

# ESTIMATION OF TSUNAMI-INUNDATED AREAS USING SATELLITE IMAGES AND NUMERICAL MODEL IN ASAHI CITY, CHIBA PREFECTURE, AFTER THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

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**KEY WORDS:** The 2011 off the Pacific Coast of Tohoku Earthquake, Tsunami-inundated Area, GIS, Numerical simulation of tsunami propagation, Asahi City, Chiba Prefecture

**Abstract:** The 2011 off the Pacific coast of Tohoku Earthquake triggered an extremely large tsunami. The authors conducted a field survey in Asahi City, Chiba Prefecture, after the occurrence of the earthquake. Tsunami-inundated areas in Asahi City were identified from the map developed by disaster relief volunteers and the satellite images captured after the event. Polygons to demonstrate the tsunami-inundated areas were developed in the geographic information system. The authors compared the identified affected areas with the existing tsunami hazard map of Asahi City. The relationship between the tsunami-inundated areas and the locations of seawalls and tide prevention forests was evaluated. In addition, a numerical simulation of tsunami propagation was performed and the ratio of damaged buildings to the total number of buildings, i.e., damage ratio, in terms of the estimated inundation depths was evaluated.

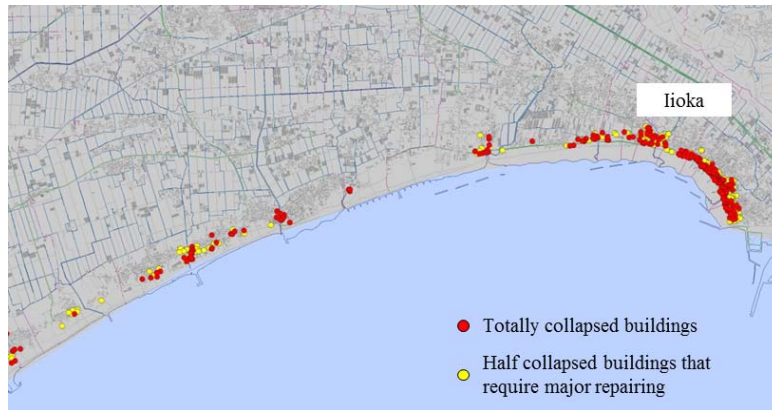
## INTRODUCTION

The 2011 off the Pacific coast of Tohoku Earthquake, which occurred on March 11, 2011, triggered an extremely large tsunami. The run-up reached a maximum height of 40.4 m in Tohoku district (The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011). The Japanese National Police Agency (2011) confirmed more than 15,000 deaths and 2,900 people missing. According to the Cabinet Office, Government of Japan (2011), 92.4% of the fatalities in Iwate, Miyagi, and Fukushima prefectures resulted from drowning.

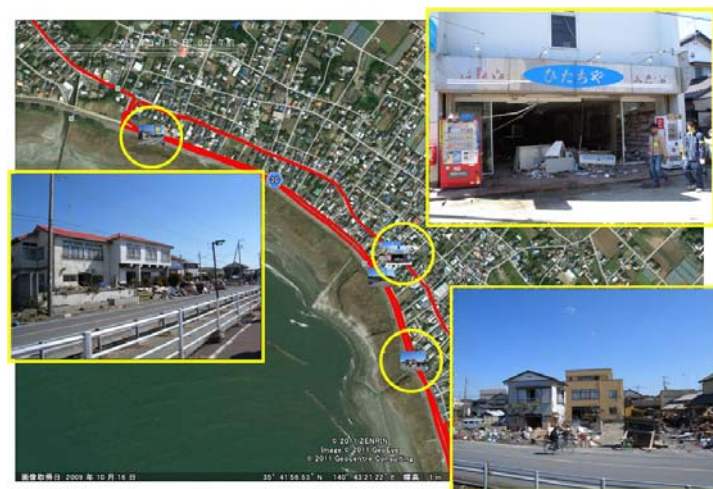
The tsunami also hit Chiba Prefecture. With 13 fatalities in Asahi City and two people reported still missing, the eastern part of the prefecture was severely affected. In Asahi City, 336 family units collapsed as a result of this event (Asahi City, Chiba Prefecture, 2011). These buildings were mainly affected by the tsunami, and liquefaction, although they were away from the most severely affected areas.

Figure 1 shows the distribution of damaged buildings by the tsunami in Asahi City. In the figure, the locations of totally collapsed buildings, and half collapsed buildings that require major repairing are illustrated. The damage to buildings was concentrated in the Iioka district in the eastern part of the city. The authors surveyed Asahi City for the first time on March 18, a week following the earthquake. Figure 2 shows the survey route and photographs of damaged buildings. Many damaged buildings were observed along not only the coastline but also a road on the survey route, further away from the coastline.

In this study, tsunami-inundated areas in Asahi City, Chiba Prefecture, were identified on the basis of the map compiled by disaster relief volunteers, the interpretation of satellite images, and a numerical simulation of tsunami propagation. The relationship between the fraction of totally collapsed buildings in Asahi City and the hydrodynamic features of tsunami inundation flow, obtained from the numerical simulation, was determined.



**Figure 1:** Distribution of damaged buildings after tsunami in Asahi City, Chiba Prefecture



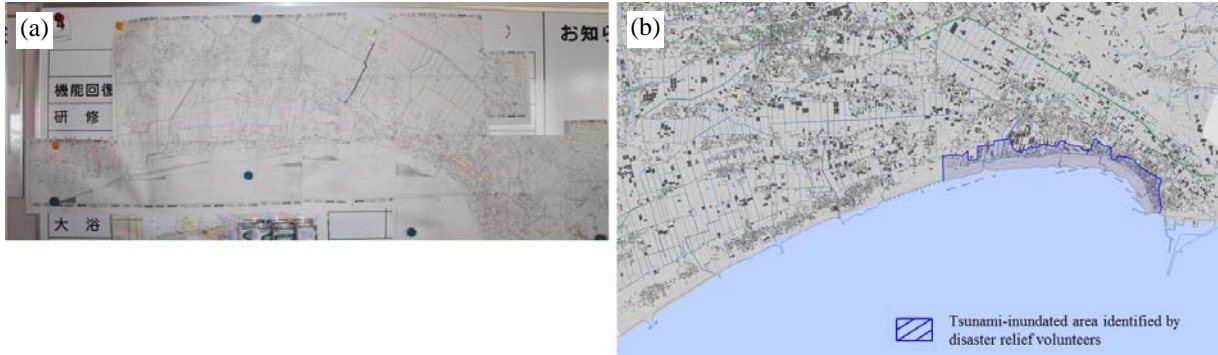
**Figure 2:** Survey route and examples of damaged buildings in Asahi City, Chiba Prefecture

## DEVELOPMENT OF GEOGRAPHIC INFORMATION SYSTEM FOR TSUNAMI-INUNDATED AREAS IN ASAHI CITY, CHIBA PREFECTURE

To confirm the areas inundated by tsunami, the authors visited Asahi City on three occasions and conducted field surveys and interviews. The map developed by the disaster relief volunteers showing the extent of tsunami inundation was provided by the city government during the second field survey conducted on April 12, 2011. The tsunami-inundated areas identified by the volunteers were highlighted on a city map (Fig. 3(a)). The authors obtained photographs of these maps and developed polygons demonstrating the tsunami-inundated areas. These were then projected onto a geographic information system (GIS) (Fig. 3(b)). The map mainly covered the Iioka district in the eastern part of Asahi City.

Remotely sensed imageries are effective tools for identifying the tsunami-inundated areas (Inoue et al., 2007; Kouchi and Yamazaki, 2007; Koshimura et al., 2009; Chen et al., 2005). To this end, critical information about the tsunami of March 2011 was resourced from Google Crisis Response (Google Crisis Response, 2011). The satellite images of the eastern part of Asahi City, captured by Digital Globe on March 12, 2011, were used. The quality of images permitted identification of the tsunami-inundated areas by visual inspection (Fig. 4(a)). The change in color on the ground was mainly used to identify the tsunami-inundated areas. Figure 4(b) shows the tsunami-inundated areas identified by the visual inspection of the satellite images.

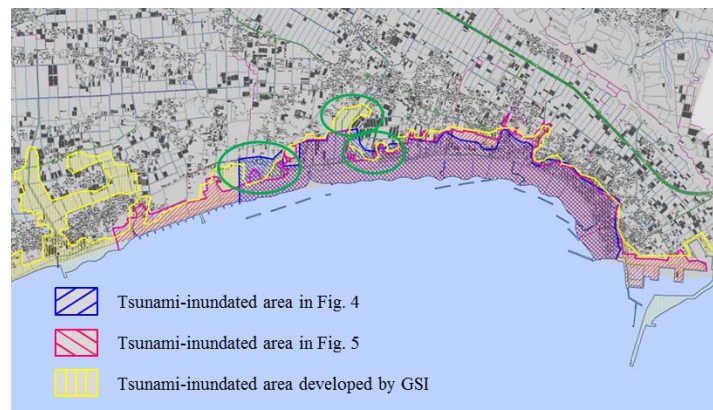
The Geospatial Information Authority of Japan (GSI) has developed the tsunami inundation maps by interpreting satellite and aerial images taken after the earthquake (GSI, 2011). Figure 5 presents a comparison among the tsunami-inundated areas shown in Figs. 3 and 4 and those developed by the GSI. Overall, the areas of tsunami inundation on the three maps overlapped with each other in the eastern part of Asahi City. The three areas marked



**Figure 3:** (a) Tsunami-inundated areas identified by disaster relief volunteers in Asahi City and (b) the identified areas projected onto a GIS system



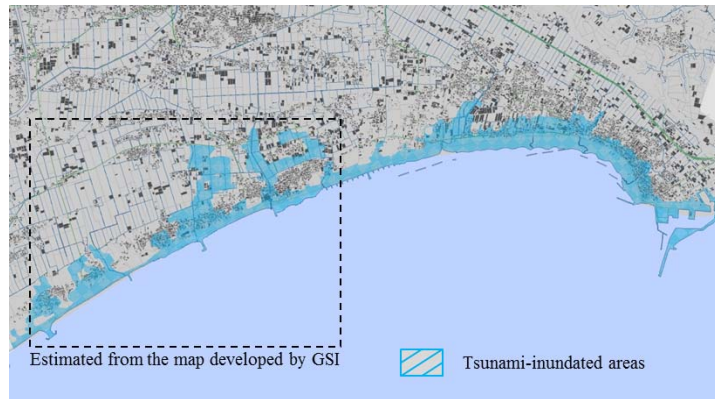
**Figure 4:** (a) Example of visual inspection of satellite images to identify tsunami-inundated areas and (b) their visualization in GIS system



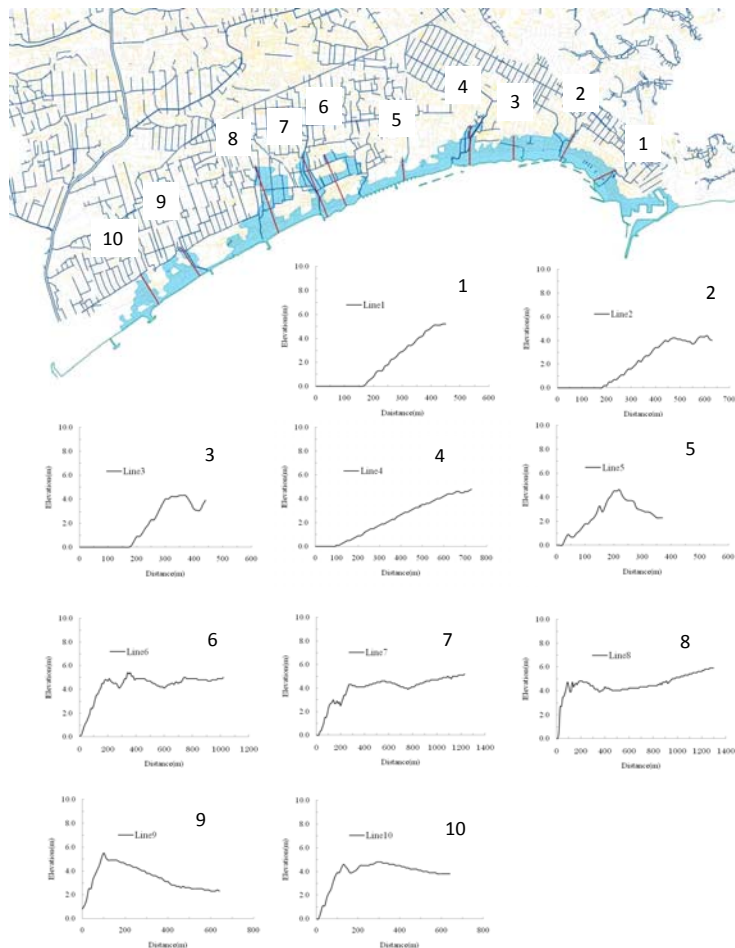
**Figure 5:** Comparison among the tsunami-inundated areas shown in Figs. 4 and 5 and those developed by GSI

with circles indicate sites where the estimates did not coincide. Hence, the authors revisited these sites on June 28, 2011, and interviewed inhabitants to reassess the tsunami-inundated areas. The final estimates of the tsunami-inundated areas are shown in Fig. 6. It should be noted that only the map developed by the GSI was available for the western part of Asahi City. The inundated areas in the eastern part could be validated from three different sources: the map drawn by the volunteers, the result of visual inspection of satellite images, and the tsunami inundation map developed by the GSI.

The authors set 10 traverse lines in the identified inundated area and the elevations were extracted along the lines (Fig. 7). The digital elevation model with a grid size of 10 m compiled by the GSI was employed in this study. The results show that the run-up reached a height of approximately 5 m in Asahi City, Chiba Prefecture.



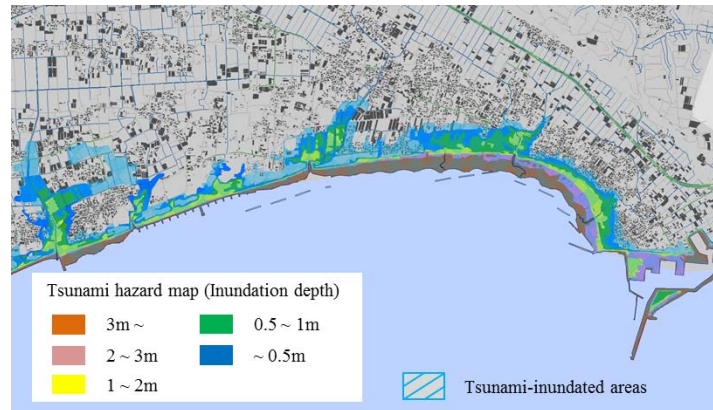
**Figure 6:** Final estimates of tsunami-inundated areas in Asahi City, Chiba Prefecture, after the 2011 off the Pacific coast of Tohoku Earthquake



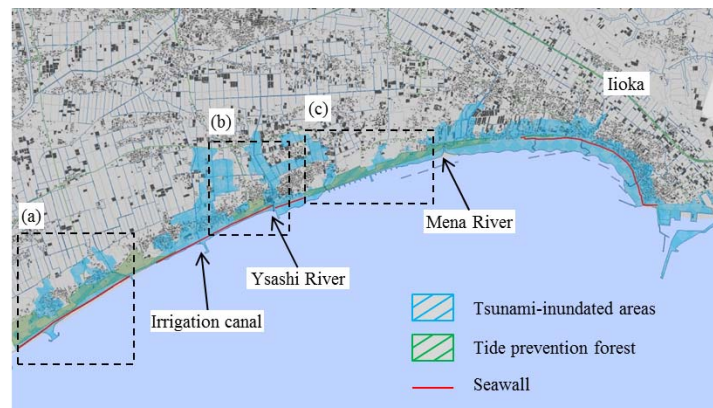
**Figure 7:** Distribution of land elevations along the transverse lines in the identified tsunami-inundated areas in Asahi City, Chiba Prefecture

Tsunami hazard maps have already been developed for Asahi City (Asahi City, 2008). In these maps, the areas of tsunami inundation were estimated in the context of the 1677 Empo Boso-oki and the 1703 Genroku Kanto earthquakes (Iwabuchi et al., 2008). Figure 8 shows a comparison of a tsunami hazard map with the identified tsunami-inundated areas of the city after the 2011 Tohoku Earthquake. It can be observed that eastern parts of the





**Figure 8:** Comparison between tsunami hazard map and identified tsunami-inundated areas in Asahi City, Chiba Prefecture, after the 2011 off the Pacific coast of Tohoku Earthquake



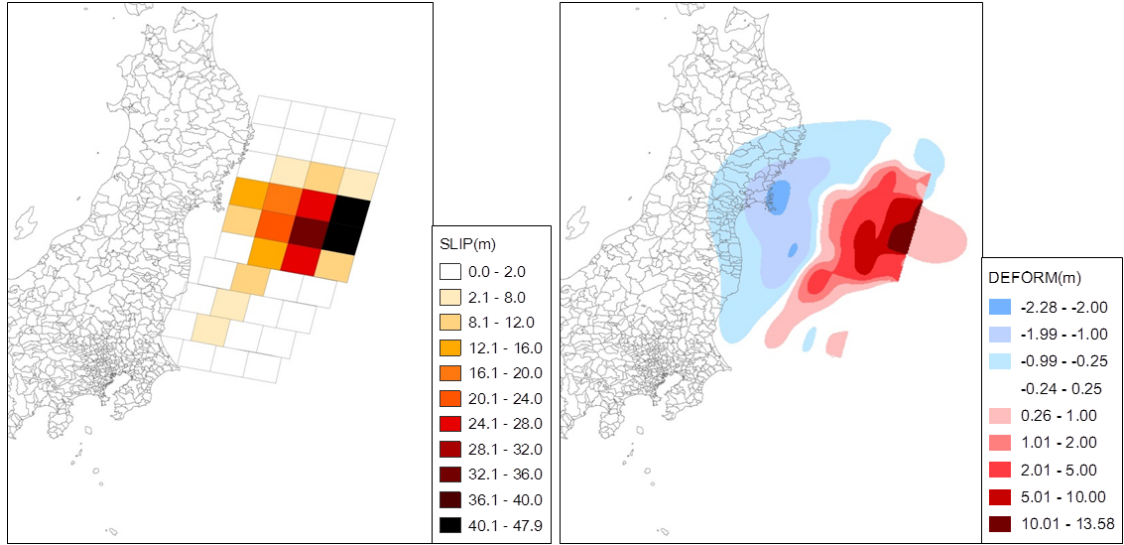
**Figure 9:** Land use classifications along the coast in Asahi City, Chiba Prefecture, and the tsunami-inundated areas

city, such as Iioka, were affected more severely than expected. However, despite the installation of seawalls approximately 4 m in height in Iioka, the tsunami waves climbed over the walls and struck the residential areas.

Land use classifications along the coast were interpreted from satellite images presented in Google Earth before the tsunami. The images were projected onto the map coordinate system, and the locations of tide prevention forests and the seawalls were manually identified (Fig. 9). It was observed that the tsunami-inundated areas spread mostly along the rivers. In general, the height of tsunami waves exceeded that of the seawalls. In the areas labeled (b) and (c), there are comparatively less inundations behind the tide prevention forests except for the areas along the rivers. There are both seawalls and tide prevention forests in the area identified as (a), but this region experienced tsunami inundation. The problem of tsunami inundation with mixed natural and artificial approaches to tsunami mitigation has mixed results. As a whole, the integrity of the trees was such that they were able to withstand the forces of the tsunami inundation, and there was a high enough density of trees that they minimized the inundation by tsunami in several areas. Overall, the ability of tide prevention forest to minimize tsunami inundation remains somewhat controversial because in Tohoku district, large areas of coastal forest failed to protect from the tsunami (EERI 2011a). In most cases, this was simply because the tsunami force was too large and the trees were destroyed. For Asahi City, Chiba Prefecture, the tsunami forces might be smaller and the trees survived, providing some measure of protection.

## NUMERICAL SIMULATION OF TSUNAMI PROPAGATION

Numerical simulation of tsunami propagation was performed to estimate the tsunami-inundated areas in Asahi City. The seismic fault model developed by Fujii and Satake (2011) was employed to estimate the vertical displacement of the seabed. Figure 10 shows the fault model developed by Fujii and Satake (2011) (Fig. 10(a)) and the vertical displacement (Fig. 10(b)) estimated by Okada's method (Okada, 1985). Assuming the water



**Figure 10:** (a) Fault model developed by Fujii and Satake (2011) and (b) vertical displacement of seabed as estimated by Okada's method (1985)

**Table 1:** Definition of Manning's roughness coefficient in this study

Land use	Manning's roughness coefficient ( $m^{-1/3}s$ )
Residential district	0.040
Agricultural land	0.020
Forest land	0.030
Body of water	0.025
Others	0.025

layer to be incompressible, the estimated vertical displacement of the seabed was regarded as the initial profile of the tsunami.

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

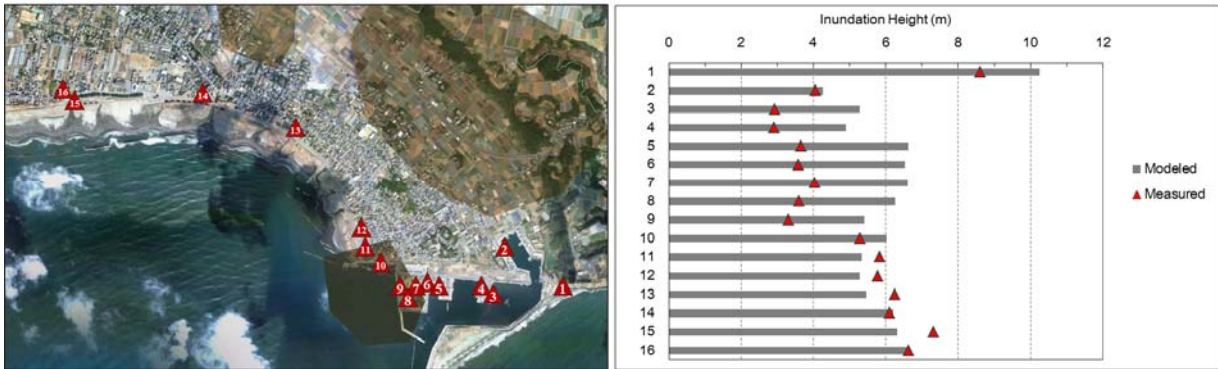
$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0$$

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

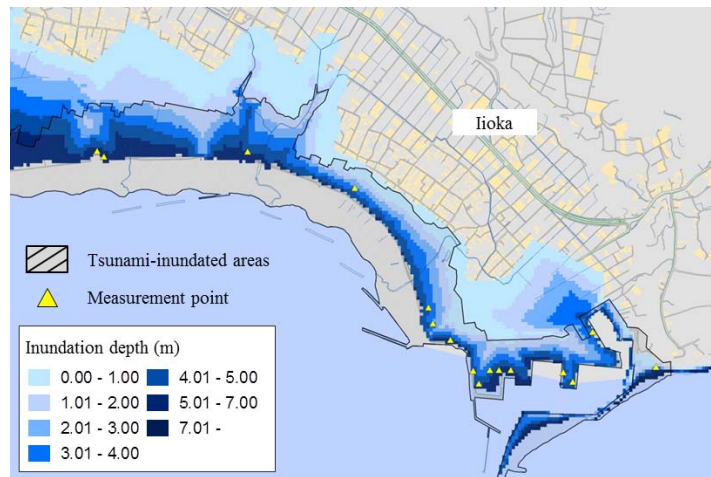
$$\begin{aligned} \frac{\partial M}{\partial t} + \frac{\partial}{\partial x} \left( \frac{M^2}{D} \right) + \frac{\partial}{\partial y} \left( \frac{MN}{D} \right) &= -gD \frac{\partial \eta}{\partial x} - \frac{gn^2}{D^{7/3}} M \sqrt{M^2 + N^2} \\ \frac{\partial N}{\partial t} + \frac{\partial}{\partial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

where  $D$  is the summation of  $\eta$  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, 50 and 16.7 m. The sub-region characterized by coarse grids was set in the deep sea and the one with fine grids



**Figure 11:** Comparison between the measured tsunami inundation heights and those estimated by numerical simulation in Asahi City, Chiba Prefecture



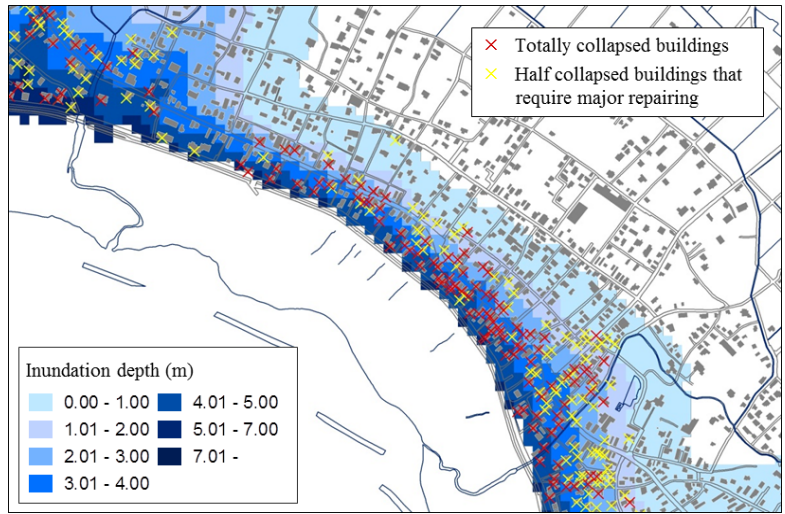
**Figure 12:** Comparison between inundation depths estimated by numerical simulation and the tsunami-inundated areas identified in this study

was set closer to the shore (Shuto, 1991).  $h$  for each grid cell was assigned using the bathymetry data collected by the Japan Coast Guard. The elevations of the land, determined by the GSI were also considered for estimating the inundated areas.

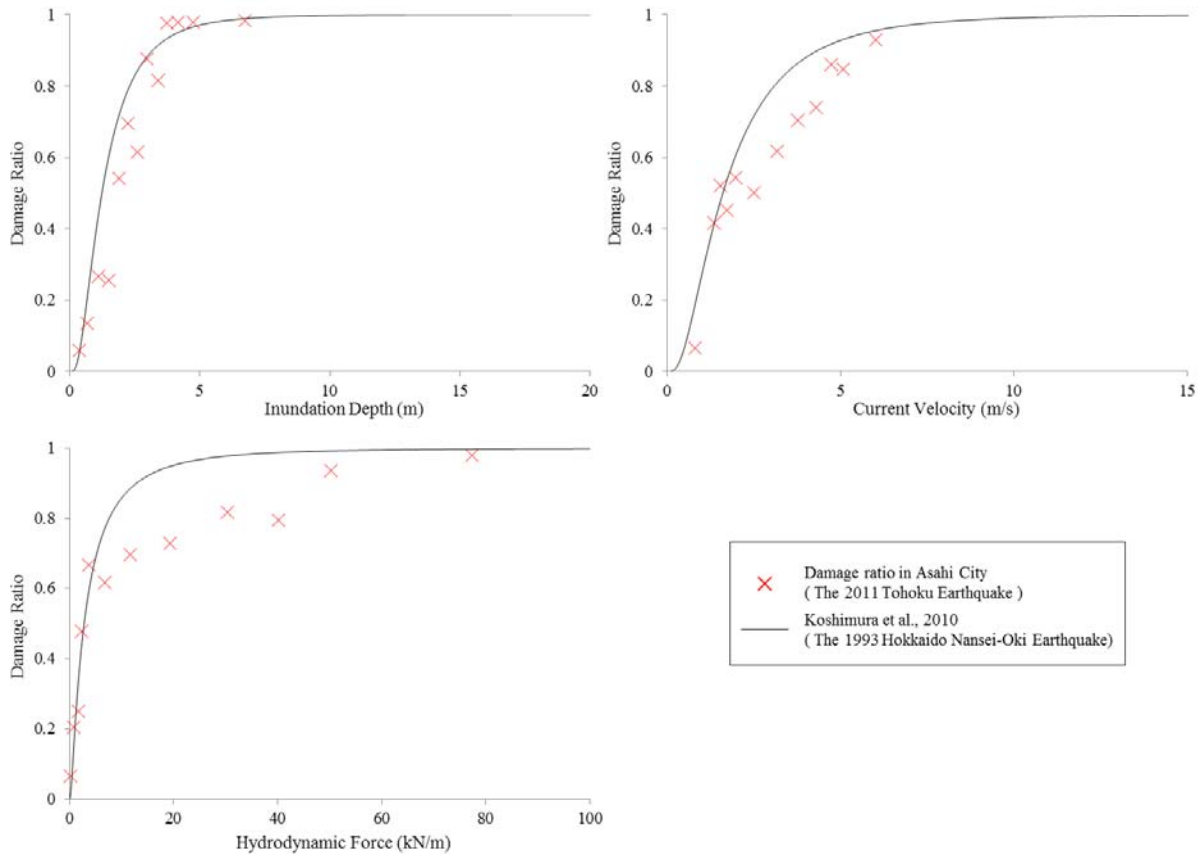
Manning's roughness coefficients were assigned with respect to the land use classifications, as listed in Table 1 (Kotani et al., 1998). We considered that tsunami propagation occurred for three hours after the earthquake. The time step in the numerical simulation was selected to be 0.15 s.

The simulation result was compared with the findings of tsunami surveys conducted by the 2011 Tohoku Earthquake Tsunami Joint Survey Group (2011). Figure 11 shows a comparison of tsunami inundation heights estimated by the numerical simulation with those surveyed in the eastern part of Asahi City. The locations of measurement points of tsunami inundation heights along the coastline compiled by the group are also illustrated in Fig. 11. The inundation height collected by the survey group is defined as the elevation of water level with reference to the sea level (Tokyo Peil: T.P.). According to the comparison, the estimated inundation heights show good agreement with the observations especially in the residential areas, which are labeled as 10-16.

Figure 12 shows a comparison of the tsunami-inundation depths obtained by the numerical simulation with the tsunami-inundated areas identified in this study. We focus on the eastern part of Asahi City, where the inundated areas were verified through different sources. The simulated distribution of the tsunami-inundated areas and the distribution identified through our surveys show similar trends especially in Iioka district.



**Figure 13:** Distribution of damaged buildings according to estimated tsunami-inundation depths



**Figure 14:** Damage ratios of buildings in Asahi City, Chiba Prefecture, with respect to the estimated tsunami-inundation depths, current velocities, and hydrodynamic forces

This study tries to obtain the statistics related to structural damage. Since the exact locations of the damaged buildings following the tsunami were available (see Fig. 1), a dataset of the actual damage could be established. Then, the damage ratios of the buildings in terms of the inundation depth, current velocity, and hydrodynamic force were evaluated by combining this dataset with the results of the numerical simulation. We consider the damage ratios only in Iioka district, in which damage to buildings was concentrated, because the result of our numerical



simulation was verified as in Figs. 11 and 12. The hydrodynamic force applied to structures during a tsunami can be expressed as

$$F = \frac{1}{2} C_D \rho v^2 d$$

where  $C_D$  is the drag coefficient,  $\rho$  is the density of water  $v$  is the current velocity, and  $d$  is the inundation depth.

Figure 13 shows the distribution of damaged buildings in the tsunami affected area according to the estimated inundation depths. Building inventory compiled by Zenrin, a Japanese map publisher, in 2009 was used in this study (Zenrin, 2012). Figure 14 shows the relationships between the damage ratio of buildings and the estimated tsunami-inundation depths, current velocities, and hydrodynamic forces. The figure also shows a fragility curve constructed after the 1993 Hokkaido-Nansei-Oki earthquake (Koshimura et al., 2010). In the study, pre- and post-event satellite images were employed to perform visual damage inspection. The buildings were interpreted as “survived” and “destroyed” by detecting the roofs were remained or not, and the fraction of “destroyed” buildings was used as the damage ratio. The damage ratios in Asahi City were in a similar level as those after the 1993 Hokkaido-Nansei-Oki earthquake with respect to the inundation depth. However, the damage ratios associated with the current velocities and hydrodynamic forces show smaller values than the estimations by fragility function. The tsunami vulnerabilities, such as topological conditions, structural characteristics, and so on resulted in these differences.

## CONCLUSIONS

In this study, the tsunami-inundated areas in Asahi City, Chiba Prefecture, after the 2011 off the Pacific coast of Tohoku Earthquake were estimated. First, maps drawn by disaster relief volunteers and satellite imageries were employed to identify the tsunami-inundated areas. Then, the propagation of the tsunami was numerically simulated and the simulated inundation areas were compared with the identified areas. Finally, the damage ratios of buildings were evaluated in terms of the estimated tsunami inundation depths, current velocities, and hydrodynamic forces.

The GIS dataset for tsunami-inundated areas was constructed by gathering information from different resources and conducting interviews with the residents of the affected areas. It was observed that the tsunami run-up reached a height of approximately 5 m in Asahi City, Chiba Prefecture. The seawalls were not very effective; however, tide prevention forests might be effective in containing the tsunami waves in some areas.

A comparison of the simulated and identified tsunami-inundated areas revealed that both areas fit each other in the eastern part of Asahi City, especially in Iioka district. The estimated inundation heights were compared with the observed ones to confirm the accuracy of numerical simulation. Based on the comparison, the results of numerical simulation could be verified in Iioka district, in which damage to buildings by tsunami was concentrated.

According to the relationships between the damage ratios of buildings in Iioka district and the estimated tsunami inundation depth, current velocity, and hydrodynamic forces, the damage ratios with respect to the inundation depths coincided with those after the 1993 Hokkaido Nansei-Oki earthquake. Employing the fragility functions discussed in the paper, damage assessment of buildings in Chiba Prefecture will be performed in our future study.

## ACKNOWLEDGEMENT

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