Estimation of Tsunami-Inundated Areas in Asahi City, Chiba Prefecture, after the 2011 off the Pacific Coast of Tohoku Earthquake based on Satellite Images and Numerical Simulation

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LISBOA 2012

SUMMARY:
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. In addition, a numerical simulation of tsunami propagation was performed and the ratio of totally collapsed buildings to the total number of buildings, i.e., damage ratio, in terms of the estimated inundation depths was evaluated.

Keywords: The 2011 off the Pacific coast of Tohoku Earthquake, Asahi City, Chiba Prefecture, Tsunami

1. 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 Iwate Prefecture (The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011). The Japanese National Police Agency (2011) confirmed more than 15,000 deaths and 3,400 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 (Fig. 1) 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 some by liquefaction. The people in Asahi City suffered from both tsunami and liquefaction, although the city was away from the most severely affected areas.

Figure 2 shows the distribution of totally collapsed buildings by tsunami in Asahi City. The dataset was compiled by the city and the number of totally collapsed buildings was reported as 229. The damage to buildings was concentrated in the Iioka district in the eastern part of the city.

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 ratio of totally collapsed buildings in Asahi City and the depth of inundation, obtained from the numerical simulation, was determined.

2. 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

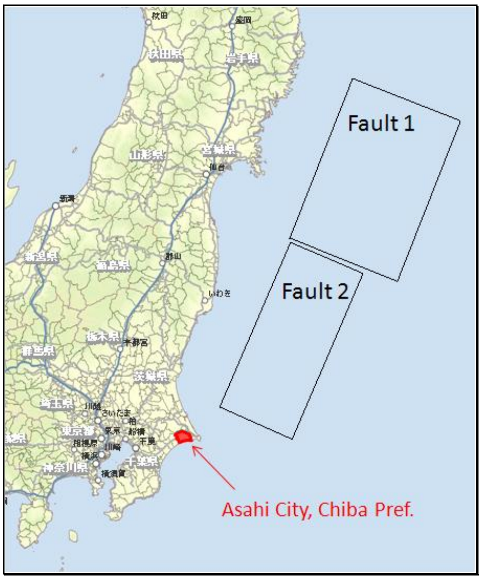

Figure 1. Locations of Asahi City, Chiba Prefecture, and the fault model developed by the Geospatial Information Authority of Japan (GSI)

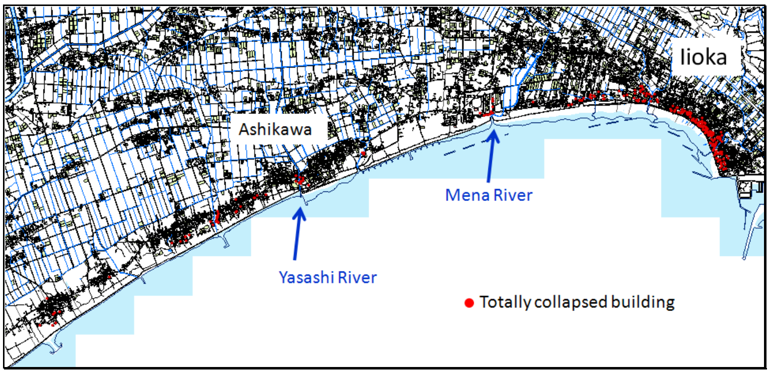

Figure 2. Distribution of totally collapsed buildings after tsunami in Asahi City, Chiba Prefecture

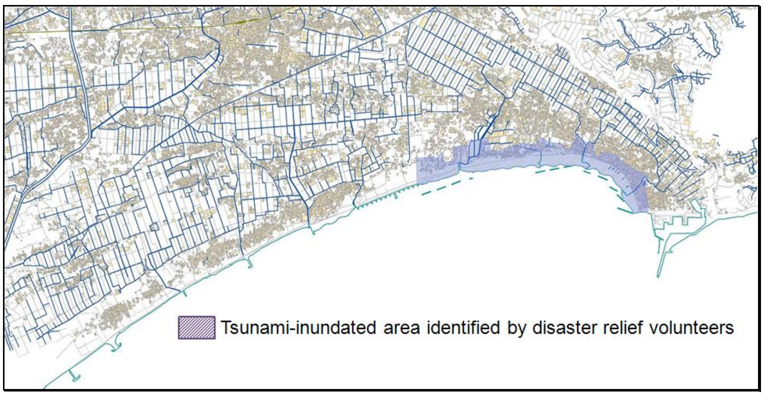

Figure 3. Tsunami-inundated areas identified by disaster relief volunteers in Asahi City

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. 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) as shown in Fig. 3. The map mainly covered the Iioka district in the eastern part of Asahi City.

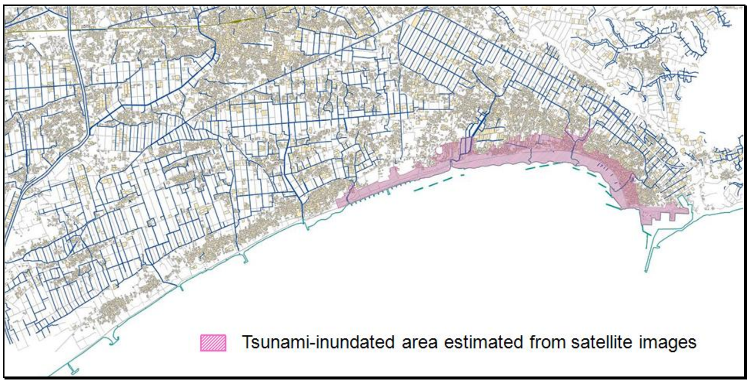

Figure 4. Tsunami-inundated areas identified by visual inspection of satellite images

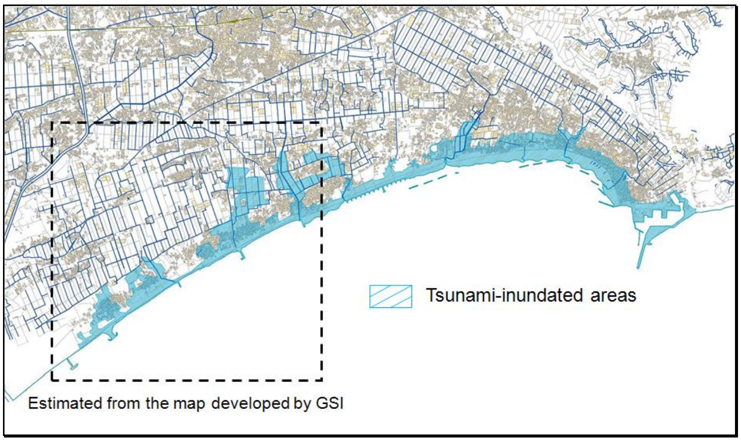

Figure 5. Final estimates of tsunami-inundated areas in Asahi City, Chiba Prefecture, after the 2011 off the Pacific coast of Tohoku Earthquake

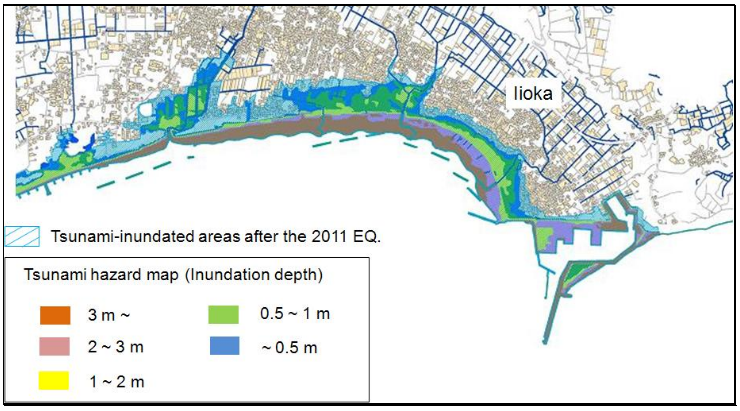

Figure 6. Comparison between tsunami hazard map and identified tsunami-inundated areas in Asahi City, Chiba Prefecture, after the 2011 off the Pacific coast of Tohoku Earthquake

Remotely sensed imageries are effective tools for identifying the tsunami-inundated areas (Inoue et al., 2007; Kouchi and Yamazaki, 2007; Koshimura et al., 2009a; 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 DigitalGlobe on March 12, 2011, were used. The change in color on the ground was mainly used to identify the tsunami-inundated areas. Figure 4 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

Table 1. Specifications of the seismic fault model developed by the GSI (2011b)

	Depth (km)	Length (km)	Width (km)	Strike (deg)	Dip (deg)	Rake (deg)	Slip (m)
Fault 1	5.1	186	129	203	16	101	24.7
Fault 2	17.0	194	88	203	15	83	6.1

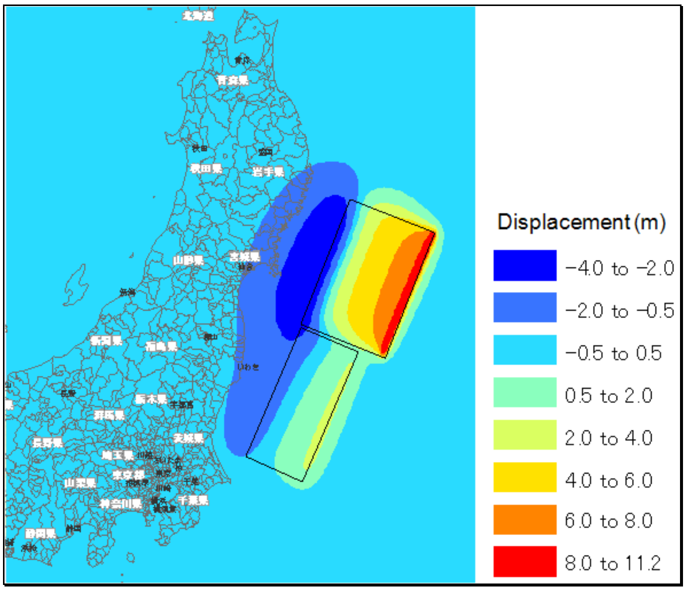

Figure 7. Vertical displacement of seabed as estimated by Okada's method (1985)

interpreting satellite and aerial images taken after the earthquake (GSI, 2011a). Comparing this result with Figs. 3 and 4, the final estimates of the tsunami-inundated areas were developed in Fig. 5.

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 6 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 the eastern parts of the 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.

3. NUMERICAL SIMULATION OF TSUNAMI PROPAGATION

Numerical simulation of tsunami propagation was also performed to estimate the tsunami-inundated areas in Asahi City. The seismogenic fault model developed by the GSI (GSI, 2011b) was employed to estimate the vertical displacement of the seabed (see Fig. 1). The specifications of this fault model are listed in Table 1. Figure 7 shows the vertical displacement estimated by Okada's method (Okada, 1985). Assuming the water layer to be incompressible, the estimated vertical displacement of the seabed was regarded as the initial profile of the tsunami.

Various methodologies have been employed to simulate tsunami propagation (Ohmachi et al., 2001; Furumura and Saito, 2009; Liu et al., 2008). 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).

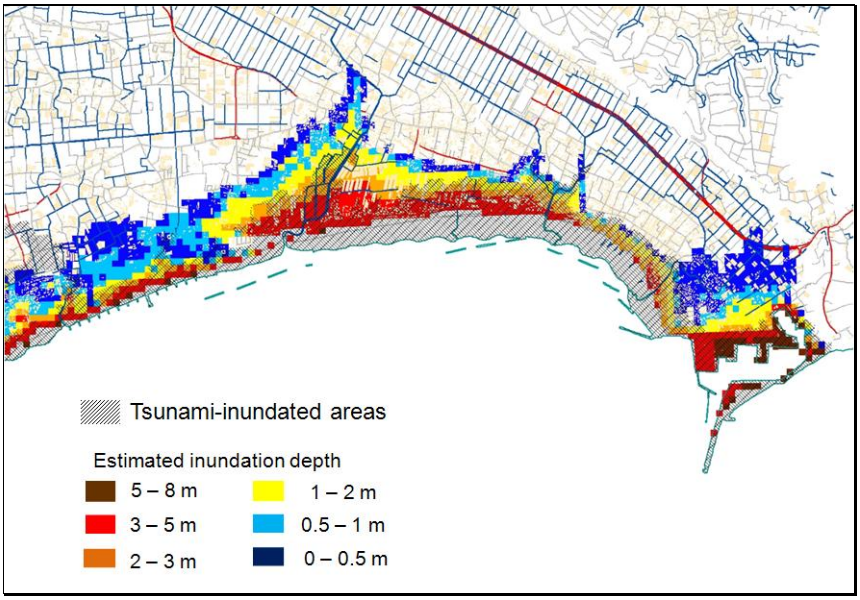

Figure 8. Comparison between inundation depths estimated by numerical simulation and the tsunami-inundated areas identified in this study

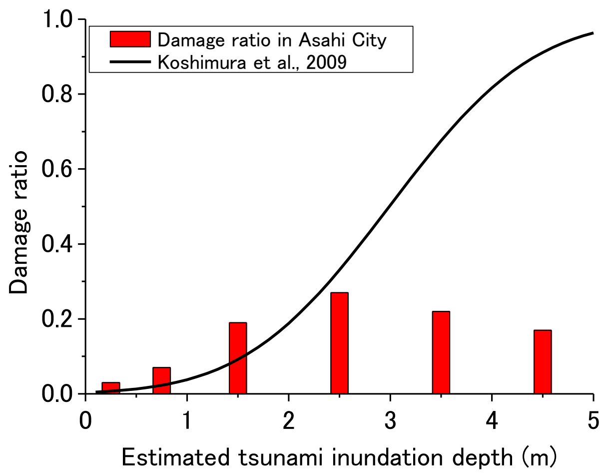

Figure 9. Relationship between the damage ratio of buildings and the estimated tsunami-inundation depth

In the numerical simulation, the target region was divided into four sub-regions having grid lengths of 1350, 450, 150, and 50 m. The sub-region characterized by coarse grids was set in the deep sea and the one with fine grids was set closer to the shore (Shuto, 1991). The still water depth 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 (Kotani et al., 1998). We considered that tsunami propagation till three hours after the occurrence of earthquake. The time step in the numerical simulation was selected to be 0.15 s.

Figure 8 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 the surveys show similar trends. The tsunami-inundated areas include almost all the surveyed areas with a simulated inundation depth greater than 1 m. The tsunami-inundated areas were identified primarily through the satellite and aerial images captured a few days after the earthquake. Hence, the areas inundated with shallow waters might have been identified with limited accuracy. This may explain the difference between the inundated areas determined by the simulation and those identified in this study.

The structural performance due to tsunami forces has been investigated by various research teams (Bertero et al., 1985; Saatcioglu; 2006; Ruangrassamee et al., 2006). This study tries to obtain the statistics related to structural damage. Since the exact locations of the totally collapsed buildings following the tsunami were available (see Fig. 2), a dataset of the actual damage could be established. Then, the damage ratio of buildings—the ratio of totally collapsed buildings to the total number of buildings—in terms of the inundation depth was evaluated by combining this dataset with the results of the numerical simulation. Building inventory compiled by Zenrin, a Japanese map publisher, in 2009 was used in this study (Zenrin, 2012). Figure 9 shows the relationship between the damage ratio of buildings and the estimated tsunami-inundation depths. The figure also shows a fragility curve constructed after the 2004 Sumatra–Andaman earthquake (Koshimura et al., 2009b). 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 the same as those in Banda Aceh, Indonesia, with an estimated inundation depth of around 3 m. However, the damage ratios associated with the inundation depth of more than 3 m were smaller than the estimations of the fragility function.

In the numerical simulation, a land elevation model with a grid size of 50 m was employed. However, a finer elevation model should be considered to obtain a more accurate result. In addition, the effects of seawalls were not included in this simulation. To estimate the hydrodynamic forces applied to structures during a tsunami, it is necessary to estimate not only the inundation depth but also the flow velocity that caused the observed damage. This event provided an opportunity to analyze tsunami flow conditions using video and field evidence (EERI, 2011). The damage ratio of buildings in Asahi City, Chiba Prefecture, will be evaluated in terms of the hydrodynamic forces. Furthermore, the structural details of buildings were not considered while evaluating their damage ratios, but their effects should be investigated in a future study. Further research is necessary to draw solid conclusions on the relationship between the damage ratio of buildings and the tsunami inundation depth.

4. 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 tsunami was numerically simulated and the simulated inundation areas were compared with the identified areas. Finally, the damage ratio of buildings was evaluated in terms of the estimated tsunami inundation depth.

A comparison of the simulated and identified tsunami-inundated areas revealed that the latter covered almost all the areas where the estimated inundation depth was more than 1 m. Since the tsunami-inundated areas were mainly identified based on the satellite images captured a few days after the earthquake, only the areas completely inundated with deep water could be detected. This may explain the difference between the simulated results and those obtained by imagery.

According to the relationship between the damage ratio of buildings and the estimated tsunami inundation depth, the damage ratios associated with the inundation depth of less than 3 m coincided with those at Banda Aceh after the 2004 Sumatra–Andaman earthquake. However, the damage ratios decreased at inundation depths greater than 3 m. In order to arrive at more definite conclusions, it is essential to improve the accuracy of numerical simulation by employing a finer digital-elevation model and considering the locations of the seawalls.

AKCNOWLEDGEMENT
The authors would like to express their sincere gratitude to Professor Shunichi Koshimura of Tohoku University for providing the TUNAMI-CODE (Tohoku University's Numerical Analysis Model for Investigation of Tsunami).

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