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Development of a Simulator for Urban Evacuation Behavior in the Event of a Tsunami Using a Game Engine

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Abstract

This paper presents a tsunami evacuation behavior simulator developed using a game engine. The purpose of this study is to visualize areas where disaster is predicted, and to provide data for disaster prevention planning.

The basic map information service of the Geographical Survey Institute Japan, which provides open-access data, was used for the geographic information. The latter was downloaded, and the processed model was loaded into the UNITY game engine via three-dimensional computer graphics software as three layers: landforms, roads, and buildings respectively. In the game engine, agents that autonomously evacuate from a tsunami were created. Each agent performed a refuge action; however, they influenced each other in the simulation. During the simulation, 10,000 agents performed a refuge action simultaneously.

Two types of evacuating agents were assumed: residents and visitors. The residents were designed to know the refuge locations in advance. After the occurrence of a tsunami, they moved at a specified speed toward the hill or tsunami evacuation building nearest to their coordinates; these regions are highlighted in red in the simulator. By contrast, the visitors were designed to not know the evacuation places, and they evacuated by following the agents closest to their coordinates after the occurrence of a tsunami. One of three age attributes, which affect the movement speed, was assigned to each agent: adult, child, or elderly.

In this system, at the start of the simulation, agents registered in the setting screen are randomly arranged on a road surface within the simulation region. Subsequently, the simulation proceeds with the residents and visitors moving according to their prescribed behaviors. Agents whose evacuations have been completed are represented by orange bars, indicating where evacuees are concentrated; however, affected agents are highlighted by pink bars and remain in the affected positions. The areas with concentrations of pink bars are areas with several victims.

Using this system, an evacuation behavior simulation was performed with Kamakura City, Kanagawa Prefecture, as the target area. It was discovered that the disaster rate increased in a geometric series according to the tsunami height. In addition, the children and the elderly had a higher rate of suffering compared to the adults. Evidently, the disaster victims were concentrated in inland areas. In addition, although the victims were evacuated after the occurrence of the tsunami, some inland areas remained affected by the tsunami.

However, because the landscape plan based on the Landscape Act was implemented in Kamakura City, the height of buildings is restricted to 8–15 m. In the future, it will be necessary to plan and designate appropriate tsunami evacuation buildings, with the cooperation of local governments and local inhabitants, in places where significant damage is predicted.

Keywords: tsunami evacuation building, disaster prevention planning, multi-agent simulation, game engine

1. Introduction

In this study, a system that simulates the evacuation behavior of residents and visitors in real time during a tsunami is implemented and evaluated. A tsunami is a natural disaster caused by a shock wave in the sea owing to a short-time rapid deformation of the seafloor topography during an earthquake, with the epicenter at the seafloor. A tsunami exhibits an extremely high water pressure, even at low wave heights, causing severe damage over a wide area of the coastal [1]. In previous tsunami simulations, studies have been performed on tsunami arrival time and tsunami concentration owing to topographical effects, primarily from numerical calculations of tsunami waves [2, 3]. These studies focused on the relationship between tsunamis of several kilometers in wavelength and terrain, which is important when considering disaster prevention plans at the national land level.

Meanwhile, regarding disaster prevention information that is familiar to residents, such as tsunami hazard maps, local governments primarily implement disaster prevention plans [4]. The source data of these hazard maps are not unique to local governments but are prepared based on tsunami predictions by national and prefectural governments. A Japanese tsunami hazard map can be obtained from the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) of Japan's hazard map portal [5, 6]. In this portal, disaster prevention information prepared by each related organization regarding tsunamis, floods, and landslide disasters is summarized, and assorted information such as tsunami inundation assumptions, flood inundation assumed areas, and landslide disaster areas can be displayed in a superimposed manner. In addition, places with assumed road submergence, advanced traffic regulation zones, and emergency transportation roads can be obtained. It is possible to display the risk of the natural disaster over a wide range as a single plane, and the risk of each parcel of land can be obtained collectively when a specific place to examine is selected. The national government has prepared a manual that summarizes the basic concept of the technology and utilization of hazard maps, and develops these hazard maps nationwide [7]. Administrators such as local governments must formulate disaster prevention plans using hazard maps, e.g., the inspection of both the disaster prevention action and base improvement plans, the inspection of evacuation and rescue plans, and must offer evacuation decision information.

Hence, the "Tsunami Inundation Forecast Map" [8] and "Guidance for Preparing Tsunami Hazard Maps" [9] have been published for the Kanagawa Prefecture as basic data for preparing tsunami hazard maps to be provided to citizens by municipalities in the prefecture. This Tsunami Inundation Prediction Map is based on numerical simulations. The calculation conditions were as follows: the analysis area was from the sea of Sagami to off the Boso Peninsula; the mesh configuration varied from large areas measuring 324 m to a detailed study area measuring 12 m; the initial conditions were the vertical displacement of the seabed based on the fault parameters; the initial water level distribution was set; analysis was performed using the finite difference method and a nonlinear two-dimensional model. As a result of these calculations, the inundation depth, arrival time of the tsunami, and the traveling direction of the tsunami were described in the tsunami prediction map, which served as basic data for creating hazard maps in each municipality.

In 2013, the Cabinet Office presented new scientific findings on the largest class of earthquakes along the Sagami Trough, whose activity is considered to have been going on for 2000–3000 years or more. Therefore, the tsunami inundation prediction mentioned above was revised to eliminate unforeseen earthquakes. Hence, the Tsunami Inundation Forecast Map [6] for five earthquakes with maximum tsunami height or inundation area in the coastal area of Kanagawa Prefecture and four re-evaluated earthquakes was newly prepared [10]. This Tsunami Inundation Forecast Map was divided into 24 areas in the prefecture for these nine earthquakes. Furthermore, based on these Tsunami Inundation Forecast Maps, a Tsunami Inundation Assumption Map [11] was created and published, in which inundation areas and depths were overlapped to obtain maximum value.

Meanwhile, in local government, the disaster prevention plan must be comprehensively reviewed when the original data are changed, because the disaster prevention plan is governed by the provided data. In Kamakura City, hazard maps were recreated for large-scale updates of the tsunami inundation area data before and after the Great East Japan Earthquake (Fig. 1) [12, 13, 14]. At the local government level, a tsunami simulation system cannot be built or operated because of its high cost; therefore, it is difficult to perform detailed simulations in city units under various conditions, such as the number and type of evacuees and evacuation sites.

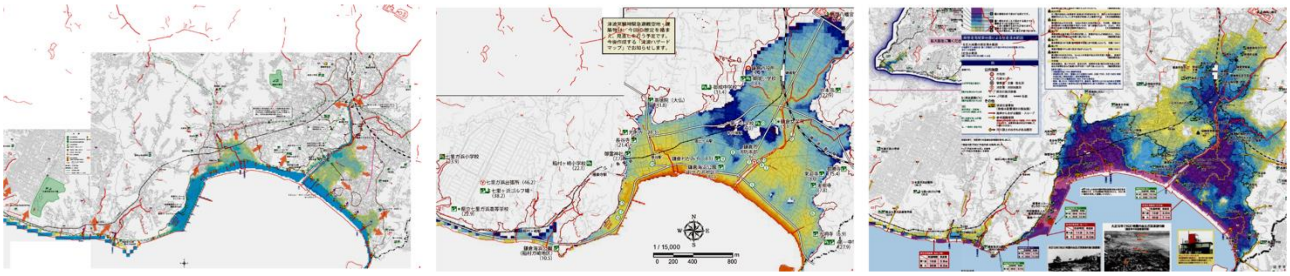

Fig. 1 – Transition of tsunami hazard map in Kamakura City. Left: 2009 version, Centre: 2012 version, Right: 2013 version.
(Author's drawing based on literature [12, 13, 14])

Therefore, we developed a simulation system to visualize tsunami evacuation behavior using a game engine, as a tool that is expected to be used when formulating disaster prevention plans for tsunami disasters by local governments. Utilizing the open data of national government and public organizations, in addition to using game engines and free- and open-source software, a simple tsunami evacuation behavior simulation system for each region can be introduced at low cost. Using this system, the location of disasters can be predicted and the selection of evacuation sites at street level can be verified.

2. Material and Method

2.1 Target area

In this study, Kamakura City, Kanagawa Prefecture, located along the coast of Sagami Bay, was selected as the simulation target area. Because Kamakura City faces the Sagami Trough, large earthquakes are highly likely, and as a tourist destination with a historic cityscape, several tourists visit the city.

Kamakura City has a long history, which began at the end of the 12th century when Minamoto no Yoritomo became Seii Taishogun (literally, “a great general who subdues the barbarians”) and established Shogunate as the capital of Japan in Kamakura. Urban development began in the Kamakura Shogunate, reaching its peak in 1230, when Kamakura became the center of Japan in all aspects of politics, military affairs, diplomacy, and culture. Various foreign cultures were introduced to Kamakura owing to its economic development, and the Great Buddha and Zen temples were constructed. However, the Kamakura Shogunate was destroyed in 1333, and the Muromachi Shogunate was subsequently established in Kyoto. Owing to conflict between the Muromachi Shogunate and the Kamakura Prefecture, Kamakura rapidly lost its vitality and became an agriculture and fishery center. Subsequently, in the Edo era, shrines and temples were restored, and Kamakura began attract tourists once again. In 1889, when the Yokosuka railway line was opened to connect Tokyo with Yokosuka, which contains a naval port, Kamakura became a beach and villa area, and its tourism industry developed further. Since the electrification of the Yokosuka Line in 1930, large-scale housing development has occurred, and its characterization as a “bedroom town” in the suburbs of Tokyo has been strengthened. In the 1960s, a civil movement called for the suspension of large-scale development, which triggered the enactment of the Ancient Capitals Preservation Law.

In addition, Kamakura City, which faces the Sagami Trough, is an area that has been damaged repeatedly by great earthquakes and tsunamis [15, 16]. At least four times to date, Kamakura has been damaged significantly; by the 1923 Great Kanto earthquake [17, 18], the 1854 Tokai earthquake, the 1703 Genroku earthquake, and the 1241 Ninji earthquake [19]. These earthquakes, together with house collapses, landslides, and cliff collapses caused by earthquake vibrations, are assumed to have caused tsunamis with a maximum height of 12 m in coastal areas five minutes after the occurrence of the earthquake. According to the tsunami inundation prediction prepared by Kanagawa Prefecture and hazard maps of Kamakura City based on the prediction, the maximum tsunami height in this area is 14.5 m, the shortest arrival time is 11 min, and the maximum inundation area is 4.7 km^2 [14].

Further, Kamakura City continues to receive several tourists as it is a tourist destination with a historic townscape. The number of tourists visiting Kamakura City throughout the year is approximately 51,000 daily, except during the New Year season when tourist numbers peak for that first visit of the year to the Tsuruoka Hachimangu Shrine [20, 21]. Therefore, in this system, two types of agents, a resident who knows the evacuation destination and a visitor who does not, were prepared, and the evacuation behavior simulation was performed.

2.2 Geographic model

In this system, the basic geospatial information download service of the Geospatial Information Authority (GSI) of Japan was used as a geographic information resource [22, 23]. Various types of base map information can be acquired from the portal in extensible markup language (XML) data format. The downloaded XML data were read using a basic geospatial information viewer [24], dedicated software to display basic items and digital elevation models, and then converted into Shape format data and exported. Next, the converted Shape file was read into QGIS [25], an open-source geographic information system, as a vector layer. On QGIS, TileLayer Plugin [26], a plug-in to add a tile map to the map canvas, and Qgis2threejs [27], a three-dimensional (3D) visualization plug-in, were used to create 3D geographic data with altitude information. Furthermore, an aerial photograph was projected onto the terrain model using TileLayer Plugin as well as the map and aerial photograph browsing service of GSI [28] as texture data. The 3D data processed on QGIS were exported in STL format data as three layers: landform, road edge, and building perimeter line. The processed 3D geographic information data was loaded into a blender [29], a free open source 3D computer graphics application. The polygons on the road surface were generated from the road edge data, and the road surface of the urban area was constructed in detail. The polygon representing the road surface had a different value than the height information of the terrain model in the open data; therefore, the road surface was eliminated in the terrain model using the cloth modifier of the blender. The building models were created by inputting the building height assumed from the floor-area ratio as the building height on the building perimeter line, referring to the application area of the city planning map of the target area [30]. The 3D model data generated on the blender were exported as FBX format data, which were imported into the UNITY game engine [31], and the algorithm for evacuation behavior was applied (Fig. 2).

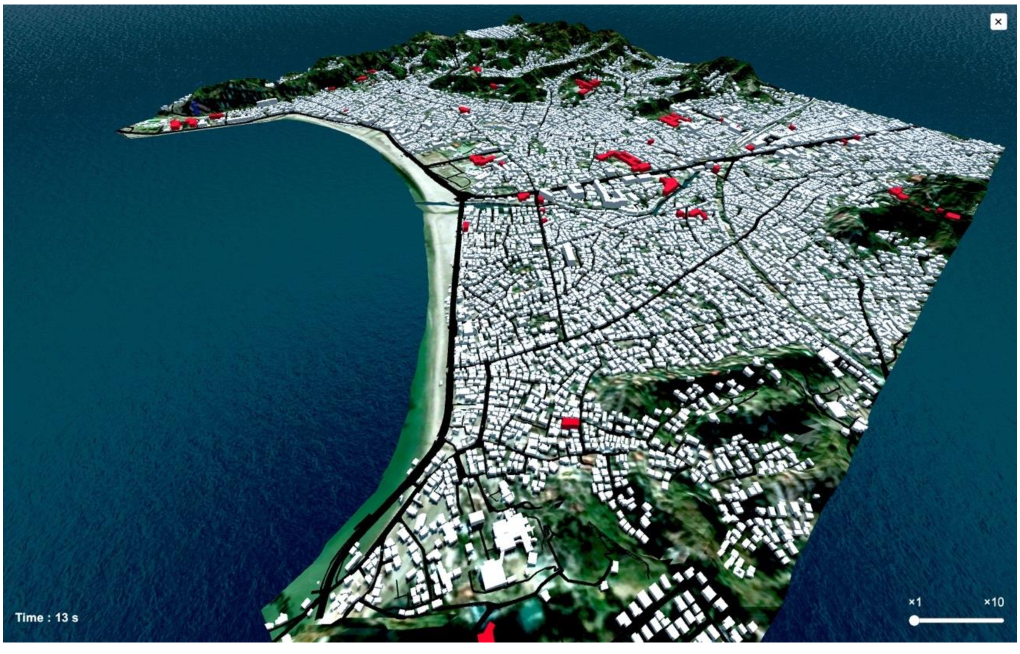

Fig. 2 – Geographical model of Kamakura City expressed by the system

2.3 Tsunami model

According to the Tsunami and Storm Surge Hazard Map Manual [7] prepared by the Cabinet Office and MLIT, the inundation prediction method must exhibit an accuracy level that corresponds to the creation purpose evaluation target. The tsunami prediction method based on numerical simulation can accurately obtain the data necessary for hazard map preparation, such as the time course of inundation and the inundation depth data of each spot. However, the calculation cost is high. Meanwhile, as a simple method, the setting method using the ground height can be performed at low cost; however, accurate flow velocity, inundation start time, and time series effects of tsunami run up owing to topography cannot be predicted. In this system, based on the method of setting the ground height in the Tsunami and Storm Surge Hazard Map Manual, the tsunami model was moved at a constant speed, and the time series such as the inundation start time was partially considered.

Initially, a large plane object was prepared at 0 m height for a 3D geographic model as an object representing the sea surface. Next, as an object representing the tsunami, a similar large plane object rotated by 0.10° was prepared. In this system, a tsunami model was created by inserting this slightly sloping large plane object into the sea surface and terrain object, and translating it at a speed of 40 km/h. The movement of the tsunami object with time enabled the situation of gradual inundation from an area with a low elevation value to be reproduced. This method using a large inclined plane insertion was adopted in this system although it was inferior in accuracy as it did not consider flow velocity owing to the terrain; however, it was adopted in the proposed system because it could be processed quickly, with simple calculations. In this system, the tsunami height with respect to the sea surface can be simulated variably in the range of 0–30 m. In addition, the time required for the arrival of the tsunami on land can be set. The simulation playback speed can be reproduced on a time scale of 1–10 times real time (Fig. 3).

Fig. 3 – Inundation into geographic model by tsunami model expressed. Left: Immediately after the tsunami occurred, Right: 12 minutes after the tsunami arrived

2.4 Evacuation agent

In this system, massive agents that autonomously performed the evacuation behavior were prepared. The road model was created from GIS data separately from the terrain and buildings; it was reconstructed as a 3D object and placed on the terrain model. The road model combined with the entire city area was designated as the action range of the evacuation behavior agent. A large number of agents were placed randomly on the road surface of the entire target area after the simulation began. The number of agents and the ratio of agent types can be entered numerically on the initial setting screen. Although the operation was confirmed by the simulation using tens of thousands of agents, processing delays were not apparent because the agents individually performed the searching action after the first calculation.

Two types of evacuation behavior patterns and three types of age attributes were set as the characteristics of the agents. Two types of evacuation behavior patterns were prepared: residents and visitors. The resident is the agent who knows the refuge place, whereas the visitor is one who does not. In addition, three types of age attributes were prepared: adult agent, child agent, and elderly agent, which have different moving speeds and tsunami heights. The adult agents moved at 0.8 m/s and the depth of the tsunami was 0.6 m; the child agents moved at 0.8 m/s and the depth of the tsunami was 0.3 m; the elderly agents moved at 0.6 m/s and the depth of the tsunami was 0.6 m. The six types of agents were colored according to their characteristics (Fig. 4).

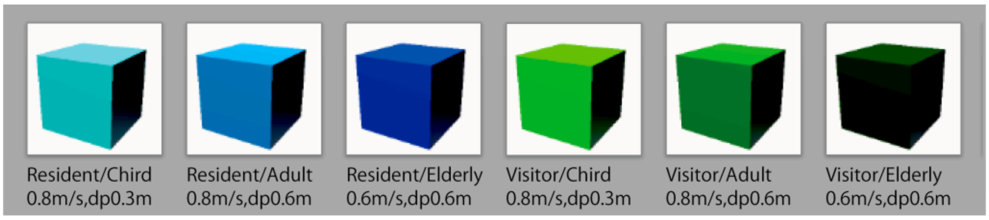

Fig. 4 – Six types of evacuation agents. Green: Resident, Blue: Visitor, Light color: Child, Middle color: Adult, Dark color: Elderly

After the simulation began, the agents were placed randomly on the roads in the target area. The resident agent searched the nearest tsunami evacuation building and hill from its own position, and subsequently started moving toward it at the specified moving speed. Evacuation completion to hills was assessed by the agent who evacuated to an altitude higher than the initial input tsunami height. Because the capacity of the tsunami evacuation building was set, if the capacity of the evacuation site reached its maximum by the time the agent arrived at the tsunami evacuation building, the agent would search again from that point and move to the next nearest refuge place. Meanwhile, although the visitor agent does not know the refuge place, it follows the agent who is nearest to its own position and performs the evacuation behavior. When the visitor agent loses track of the following agent, for example, when the capacity of the tsunami evacuation building is filled after the tracking agent has evacuated, or when the tracking agent is affected during the evacuation, the visitor agent searches for the nearest agent again at that time and follows that agent. The agent followed by the visitor agent is both a resident and visitor agent.

The tsunami evacuation buildings are displayed in red on the system, and several agents move toward these buildings. The number of inmates in a tsunami evacuation building is indicated by an orange bar at the top of the building, indicating the building in which the evacuees are concentrated. The damaged agent is represented as a pink bar on the spot and remains in the affected position. The location where the pink bars are concentrated is considered to be the location with several victims (Fig. 5).

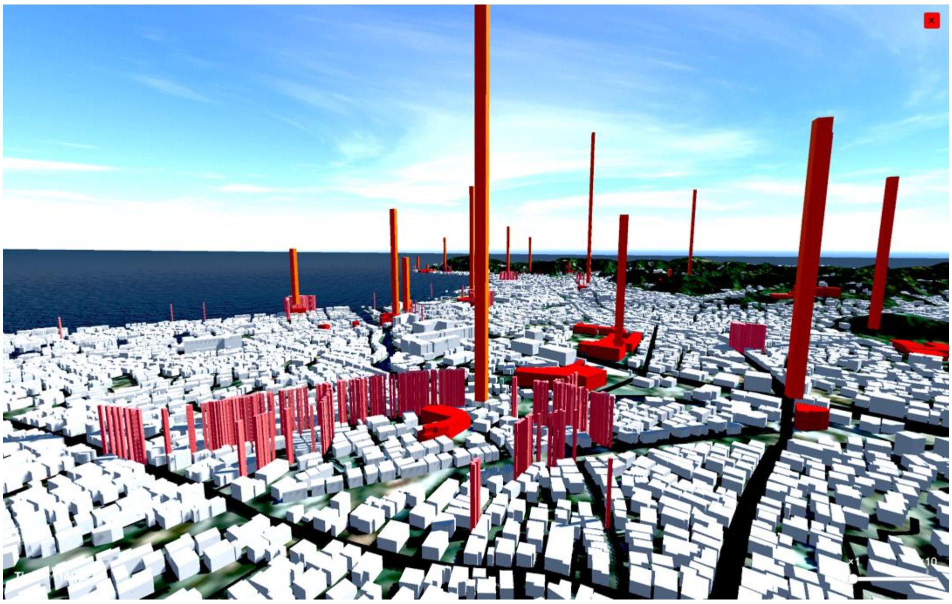

Fig. 5 – Simulation execution screen. Red: tsunami evacuation building, Orange: number of inmates in the tsunami evacuation building, Pink: location where the agent was damaged

After the simulation is completed, the result screen is displayed. The result screen displays the number of victims by six character types, and the result is output from the system as a comma separated values (CSV) file. Because the agents are randomly placed on the road surface, the results will vary depending on the initial conditions of the simulation. Therefore, after setting the condition, the system was implemented to analyze the data by repeated trials.

2.5 Evaluation by system

Using the proposed system, the evacuation behavior of the agents was simulated. The target area was an urban area of Kamakura City, and the range was approximately 7 km^2 facing Yuigahama beach. In this simulation, 10,000 agents were placed randomly on the road surface on the target area, and the evacuation behavior was simulated. For the age attribute of the agents, that of the children were set as 5–14 years old, adults were 15–64 years old, and elderly people were over 65 years old; additionally, agents under five were set to evacuate with the adults. In this simulation, based on the age-specific population of Kamakura City [32], children constituted 8%, adults 61%, and elderly people 31%. The ratio of residents to visitors was determined by calculating the average number of daily tourists from visitor surveys [20, 21], and the ratio was 78% for residents and 22% for visitors. In this study, three tsunami heights of 5, 10, and 15 m were prepared, and 20 simulations were performed for each case.

3. Results

The simulation was performed 20 times for each tsunami height; the results were tabulated, and the average disaster rate of each agent was as follows. When the tsunami height was 5 m, the disaster rate of the residents was 0.58% for children, 0.10% for adults, and 0.37% for the elderly; whereas that of the visitors was 0.31% for children, 0.13% for adults, and 0.38% for the elderly. When the tsunami height was 10 m, the disaster rate of the residents was 4.88% for children, 3.33% for adults, and 5.09% for the elderly; whereas that of the visitors was 4.63% for children, 2.99% for adults, and 5.26% for the elderly. When the tsunami height was 15 m, the disaster rate of the residents was 17.04% for children, 10.28% for adults, and 16.47% for the elderly; whereas that of the visitors was 18.10% for children, 10.73% for adults, and 16.69% for the elderly. In each case, the disaster rate was higher for the child agent at a lower tsunami height according to the disaster assessment and the elderly agent with a slower moving speed compared with the adult agent. Meanwhile, visitor agents often showed slightly higher disaster rates than resident agents. The average disaster rate for the entire target area was 0.22% at a tsunami height of 5 m, 3.96% at 10 m, and 12.84% at 15 m. The higher the tsunami wave height, the greater was the disaster scale (Fig. 6).

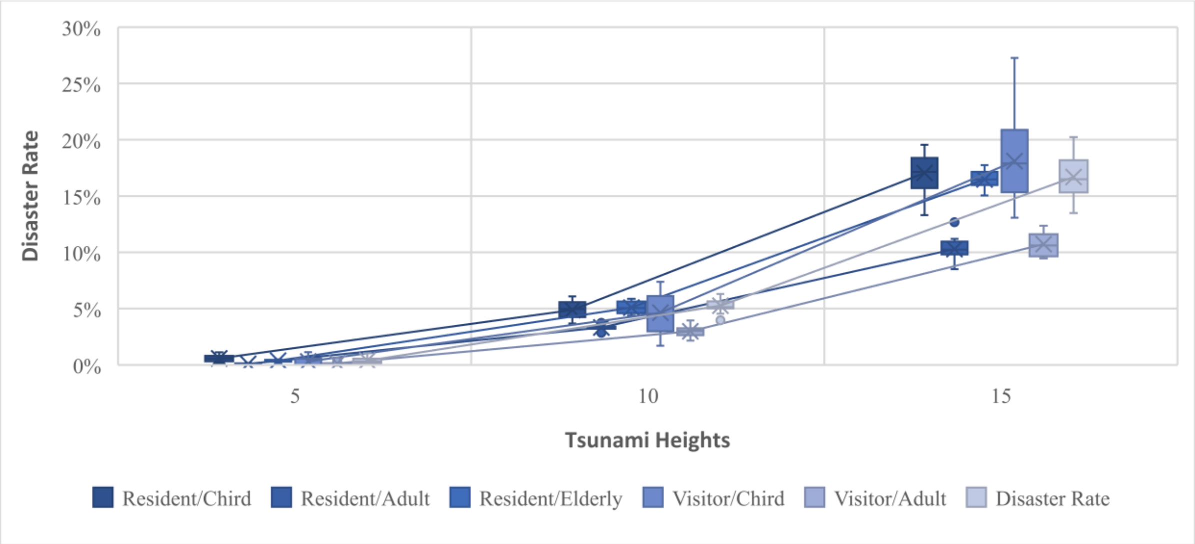

Fig. 6 – Simulation results by tsunami height and agent type

4. Discussion

It is clear from the simulation results that the victims were concentrated at certain places in the inland area. This is often in lowlands, where rivers enter the mainland, and tsunamis run down rivers and are sandwiched by tsunamis from the coast. In addition, the agents exhibited some evacuation behaviors after a tsunami occurred and subsequently evacuated to the inland area. However, in terrains where lowlands exist, it has been observed that tsunamis may be encountered and agents damaged during evacuation in inland urban areas. Therefore, tsunami evacuation buildings must be located suitably, i.e., not only along the coast but also in lowland inland areas where victims are concentrated. In addition, it was discovered that some evacuation routes required evacuation to the sea side facing the tsunami, and that evacuation signs and guidance directions required improvement.

5. Conclusion

In this study, we developed a tsunami evacuation behavior simulation system using a game engine and evaluated it by simulating Kamakura City, an actual urban area. For the reproduction of a tsunami, the processing weight was reduced by using a simple expression for a large inclined plane insertion simulating the virtual sea surface, which enabled real time analysis to be done. Meanwhile, for the evacuees, agents who autonomously searched for the refuge place and moved at a set speed, were created. Three types of agents were prepared, for which the walking speed and disaster conditions were different, and two types for which the evacuation behavior were different; additionally, the number and rate of these agents could be changed freely. In this system, as the real location of residents and visitors at the time of a tsunami occurrence is uncertain, evacuee agents were placed randomly on the road surface in the target area.

Consequently, it was discovered that, during evacuation, not only the coastal area but also the inland area in Kamakura City was severely damaged.. Furthermore, it was confirmed that a few points existed where a large-scale disaster could happen, even with tsunamis of relatively low height, such as roads with continuously low elevations and lowland areas between rivers. Meanwhile, for Kamakura City, which is a historical and cultural city, landscape planning based on the Landscape Act has been applied, and landscape districts [33] and scenic districts [34] have been designated. Therefore, the height of buildings in the simulation was restricted to 8–15 m depending on the district, and the evacuee capacity of the tsunami evacuation building was limited. In the future, it will be necessary to plan and designate appropriate locations of tsunami evacuation buildings through the cooperation of local governments and residents.

The proposed system can be developed at low cost using open data and utilizing game engines and free open source software as a development environment. Therefore, it is considered to be an effective tool for studying disaster prevention plans in local governments with local residents. Although the proposed system uses a simple tsunami representation, a more accurate simulation is possible by replacing the proposed system with a dynamic tsunami model calculated in advance with several conditions. Moreover, when examining a disaster prevention plan, it is necessary to develop them into tools that can change urban conditions more interactively, e.g., adding refuge places such as tsunami evacuation buildings and designating private roads that can be used during disasters.

This system has been developed to simulate evacuation behaviors against tsunamis. However, when an earthquake occurs in a nearby area before the occurrence of a tsunami, buildings and urban structures may be damaged by fire or collapse. In the proposed system, it is assumed that all tsunami evacuation buildings are operational, but if a large-scale earthquake occurs near the epicenter, some buildings may not be able to be used as evacuation sites. In the future, this system will be improved, a comprehensive disaster prevention simulation model combining multiple disasters, such as large-scale fires, earthquakes, and floods will be created, and a system contributing to the actual disaster prevention plan will be developed.

6. Acknowledgements

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