16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 252

Registration Code: S-K1461810527

DRIVING SIMULATOR EXPERIMENT ON VEHICULAR EVACUATION DURING TSUNAMI

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Abstract

The 2011 Tohoku earthquake that occurred off the Pacific coast of Tohoku, Japan, on 11 March, 2011, triggered an extremely large tsunami. The tsunami inflicted enormous damage on an extensive coastal area of Tohoku and Kanto regions. A number of vehicles traveling in the coastal areas were swept away by the tsunami. The government of Japan had generally recommended evacuation on foot in the case of a tsunami because of the possible traffic congestion, accidents, and entrapment of vehicles by fallen objects and collapsed houses during evacuation by vehicle. In the case of the 2011 Tohoku earthquake, however, 57% of the evacuees used automobiles. Since the population is rapidly aging in Japan, vehicular evacuation must be enhanced in any future event. Based on this background, the aim of this study was to develop a driving simulator with a tsunami inundation scenario. The selected target area was Kamakura City, in Kanagawa Prefecture, Japan, located about 50 km south-south-west of Tokyo. To achieve the objective, a numerical simulation of tsunami propagation was performed assuming an earthquake and tsunami of the scale of the 1498 Meio earthquake. The tsunami was visualized from the driver's point of view using 3D computer graphics. Further, a series of driving simulator experiments were performed to verify the safety of vehicular evacuation in the case of a tsunami.

Keywords: Driving simulator; vehicular evacuation; tsunami propagation; 2011 Tohoku earthquake

1. Introduction

The 2011 Tohoku earthquake that occurred off the Pacific coast of Tohoku, Japan, on 11 March, 2011, triggered an extremely large tsunami. The tsunami inflicted enormous damage on extensive coastal areas of Tohoku and Kanto regions. The Japanese National Police Agency confirmed more than 15,000 fatalities and 2,500 missing persons [1]. According to the Cabinet Office of the Government of Japan [2], 92.4% of the fatalities in Iwate, Miyagi, and Fukushima prefectures resulted from drowning.

A number of vehicles traveling in the coastal areas were swept away by the tsunami occurring shortly after the earthquake. In Japan, vehicular evacuation in the case of a tsunami is generally prohibited because of the possibility of traffic congestions, accidents, and entrapment of vehicles by fallen objects and collapsed houses. However, the Central Disaster Management Council of Japan [3] reported that approximately 57% of evacuees used their automobiles to reach higher ground refuges during the 2011 Tohoku earthquake. Taking this fact into consideration, vehicular evacuation should be examined in each community by considering the time it takes for a tsunami to arrive, distances to evacuation sites, number of people requiring assistance during disasters, and circumstances of evacuation routes.

Based on this background, the aim of this study was to develop a driving simulator with a scenario of tsunami inundation. To achieve the objective, a numerical simulation of tsunami propagation [4] was performed assuming a historical earthquake event. The results were visualized from the driver's point of view using 3D computer graphics (CG). In addition, a series of experiments were performed using the driving simulator to determine the safety of vehicular evacuation in the case of tsunami. A total of 31 examinees took part in the study and were tested under different experimental scenarios in order to reveal an effective means of transmitting tsunami information to drivers.

2. Numerical simulation of tsunami propagation assuming the 1498 Meio earthquake

Kamakura is a city in Kanagawa Prefecture, Japan, and is located about 50 km south-south-west of Tokyo. Kamakura's beach, 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 the associated damage in Kamakura are rather vague [5], historical landmarks such as the "Great Buddha" statue may have been deluged. To enhance tsunami countermeasures, the Kanagawa Prefectural Government has drastically upgraded the importance of its preparedness for gigantic tsunami waves inundating the city following the catastrophic damage caused by the 2011 Tohoku earthquake [6]. In the latest review, the prefectural government considered the impacts of the 1703 Genroku, 1605 Keicho, and 1498 Meio earthquakes.

Based on these circumstances, this study selected Kamakura as a target area. Numerical simulation of tsunami propagation was performed to estimate the tsunami-inundated depths and areas in Kamakura City assuming the occurrence of an earthquake of similar scale to the 1498 Meio earthquake. The seismic fault model developed by the Kanagawa Prefectural Government [6] was employed to estimate the vertical displacement of the seabed. Figure 1 shows the vertical displacement estimated by Okada's method [7]. 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 [4] 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 leapfrog finite difference scheme. Based on the shallow-water theory, the continuity equation can be expressed as

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

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

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

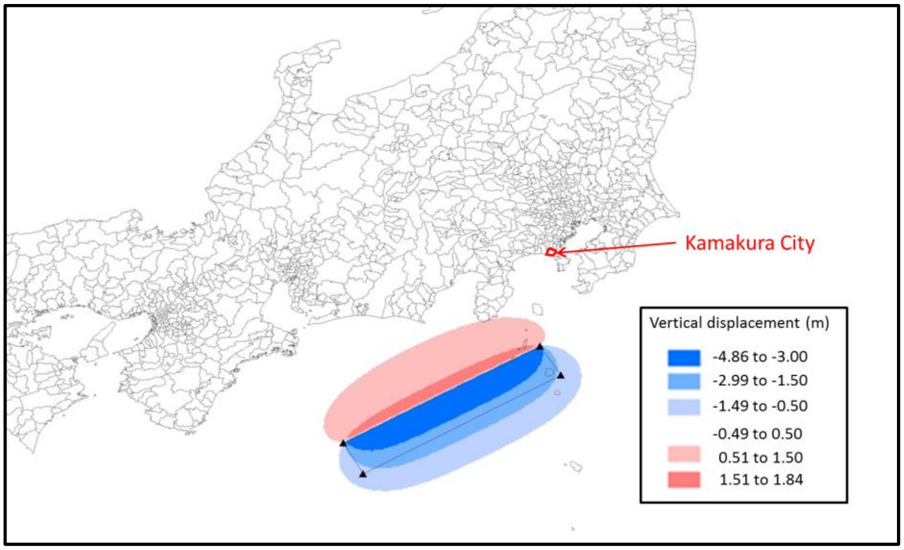
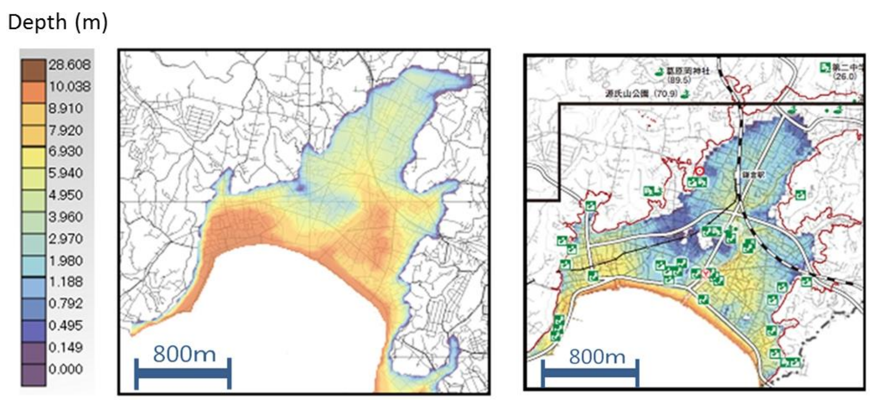


Fig. 1 – Distribution of vertical displacement of seabed assuming the 1498 Meio earthquake



(a) (b)

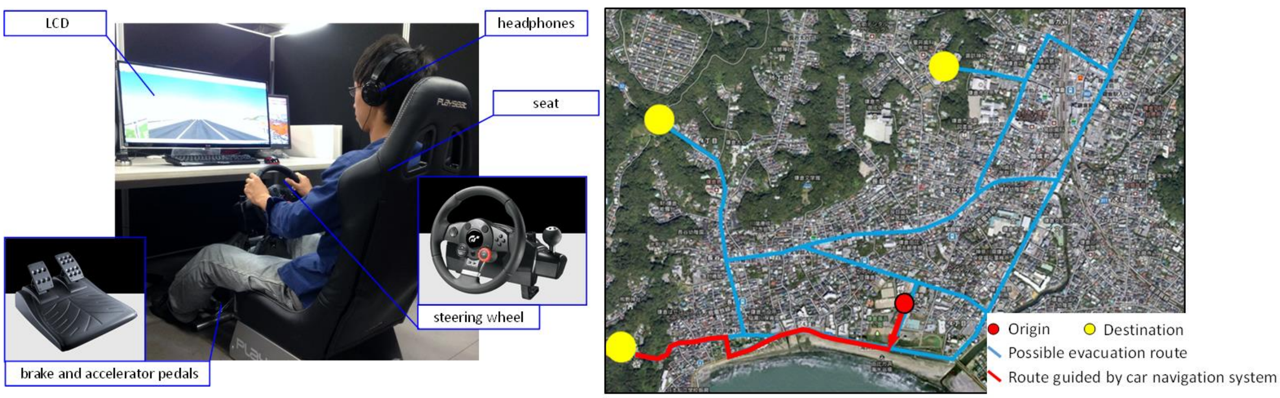
Fig. 2 – Comparison between (a) the distribution of the maximum inundation depth calculated by this study and (b) that illustrated by the Kanagawa Prefectural Government [6]

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

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 [8]. The still-water depth h for each grid cell was assigned using bathymetry data collected by the Japan Coast Guard. Land elevations determined by the Geospatial Information Authority of Japan (GSI) were also considered for estimating inundated areas. Manning's roughness coefficients were assigned according to land use classification [9]. Figure 2 shows the distribution of maximum inundation depth obtained by this study and that illustrated by the Kanagawa Prefectural Government [6]. Since these two distributions show similar trends, the time series behavior of tsunami propagation estimated by our numerical simulation was employed to visualize tsunami propagation from the driver's point of view using 3D computer graphics.

Fig. 3 – Snapshots of the developed 3D space model for Kamakura City



(a) (b)

Fig. 4 – Driving simulator and vehicular evacuation routes considered in this study

3. Driving simulator with a tsunami inundation scenario

Based on the results of numerical simulation, the tsunami propagation was visualized from the driver's point of view. This study employed UC-win/Road [10], 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 was constructed including roads, railroads, and buildings considering the terrain of Kamakura city. The space model refers to geographic coordinates, and the elevation model compiled by GSI is used to consider the terrain. The road and railroad datasets for the 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 some snapshots of the 3D space model constructed by this study.

The 3D space model was installed on a driving simulator (Fig. 4(a)) to test different driving scenarios. The driving simulator consisted of a large LCD screen, a steering wheel, and brake and accelerator pedals. The driving reactions can be recorded with respect to the elapsed time. The initial positions, destinations, and ideal routes for vehicular evacuation in the case of tsunami were chosen, as shown in Fig. 4(b). The destinations were higher ground sites outside of the tsunami inundated areas, based on the calculations of the 1498 Meio earthquake.

Fig. 5 – Tsunami propagation visualized from the driver's point of view

Table 1 – Summary of the scenarios of driving simulator experiment

Scenario	Route guidance	Hazard map	Traffic congestion	No. of examinees
1	Not available	-	-	10
2	Available	-	-	5
3	Available	-	Generated	8
4	Available *	Displayed *	Generated	8

* In Scenario 4, the car navigation system displays the route guidance before the tsunami warning, and the tsunami hazard map after the warning.

(a) (b)

Fig. 6 – (a) Route guidance by car navigation system and (b) tsunami hazard map to show the expected tsunami inundation depth

The tsunami propagation calculated in the previous chapter was also introduced to the different driving scenarios. UC-win/Road has a function to visualize the time series data of water level. Since the estimated inundation depths are projected onto the geographic coordinate system, tsunami propagation can be realized in the 3D space model of Kamakura City. If the height of the eye line is set to 1.2 m, the tsunami propagation is visualized from an average height automobile driver's point of view. Figure 5 shows an example of tsunami propagation visualized from the driver's point of view.

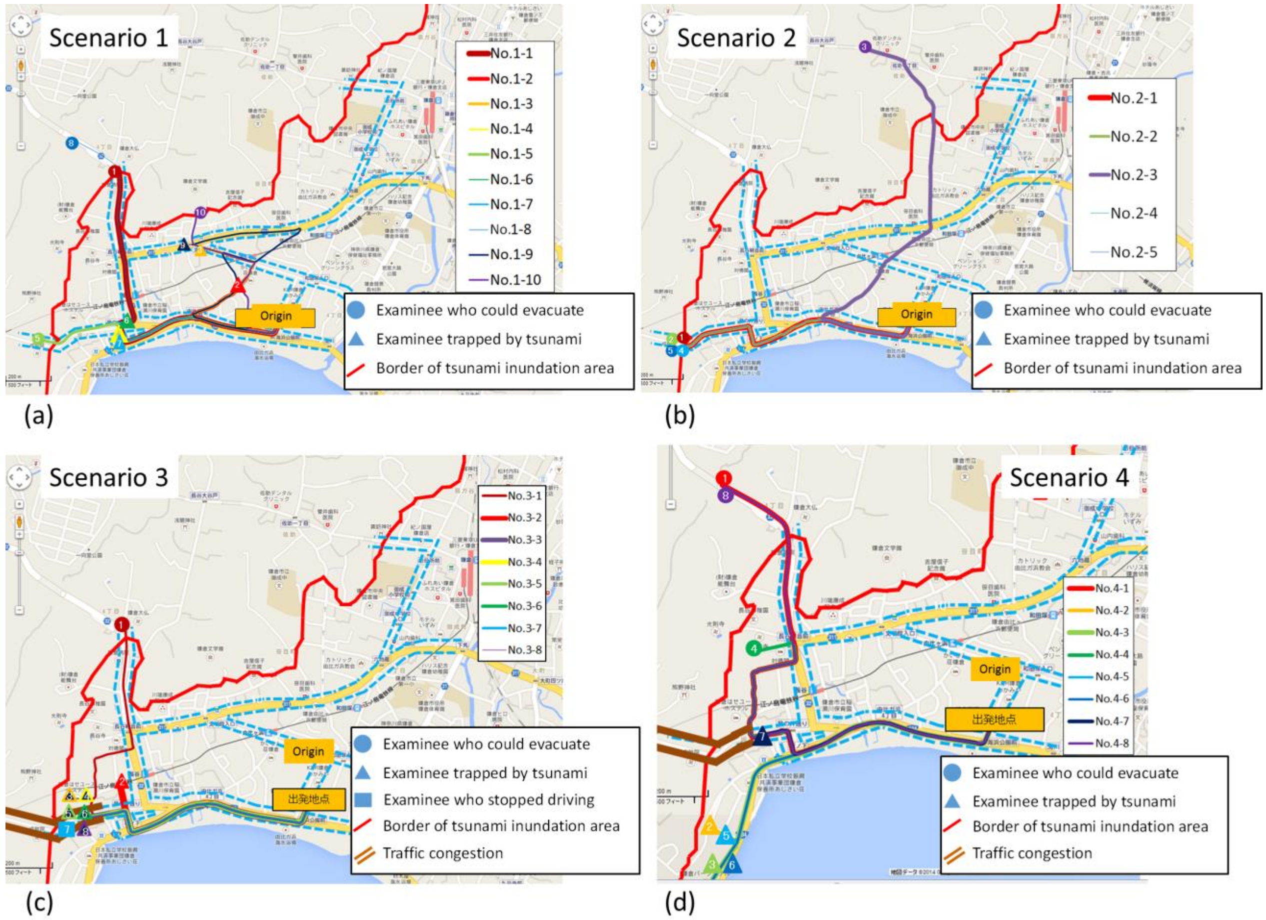


Fig. 7 – Moving trajectories of the examinees during the driving simulator experiments

4. Driving simulator experiment

Four scenarios for the driving simulator experiment were designed. Table 1 summarizes the situations of the different scenarios. The tsunami warning was issued to the examinees to take account of an approaching tsunami during the experiments. The tsunami was set to arrive at the coastline five minutes after the warning. The examinees had the option of referring to a paper map in case they lost their way. The route guidance by the car navigation system (Fig. 6(a)) was displayed on the large LCD screen during the experiment. In Scenarios 2–4, the examinees were guided to the nearest higher ground destination (Fig. 4(b)). In Scenarios 3 and 4, traffic congestion towards the nearest higher ground destination was simulated. If the examinees were in the traffic jam and simply following the route guidance, they would be trapped by the tsunami in these scenarios. In Scenario 4, the tsunami hazard map [6] was displayed (Fig. 6(b)) in order for the examinees to take account of the expected tsunami inundation depth. In total, 31 examinees consented to take part in the driving simulator experiment. The examinees had no prior knowledge of navigation around Kamakura.

Figure 7 shows the moving trajectories of the examinees. In Scenario 1 (Fig. 7(a)), four examinees out of ten evacuated safely. Three examinees drove very slowly to find their way to the higher ground destinations, but they could not reach a point outside of the tsunami-inundated area in time before the arrival of the tsunami. In Scenario 2 (Fig. 7(b)), all five examinees out of five could evacuate safely. Four examinees out of the five followed the route guidance and were able to reach the nearest higher ground destination. They drove smoothly and arrived at the destination within approximately five minutes. The other examinee (No. 2-3) evacuated to another higher ground destination without following the route guidance. Based on the results of Scenario 2, the route guidance provided by the car navigation system was helpful. In Scenario 3 (Fig 7(c)), with traffic congestion simulated, six examinees out of eight simply followed the route guidance, and five examinees were trapped by the tsunami while they were in the traffic jam. One examinee (No. 3-7) stopped driving while in the traffic jam, and insisted on walking to the higher ground destination. Another examinee (No. 3-1) was able to evacuate without following the route guidance. This examinee was not caught in a traffic jam, and could find a suitable way to reach a destination outside of the tsunami inundated area in time.

In Scenario 4 (Fig. 7(d)), after the tsunami warning, the tsunami hazard map was displayed instead of the route guidance. Two examinees (No. 4-1 and 4-8) out of eight reached the higher ground destinations. In addition, one examinee (No. 4-4) stopped driving and insisted on walking to the higher ground destination. None of the examinees was caught in a traffic jam because the examinees were aware of the expected tsunami inundation depth through the tsunami hazard map. However, the number of examinees who could evacuate did not increase significantly compared to the results of Scenario 3. Some of the examinees in Scenario 4 could not find their way to the higher ground destination in time, though they were not caught in a traffic jam. Based on these findings, only displaying the tsunami hazard map to the drivers after the tsunami warning is not an effective way of improving the safe evacuation. Route guidance considering the traffic situation is also required for safe tsunami vehicular evacuation.

5. Conclusions

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

A large-scale 3D space model considering the terrain and buildings 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 high level of detail. Time series of tsunami propagation in Kamakura City were 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 the driver's point of view.

Thirty-one examinees took part in the driving simulator experiments. Four experimental scenarios were implemented to investigate an effective means of transmitting the tsunami information to the drivers. The results showed that displaying the tsunami hazard map during driving assisted the examinees in avoiding traffic jams. However, the route guidance was also required to improve the success rate of vehicular evacuation. Further experiments are needed to arrive at a valid conclusion.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Numbers 26560173 and 16H01842.

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