DEVELOPMENT OF A TSUNAMI EVACUATION BEHAVIOR SIMULATION SYSTEM FOR SELECTION OF EVACUATION SITES

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Abstract. In this study, a tsunami evacuation simulation system was developed using a game engine and open data to reflect the conditions of a local emergency situation at low cost. Chigasaki City, which is a heavily populated urban area and tourist destination along the coast of Japan, was selected as the target area for this study. A total of 20 simulations were conducted using 20,000 evacuation agents categorized as child, adult, or elderly residents or visitors randomly placed on the road surface in the target area. The simulation results indicate that a 10.60% agent damage rate may occur for a tsunami of height 10 m. In lowland areas where the river flows inland, tsunamis were observed to move up the estuary, trapping agents between the river and the coast. In such inland areas, several areas with no tsunami evacuation buildings were observed. Thus, the low-cost simulations provided by the proposed system can provide necessary support for planning and designating appropriate tsunami evacuation buildings in disaster-prone areas.

Keywords. Tsunami; Evacuation; Agent; Simulation; Game Engine.

1. Introduction

Tsunamis are generated during underwater earthquakes via the impact of seismic waves on the seafloor, thereby causing rapid deformation of the seafloor topography over a short period of time. A tsunami produces significantly high water pressures even at low wave heights and can cause extensive damage over large areas along the coast (Matsutomi and Okamoto, 2010). Many studies have reported on the use of tsunami simulations, mainly to numerically simulate tsunami waves, tsunami arrival times, and tsunami concentrations due to topographic effects (Shimazaki and Somerville, 1978; Shuto and Fujima, 2009). These studies have focused on the relationships between tsunamis and topographies at wavelengths of several kilometers, which is important for disaster management planning at the national level.

However, local governments are the main bodies responsible for providing disaster prevention information, such as tsunami hazard maps, to local residents. Disaster management plans, including evacuation routes and tsunami evacuation buildings on individual streets, are developed by local governments by referring to the inundation areas, tsunami arrival times, and maximum tsunami heights from

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simulation data provided by the national government. Thus, any changes in the simulation data will result in major revisions to local disaster management plans. In many areas of Japan, risk reviews and large-scale data updates were conducted before and after the 2011 Great East Japan Earthquake of 2011, forcing local governments to recreate hazard maps (Koshimura and Shuto, 2015). However, it is not possible for local governments to construct and operate their own tsunami simulation systems owing to their high cost and complex technical aspects; hence, it is difficult to conduct detailed in-city simulations of disaster management plans under various conditions, such as the numbers and types of evacuees and available evacuation sites.

In this study, we accordingly used a game engine and open data to develop a low-cost system able to reflect the disaster management realities of a region. This system was designed to visualize the predicted disaster locations, with particular focus on evacuation behaviors, and to acquire data that may contribute to disaster prevention planning. Agent-based model simulations of tsunami, typhoon, and tornado evacuations have been conducted in the past. Mas et al. conducted numerical tsunami and evacuation simulations using multi-agent programming for the Great East Japan Earthquake of 2011 (Mas et al., 2012). Wang et al. conducted an agent-based evacuation simulation for Seaside, Oregon, and found that decision-making time and variability, provision of vertical evacuation, percentage of car use, and walking speed were strongly correlated with mortality (Wang et al., 2016). Mostafizi et al. presented an agent-based model to evaluate vertical evacuation behavior and evacuation sites for near-field tsunamis (Mostafizi et al., 2019). These studies were conducted at relatively low cost using geographic information system (GIS) data, but their operation and any discussion of their results require specialized knowledge. In this study, we therefore used a game engine to visualize the tsunami inundation and evacuation situation from any viewpoint in the virtual three-dimensional space of a case study city. By relying on open data, the proposed system can be developed at low cost and display easy-to-understand results with simple operations. This approach allows for small organizations such as local governments to evaluate disaster mitigation by designating tsunami evacuation buildings under various conditions.

2. Method

2.1. GEOGRAPHIC MODEL

The proposed simulation system uses the Basic Map Information Download Service of the Geospatial Information Authority of Japan to obtain the requisite geographical information. This service allows users to retrieve various types of basic map information in a mesh of an arbitrary region from the internet in the extensible markup language (XML) data format. In this study, we used data from the range of secondary mesh number 523973 (updated in 2020). Once downloaded, the XML data are imported into the Basic Map Information Viewer, which is dedicated display software for basic data and numerical elevation models, for conversion to shape format data (see figure 1).

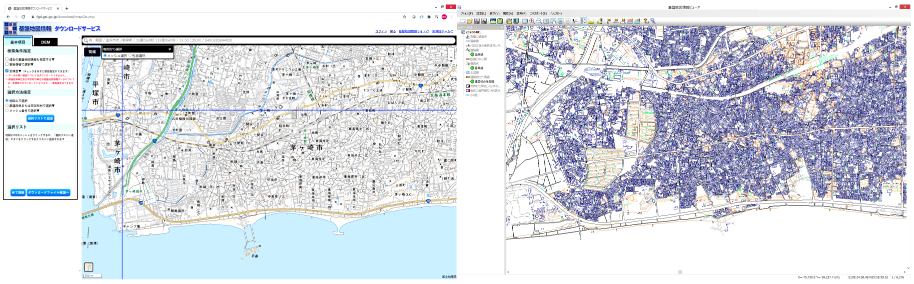

Figure 1. Display of geographic information with the Basic Map Information Service (left), and display with the Basic Map Information Viewer (right).

Next, QGIS, which is a free and open-source geographic information system, is used to import the converted shape files and display them as a new vector layer. Several previous attempts to turn open data into 3D terrain using GIS software were consulted accordingly (Herman, Russnák and Řezník, 2017; Endalew, Shiferaw and Kindie, 2019). In QGIS, a plugin is used to add a tile map to the map canvas (Akagi, 2016), and a three-dimensional (3D) visualization plugin (Akagi, 2020) is used to create the 3D geographic data with height information (see figure 2). Aerial photos of the study area are then projected as texture data onto a geographic model using the Map and Aerial Photo Viewing Service of Geospatial Information Authority. The 3D data processed in QGIS are then exported in standard triangulated language (STL) format as three layers: topography, road edges, and building perimeter lines.

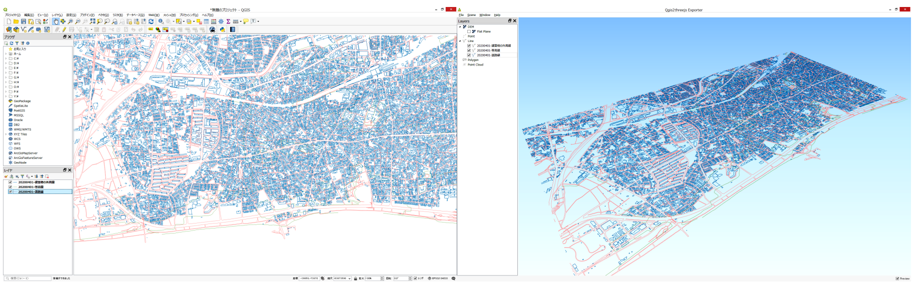

Figure 2. Display of geographic information with QGIS (left), and display of 3D geographic information with plugin (right).

In addition, these STL data are imported into Blender, an integrated 3D computer graphics environment. Based on the road-edge data, polygons are generated on the topographical surface corresponding to the roads to create a detailed urban road surface. The polygons representing the road surface are placed along the topographical model using the cloth modifier in Blender because the measured values will inevitably differ from the height information of the topographical model at certain points. Based on the building perimeter lines, buildings are created by referring to the zoning districts of the target area's city planning map and entering the expected building heights from the floor-area ratio.

However, for tsunami evacuation buildings that can be evacuated vertically, the exact height of each building is entered. Next, these 3D model data generated in Blender are exported as 3D shape data in the filmbox (FBX) format after cleaning up the polygons and reducing the data sizes of the models. These model data are then imported into the UNITY game engine, which is an integrated development environment. The resulting 3D model incorporates three elements as separate layers in the FBX format: a topographical model with height information, a building model, and a 3D road model along the elevation of the terrain (see figure 3).

Figure 3. Geographical model overlaid with topographic, building, and road models of Chigasaki City, Japan.

2.2. TSUNAMI MODEL

According to the Manual of Tsunami and Storm Surge Hazard Mapping provided by the Japanese government, the inundation forecasting method should be accurate according to the purpose and objective of the evaluation. Herein, a numerical simulation based on the time-series approach is proposed to predict and provide accurate data describing the time course of inundation and inundation depth for each point; however, it is typically difficult for local governments to obtain accurate data for the creation of hazard maps because of the required technical skills and high cost of simulation. As a result, a simplified method based on setting the inundation according to the ground level is employed, as this provides a lower cost prediction, but does not predict the exact velocity, inundation start time, or time-series effect of the tsunami run-up based on the topography.

The system proposed in this study uses a tsunami and storm surge hazard map method based on the ground level, with a tsunami model that moves at a constant rate to partially account for the time series of inundation. Thus, a tilted plane rotated by 0.1 degrees was prepared as the tsunami model and inserted within the 3D topographical model to simulate the time-series inundation according to elevation. The tsunami model moved inland at a speed of 40 km/h and then reversed after reaching the deepest point to represent the inundation of the urban area. Note that the proposed system adopts a lightweight tsunami model because it can be represented by simple calculations; however, this model includes no conditions for changes in the flow velocity due to the topography and buildings (see figure 4).

Figure 4. Maximum inundation areas for tsunami heights of 5 m (left) and 10 m (right).

2.3. EVACUATION AGENTS

In the proposed system, agents are used to simulate autonomous evacuation during a tsunami. By improving the evacuation behavior algorithm to reduce the weights of each agent, we developed a system capable of simulating a few tens of thousands of agents operating simultaneously. The evacuation agents are assumed to have two evacuation behavior patterns and are classified into three age groups.

The two types of evacuation behaviors considered are residents and visitors. Residents are established as agents who know the locations of their refuge in advance. The resident agents move at a predetermined speed to the nearest high ground or tsunami evacuation building from their current coordinates in the event of a tsunami. These tsunami evacuation buildings have predetermined capacities; therefore, if these buildings are filled beyond capacity, newly evacuated agents arriving thereafter cannot enter the building. As a result, after confirming that the capacity of a building is exceeded, the agents search for the next evacuation site nearest their current coordinates to recommence evacuation measures. In contrast, visitors are established as agents who are unaware of the evacuation sites, and are expected to follow evacuation measures according to the agents nearest their current coordinates in the event of a tsunami.

The three age groups considered for the agents are adults, children, and the elderly. The adult agents are assumed to move at a speed of 1.5 m/s up to an allowable tsunami inundation depth of 0.6 m, the child agents were assumed to move at a speed of 1.2 m/s up to an allowable tsunami inundation depth of 0.3

m, and the elderly agents were estimated to move at a speed of 1.0 m/s up to an allowable tsunami inundation depth of 0.6 m (Okamoto, 2007). As agents are assumed to have different movement speeds and disaster judgments depending on their age and different evacuation behaviors according to their status as residents or visitors, a total of six different agents are included and color coded according to their characteristics as shown in figures 5 and 6.

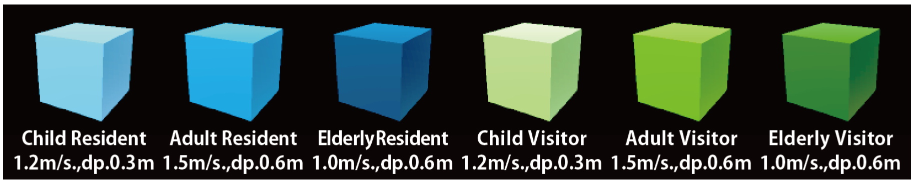

Figure 5. Six types of evacuation agents described in the system.

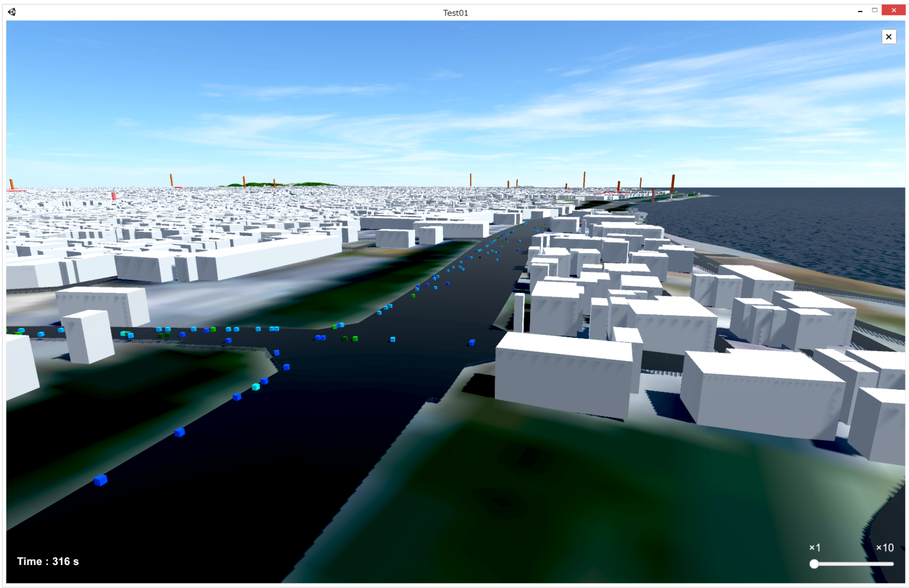

Figure 6. Resident agents (blue cubes) and visitor agents (green cubes) performing evacuation moves.

In the proposed simulation system, agents with the numbers and characteristics registered in the configuration screen are randomly placed on road surfaces within the city limits upon commencement of the simulation. The resident agents move toward the high ground or tsunami evacuation buildings (represented in red) nearest their coordinates, and the visitor agents follow their nearest resident agents. Agents housed in the high ground above the set tsunami height or in tsunami evacuation buildings are represented in orange as evacuees who have completed evacuation, as is their tsunami evacuation building. However, agents were considered damaged and determined to be a casualty if the tilt plane representing the tsunami was greater than or equal to the allowable tsunami inundation height corresponding to each type of agent. The damaged agent is then represented as a pink block at that spot, where they remain in their current position until the end of the simulation. The areas with high concentrations of pink blocks are considered to be the locations with the most victims (see figure 7). After the simulation, the results screen is displayed showing the number of residents and visitors by age group with the system outputs in a comma separated value (CSV) format file.

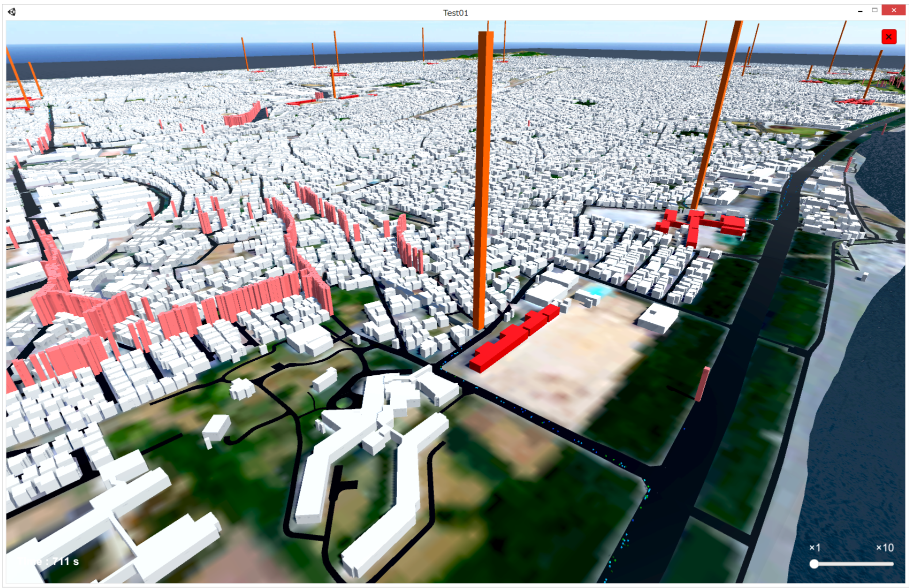

Figure 7. Simulation screen: tsunami evacuation buildings (red), number of evacuees (orange), and damaged agents (pink).

3. Results and Discussion

Chigasaki city, which is located along the coast of Sagami Bay in Kanagawa Prefecture, Japan, was selected as the study area. This area is urbanized, densely populated along the coast, and a tourist destination that requires appropriate evacuation plans in the event of a tsunami. In each simulation using the proposed system, approximately 20,000 agents were randomly placed on a road surface in the area representing Chigasaki City. The percentage of each type of agent was established from the city's age demographic data and tourist count surveys. Note that as the agents are randomly placed on the road, the results may vary depending on the initial conditions of the simulation. Therefore, after setting the initial conditions, we collected and analyzed data from repeated trials. A total of twenty simulations were performed with the results of shown in figure 8.

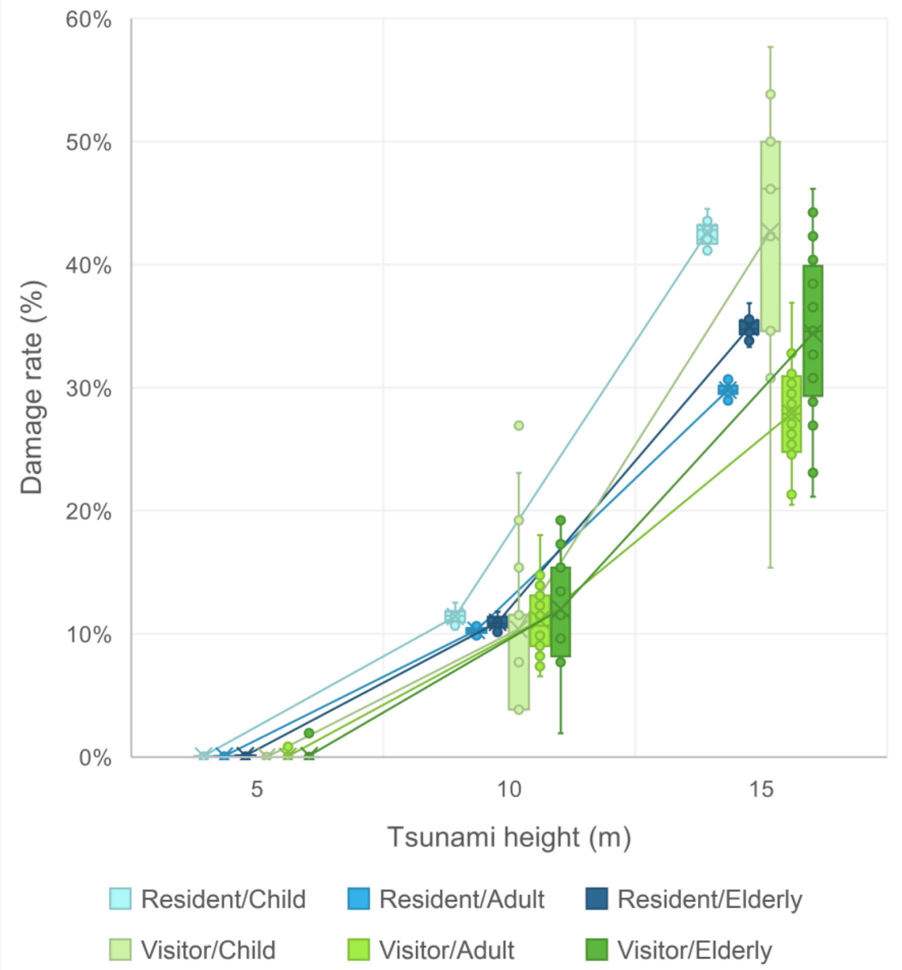

Figure 8. Simulation results of damage rates by tsunami heights and agent types.

At a 5 m tsunami height, the total damage rate was 0.07% in the coverage area. The average damage rate for residents was 0.07% for children, 0.06% for adults, and 0.09% for the elderly, and the average damage rate for visitors was 0.01% for children, 0.04% for adults, and 0.10% for the elderly. Thus, the damage was slight, but agents whose evacuations were delayed were the most affected. Child agents, with lower allowable depths of inundation than adult agents, and elderly agents who moved at lower speeds were affected the most.

At a 10 m tsunami height, the total damage rate was 10.60%. The average damage rate for residents was 11.40% for children, 10.28% for adults, and 10.93% for the elderly, and the average damage rate for visitors was 10.38% for children, 11.11% for adults, and 12.02% for the elderly. The differences in the damage rates between agents types were similar to those at the 5 m height, but the number of victims increased significantly. The largest predicted tsunami height in the Chigasaki hazard map was approximately 8 m for the Genroku-type Kanto earthquake and the Kannawa-Kouzu-Matsuda fault zone earthquake. Thus, a 10 m tsunami is higher than the maximum expected tsunami in the study area, but still represents an important case to consider in order to identify specific area trends. In particular, there were many cases of flooding deep in the urban area owing to the movement of the tsunami upriver. Thus, regardless of the specific height of the tsunami, it is necessary to plan appropriate evacuation sites in inland areas where flat terrain extends into the city.

Finally, for a 15-m high tsunami, the total damage rate was 32.78%. In particular, the damage rates for resident and visitor child agents were 42.64% and 42.69%, respectively. Note that while this class of tsunami is not designed for or expected to occur in the disaster prevention plans of the target region, if such a tsunami did occur, the proposed simulation method indicated that the results could be devastating.

The simulation results show the agents all commenced their evacuation behaviors after the tsunami occurred, and some agents were affected inland, where there were no appropriate evacuation buildings. Especially, some inland areas along the river were found to have high concentrations of victims. In these lowland areas, the tsunamis moved up from the estuary, trapping agents between the river and the coast. Thus, the results obtained using the proposed simulation method indicate that it is necessary for local governments and residents to plan and designate appropriate tsunami evacuation buildings in these areas.

4. Conclusion

In this study, a simulation of tsunami evacuation behavior was developed using open data and the UNITY game engine, then demonstrated for Chigasaki City, Kanagawa Prefecture, Japan. Notably, a low-cost environment was used to develop the simulation system based on free and open-source software, such as the game engine, along with open data, such as geographical information from the Geographical Survey Institute, population data, and tourist count data from local governments. Thus, the proposed system can be easily and cost-effectively operated by local governments to plan for disasters.

The simulation results for Chigasaki City showed that the damage rate for a tsunami height of 5 m was 0.07%; however, for a tsunami height of 10 m, this damage rate could be as high as 10.60%. The assumed maximum tsunami height in the study area is 8 m. However, attention should be paid to the fact that the damage rate exhibits an exponential increase according to the tsunami height. In particular, many inland areas were observed to be damaged as the tsunami travelled up the rivers into low-lying urban areas, indicating that it is also necessary to develop disaster prevention plans for such areas.

As the proposed system is currently limited in its ability to reproduce tsunami motion, future research will focus on accurately reproducing the time-series changes of the tsunami motions. In addition, the algorithms governing the evacuation agents may need to be improved by examining the evacuation speeds according to various conditions such as evacuation distance, evacuee density, and road gradient, and by modeling information exchange among the agents. Furthermore, in the proposed simulation, the agents were initially placed randomly, but this condition should be modified by considering the population/activity density maps according to time of day and season. Finally, the evacuation and inundation due to typhoons and flood as well as tsunamis could be simulated for real-time use by improving the inundation time axis and evacuation algorithm.

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