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DEVELOPMENT OF DRIVING SIMULATOR FOR THE EXPERIMENT OF TSUNAMI EVACUATION USING AUTOMOBILE

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ABSTRACT: The 2011 off the Pacific coast of Tohoku Earthquake, which occurred on March 11, 2011, triggered an extremely large tsunami. More than 15,000 deaths and 3,400 people missing were confirmed and 92.4% of the fatalities in Iwate, Miyagi, and Fukushima prefectures resulted from drowning. In Japan, it is basically prohibited to evacuate by automobile in case of tsunami because there may occur traffic congestions and accidents. However, Central Disaster Management Council of Japan reported that about 57% of evacuees used their automobiles to reach the upland refuges. This resulted from the social situations in the coastal residential areas in Japan. Aging of population is rather fast especially in the affected areas by the 2011 Tohoku earthquake, and the number of people in need of nursing care is increasing. Based on these circumstances, many people drove to the elevated areas after the 2011 Tohoku earthquake although the use of automobile was prohibited. This study aims to reveal the permissible limits of tsunami evacuation using automobile based on a series of driving simulator experiments. The authors perform numerical simulation of tsunami propagation, and the results are visualized from driver's point of view using 3D computer graphics (CG). The CG is installed to a driving simulator, which consists of three LCDs, steering wheel, and brake and accelerator pedals. Several tsunami scenarios are employed in the driving simulator experiments to reveal the effectiveness of evacuation using automobile quantitatively.

Keywords: Evacuation in case of tsunami, automobile, driving simulator

INTRODUCTION

The 2011 off the Pacific coast of Tohoku earthquake that occurred on 11 March 2011 triggered an extremely large tsunami. The run-up reached a maximum height of 40.4 m in the Tohoku district (The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011). The Japanese National Police Agency (2013) confirmed more than 15,000 dead and 2,600 missing people.

In Japan, it is generally prohibited to evacuate using automobiles in case of tsunami because there may occur traffic congestions and accidents. Under these circumstances, the Central Disaster Management Council of Japan (2011) reported that about 57% of evacuees used their automobiles to reach the upland refuges during the 2011 off the Pacific coast of Tohoku Earthquake. Taking the fact into consideration, vehicular evacuation should be examined in each community by accounting for the time it takes for the tsunami to arrive, distances to evacuation sites, the presence of people requiring assistance during disasters, and the circumstances of evacuation routes.

Since aging of population is rather fast in Japan, vehicular evacuation might be enhanced in the future event. Additionally, there are many sightseeing spots in the coastal areas. According to the 5th person-trip survey in the Greater Tokyo Area in 2008, the modal share of cars for the purpose of leisure shows the largest rate among the various means of transportation. Hence, vehicular evacuation process for tourists should be planned in the coastal municipalities.

Based on these backgrounds, this study develops a driving simulator with a scenario of tsunami inundation. To achieve the objective, a numerical simulation of tsunami propagation is performed assuming a historical earthquake event. The results are visualized from driver's point of view using 3D computer graphics (CG). The driving simulator will be employed for a series of experiments to reveal the permissible limits of tsunami evacuation using automobiles.

NUMERICAL SIMULATION OF TSUNAMI PROPAGATION ASSUMING HISTORICAL EARTHQUAKE EVENT

Kamakura is a city of Kanagawa Prefecture, Japan, which is about 50 kilometers south-south-west of Tokyo. Kamakura has a beach which, in combination with its temples and proximity to Tokyo, makes it a popular tourist destination. The 1498 Meio earthquake triggered a catastrophic tsunami. Although historical documents on associated damage in Kamakura are quite uncertain (Ishibashi, 1981), historic landmarks, such as the "Great Buddha" statue, might be caught in its path. To enhance tsunami countermeasures, the Kanagawa Prefectural Government has drastically revised its calculations of

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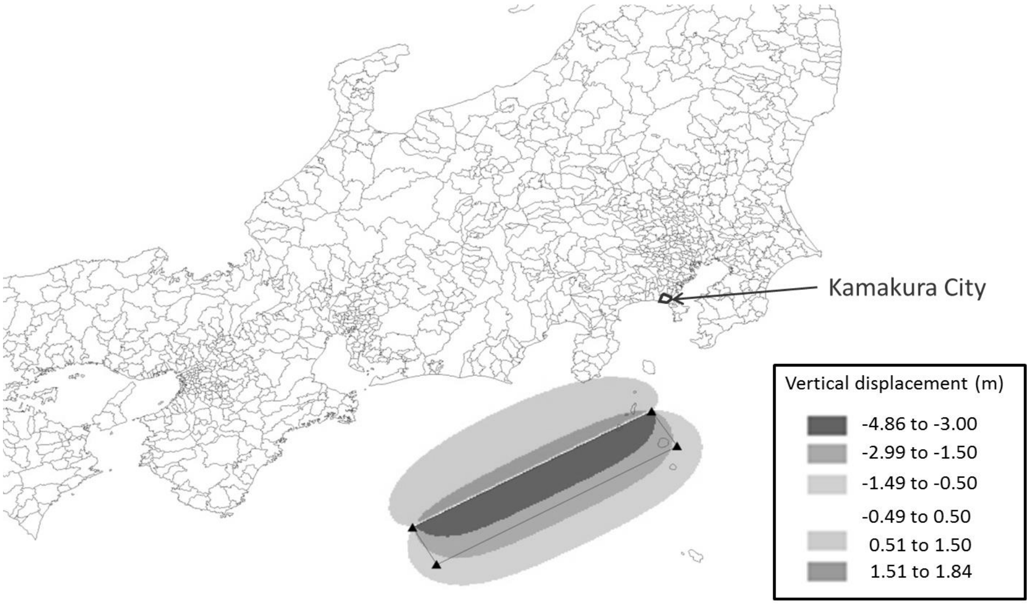

Fig. 1 Distribution of vertical displacement of seabed estimated by Okada's method (1985) assuming the 1498 Meio earthquake.

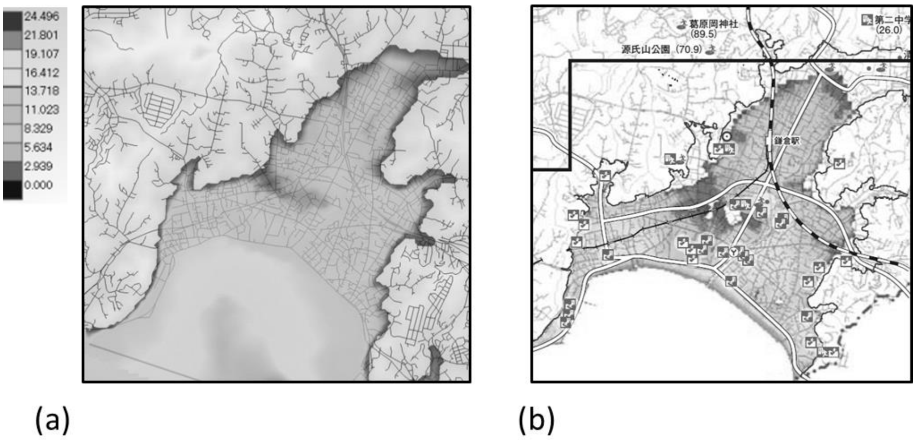

Fig. 2 Comparison between (a) the distribution of maximum inundation depth calculated by this study and (b) that illustrated by Kanagawa Prefectural Government (2012)

giant tsunami waves crashing into the city responding to the 2011 off the Pacific coast of Tohoku earthquake (Kanagawa Prefectural Government, 2012). In the latest review, the prefectural government looked at the impacts of the 1703 Genroku, 1605 Keicho and 1498 Meio earthquakes.

This study selected Kamakura as a target area. Numerical simulation of tsunami propagation was performed to estimate the tsunami-inundated areas in Kamakura City assuming the occurrence of the 1498 Meio earthquake. The seismic fault model developed by Kanagawa Prefectural Government (2012) was employed to estimate the vertical displacement of the seabed. Figure 1 shows the vertical displacement estimated by Okada's method (Okada, 1985). Assuming that the water layer is incompressible, the estimated vertical displacement of the seabed was regarded as the initial profile of the tsunami.

In this study, we used TUNAMI code (Imamura, 1995) to model the tsunami propagation and resulting coastal inundation. The model employs a set of nonlinear shallow water equations in which bottom friction terms are discretized by a leap-frog finite difference scheme. This model is widely used for simulating tsunami propagation and inundation on dry land (Koshimura et al., 2006). Based on the shallow water theory, the continuity equation can be expressed as

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \tag{1}$$

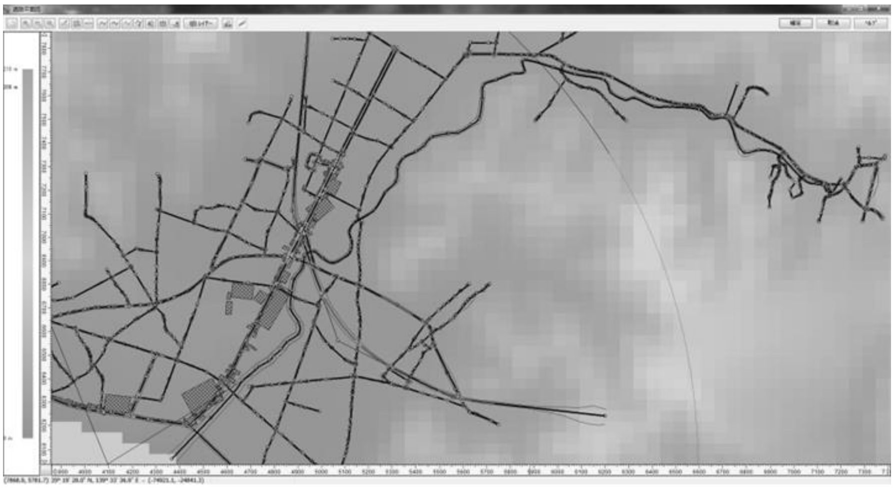

Fig. 3 Installation of road and railway networks in the 3D terrain model of Kamakura City

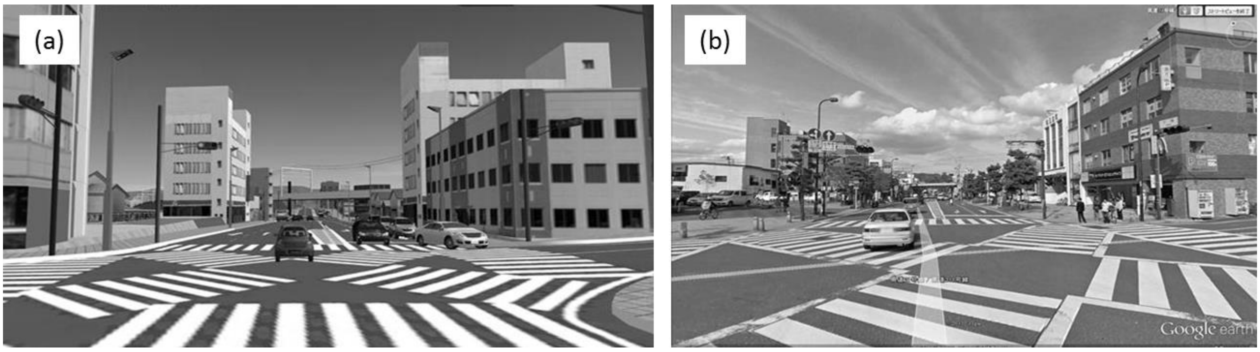

Fig. 4 Comparison between (a) the 3D space model developed by this study and (b) an image installed in Google Street View

where M and N are the discharge fluxes in the x and y directions, respectively and η is the vertical displacement of the water surface above the still-water level. The equations of motion are written as

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)=-gD\frac{\partial \eta}{\partial x}-\frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2} \quad (2)$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)=-gD\frac{\partial \eta}{\partial y}-\frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2} \quad (3)$$

where D is the summation of η and the still-water depth h and n is Manning's roughness coefficient.

In the numerical simulation, the target region was divided into five sub-regions having grid lengths of 1350, 450, 150, and 50 m. The sub-regions characterized by coarser grids were in the deep sea, and those with finer grids were closer to the shore (Shuto, 1991). h for each grid cell was assigned using bathymetry data collected by the Japan Coast Guard (Japan Hydrographic Association, 2013). Land elevations determined by the Geospatial Information Authority of Japan (GSI) were also considered for estimating inundated areas (GSI, 2013). Manning's roughness coefficients were assigned according to land use classification (Kotani *et al.*, 1998). Figure 2 shows the distribution of maximum inundation depth obtained by this study and that illustrated by Kanagawa Prefectural Government (2012). Since these two distributions show similar trends, the time series behavior of tsunami propagation estimated by our numerical simulation is employed to visualize tsunami propagation from driver's point of view using 3D computer graphics.

VISUALIZATION OF TSUNAMI PROPAGATION FROM DRIVER'S POINT OF VIEW

Based on the results of numerical simulation, time series of tsunami propagation is visualized from driver's point of view. This study employs UC-win/Road (FORUM8 Co., Ltd., 2013), which is a real time 3D virtual reality software, to develop a tsunami propagation scenario in Kamakura City.

First, a large-scale 3D space model is developed including roads, railroads, and buildings considering the terrain of Kamakura city. The space model refers geographic coordinates, and the elevation model compiled by GSI is used to consider the terrains. The

Fig. 5 Snapshots of the 3D space model for Kamakura City constructed by this study

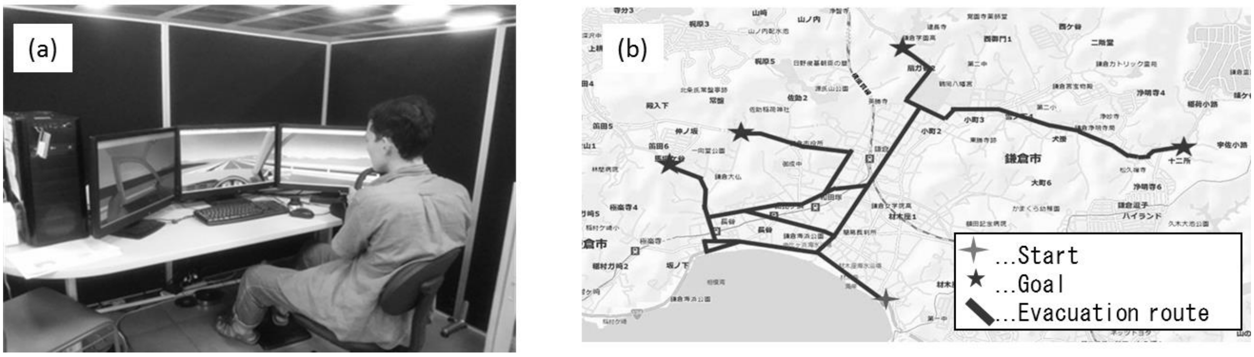

Fig. 6 (a) Driving simulator used in this study and (b) evacuation routes by automobile in case of tsunami assumed by this study

road and railroad datasets for geographic information system (GIS) can be handled by UC-win/Road because the 3D model is projected onto the geographic coordinate system. Figure 3 shows the installation of road and railroad networks in Kamakura City in the 3D space model considering the terrain. The texture of road component can be edited with the software, and building models are also allocated at proper positions and aspects. Figure 4 shows a comparison between the 3D space model developed by this study and an image installed in Google Street View. Figure 5 shows some snapshots of the 3D space model. The reality-based 3D model for Kamakura City was constructed as shown in these figures.

The 3D space model was installed to a driving simulator (Fig. 6(a)) as a scenario course. The driving simulator consists of three LCDs, a steering wheel, brake and accelerator pedals, and the driving reactions can be recorded with respect to elapsed time. We set the initial position and the ideal routes for vehicular evacuation in case of tsunami as shown in Fig. 6(b). Four upland sites were selected as goals outside of the tsunami inundated areas estimated during the 1498 Meio earthquake.

Time series of tsunami propagation calculated in the previous chapter was also introduced to the scenario course. UC-win/Road has a function to visualize the time series data of water level. Since the estimated inundation depths are revealed onto the geographic coordinate system, tsunami propagation can be realized in the 3D space model of Kamakura City. If the height of eye line is set to be 1.2 m, the tsunami propagation is noticed from standard-sized automobile driver's point of view. Figure 7 shows examples of tsunami propagation visualized from driver's point of view.

So far, we could develop a driving simulator with a scenario of tsunami propagation. A series of driving simulator experiments on vehicular evacuation in case of tsunami will be performed in our future study. The study aims to reveal the conditions that permit vehicular

Fig. 7 Visualization of tsunami propagation from driver’s point of view

evacuation by inhabitants, and effective measures to lead tourists on automobiles to upland refuges.

CONCLUSIONS

This study developed a driving simulator with a tsunami propagation scenario. We assumed the occurrence of the 1498 Meio earthquake, and the numerical simulation of tsunami propagation was performed. Kamakura City, Kanagawa Prefecture, which is one of the popular tourist destinations in Japan, was selected as a target area because it was affected by the tsunami following the Meio earthquake.

A large-scale 3D space model considering the terrain in Kamakura City was constructed, and projected onto the geographic coordinate system. The road and railroad GIS datasets were employed to allocate transportation networks with a good reality. Time series of tsunami propagation in Kamakura City was also visualized in the 3D space model. Since the results of our numerical simulation were projected onto the geographic coordinate system, the change of water level with respect to time could be illustrated in the 3D space model. Finally, the 3D model was installed in the driving simulator to realize the tsunami propagation from driver’s point of view.

In a future study, we plan to make a series of experiments on vehicular evacuation in case of tsunami using the driving simulator. The study aims to reveal the permissible limits of vehicular evacuation considering topological conditions and traffic volume in the affected area. The effective measures to transmit the information of evacuation to tourists will be discussed through the results of driving simulator experiments.

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