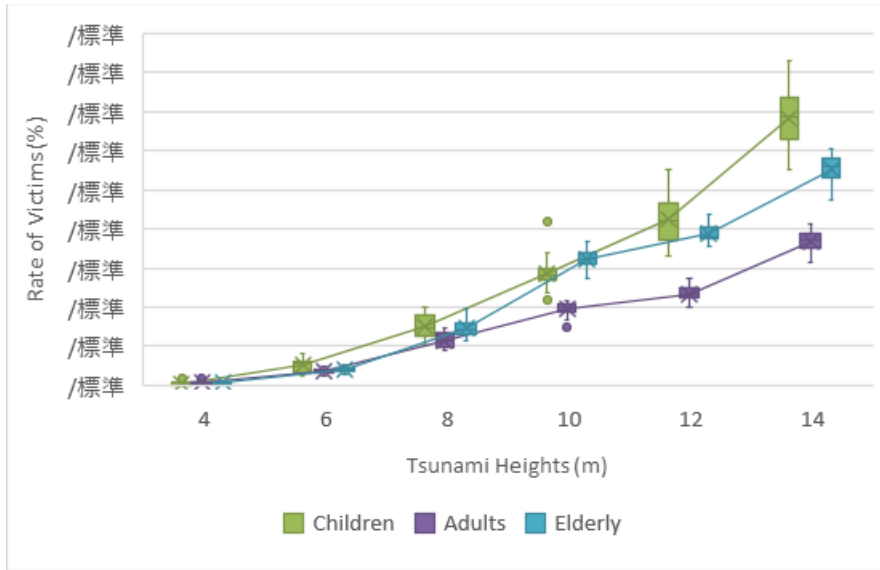


Fig. 8. Rate of damage of agents by tsunami height when evacuation begins after tsunami arrival (9 min after earthquake).

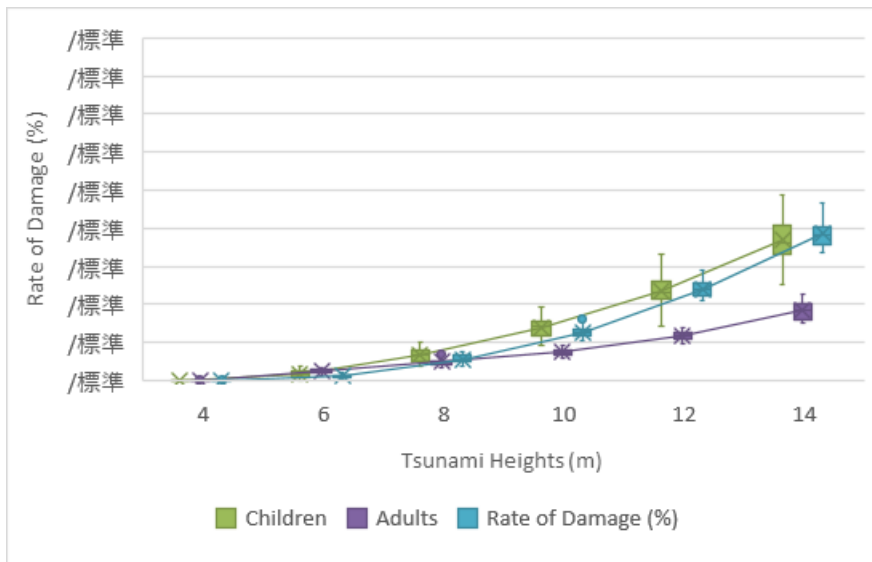


Fig. 9. Rate of damage of agents by tsunami height when evacuation begins 4 min before tsunami arrival (5 min after earthquake).

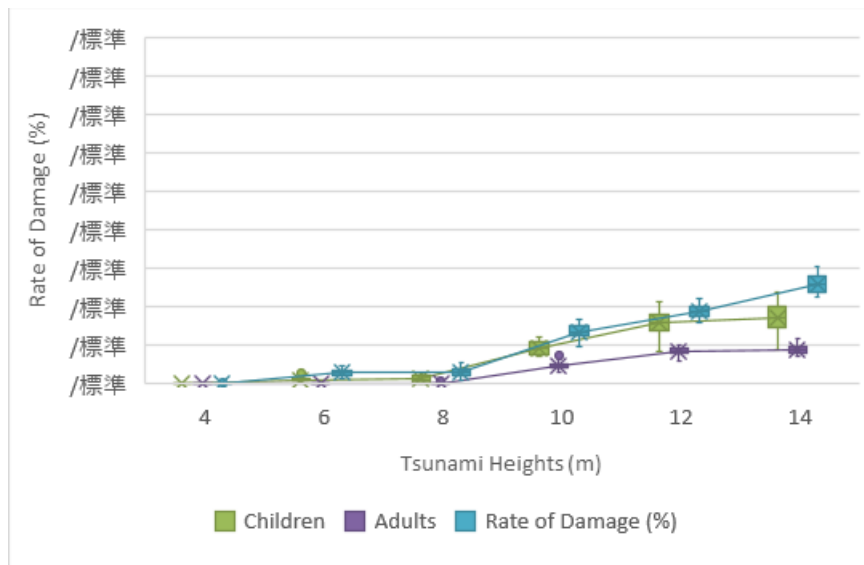


Fig. 10. Rate of damage of agents by tsunami height when evacuation begins immediately after the earthquake.

Table 1. Rate of damage by tsunami height and evacuation start time.

Tsunami heights (m)	Affected Rate (%)											
	Start evacuation after tsunami arrival (9 min after the earthquake)				Start evacuation 4 min before tsunami arrival (5 min after the earthquake)				Start evacuation immediately after the earthquake			
	Overall	Children	Adults	Elderly	Overall	Children	Adults	Elderly	Overall	Children	Adults	Elderly
4	0.14	0.11	0.15	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.78	1.04	0.73	0.82	0.38	0.36	0.48	0.20	0.21	0.19	0.01	0.57
8	2.56	3.00	2.30	2.93	1.04	1.35	0.96	1.12	0.22	0.21	0.02	0.59
10	4.85	5.70	3.88	6.46	1.92	2.79	1.47	2.55	1.54	1.79	0.90	2.69
12	5.97	8.51	4.66	7.80	3.32	4.73	2.33	4.82	2.43	3.13	1.62	3.78
14	9.06	13.65	7.39	11.06	5.27	7.39	3.70	7.68	2.99	3.43	1.78	5.15

Next, see the affected areas indicated by the pink bars in Fig. 11. Along the coast, the central part was less affected, and the northern and southern parts were more affected. The agents who were near the coast when the evacuation started evacuated towards the tsunami evacuation building located in the middle of the coast or towards the high ground in the northern or southern part of the coast. Because the coast is wide, agents who evacuated parallel to the sea were affected before they reached higher ground. In addition, because the tsunami evacuation building located in the centre of the coast is a school facility (Zushi Kaisei Junior and Senior High School) and the number of evacuees who can be accommodated is limited due to the presence of students during the daytime on weekdays, the agents who could not enter the building and had to move towards other evacuation sites were also affected. In the southern part of the

coast, there are only small tsunami evacuation buildings with small capacities, which caused some agents to not escape. Therefore, more tsunami evacuation buildings should be constructed along the coast.

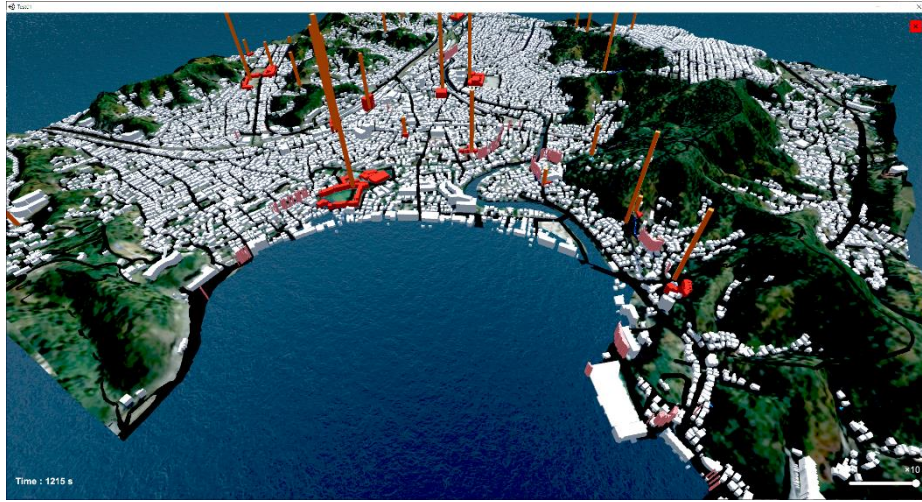


Fig. 11. Concentrated pink bars indicate the most affected areas.

In some areas, the number of affected people was concentrated inland as well as along the coast. Zushi City has a river running through its centre, and many victims can be seen along the river. Although inland areas cannot see the sea, tsunamis traveling up rivers can cause damage to agents evacuating inland. The inland areas along the rivers are far from high ground, and there are few tsunami evacuation buildings, so many people were affected during evacuation. When local governments make disaster prevention plans, it is necessary to set up tsunami evacuation buildings not only along the coast but also in the inland areas with flat land, especially along rivers. However, the maximum height of buildings in Zushi City is limited to 10–20 m by the city’s landscape ordinance. In the future, it may be necessary to relax the maximum height limit for new buildings under the condition that they are designated as tsunami evacuation buildings.

4 Conclusion

In this study, we developed a tsunami crowd evacuation simulation system using a game engine and open data, which can be used by local governments to develop disaster prevention plans. The simulation system was applied to Zushi City with different tsunami heights and evacuation start times. By using free and open-source software and game engines as the development environment and by using open geographic information data from the Geospatial Information Authority of Japan and population data

from local governments as the dataset, we were able to develop a system that can be operated at the local government level.

As a result of the simulation of Zushi City, the overall disaster rate was 0.14% for evacuation after tsunami arrival at a height of 4 m. However, 5.97% and 9.06% were observed when the tsunami height was 12 m and 14 m, respectively, indicating that the damage rate increases rapidly with tsunami height. Moreover, when the evacuation started 4 min before the arrival of the tsunami, the total disaster rate was 3.32% at 12 m height and 5.27% at 14 m height, and when the evacuation started 9 min before the arrival of the tsunami, it was 2.43% at 12 m height and 2.99% at 14 m height. Although the time before the arrival of a tsunami depends on the earthquake epicentre, it was found that the time margin for tsunami evacuation has a great influence on the reduction of damage.

The locations where the agents were affected revealed that there were insufficient tsunami evacuation buildings. In particular, many inland areas along rivers were affected by the tsunami. Therefore, it is necessary to establish appropriate tsunami evacuation buildings in inland areas, which are far from high ground, in cooperation with local governments and residents. However, Zushi City has a landscape ordinance that sets a maximum height limit for buildings, so it is necessary to find a balance between disaster prevention and landscape planning.

In a real disaster, an earthquake close to the epicentre can cause damage to buildings and block roads. The speed of movement of evacuees also depends on the slope of the hill and congestion of people. In the future, we will conduct simulations to reproduce more detailed urban conditions during a disaster. Zushi City has a long stretch of beach where many marine sports are practised. Many tourists visit Zushi, mainly in summer, and 500,000 people visit the beaches annually. Therefore, it is necessary to consider simulations with agents who do not know where to evacuate, assuming that they are tourists.

In this system, small children under 4 years old are assumed to be evacuated with their parents. However, the system does not take into account the evacuation of family members, including the elderly. In the case of family evacuation, the slowest agent's speed should be applied to all members. Currently in Japan, the independent evacuation method called "Tsunami Tendenko" is recommended for each individual. However, in a real disaster, people may help their family members or acquaintances to evacuate. In the future, we will study group behaviour based on the data of family structure.

In the future, we will cooperate with local government and residents for disaster prevention planning in actual community development, such as the establishment of tsunami evacuation buildings and evacuation guidance in the agent-affected areas indicated by this system. In addition, we will refine the behavioural conditions of the agents and improve the simulation so that it is closer to an actual disaster, for example, accurately reproducing the inundation time of the tsunami and occurrence of impassable roads. Furthermore, we will apply our method not only to tsunamis but also to other natural disasters, such as floods and wildfires.

Acknowledgements

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