Extreme tsunami inundation in Onagawa, due to the 2011 Tohoku Tsunami

Graduate School of Engineering, Tohoku University Student Member ○ Bruno ADRIANO
IRIDeS, Tohoku University Regular Member Erick MAS
IRIDeS, Tohoku University Regular Member Shunichi KOSHIMURA

1. Introduction

A devastating tsunami, which was triggered by a M$_W$9.0 earthquake (the 2011 Great East Japan Earthquake), struck the northern Pacific coast of Japan and completely destroyed several coastal communities, including Iwate Prefecture, Miyagi Prefecture, and Fukushima Prefecture. The maximum reported run-up height of the tsunami was 40 m (Mori et al., 2012). A thorough analysis of the extreme tsunami inundation recorded in Onagawa town was conducted using numerical modeling. In addition, the influence of the breakwater in the bay was considered to analyze its possible contribution on reducing the tsunami inundation depth. The results of our simulations show that the maximum inundation depth due to the first incoming wave was at least 16.0 m height. Furthermore, the breakwater, which was not originally designed against tsunami waves, positively influenced the results by reducing the maximum tsunami inundation depth at least in 2.0 m in Onagawa town

2. Methodology

2.1. Study area

The study area is Onagawa town, which is located approximately 50 km northeast of Sendai in Miyagi Prefecture in Japan. Onagawa has a ria coast and is located in a narrow bay. The urban areas were mainly concentrated in three sectors (Fig. 1).

2.2. Numerical modeling

The tsunami source model proposed by the Cabinet Office, Government of Japan Cabinet Office (2012) is used to compute the initial sea surface displacement. This source is characterized by a temporal-spatial slip distribution of 4,575 sub-fault segments, with an average area of 46 km × 56 km, at 60 seconds interval within the first five minutes after the main-shock. The initial tsunami condition assumes instantaneous displacement of the sea surface, which is identical to the calculated vertical sea floor displacement that considers a rectangular fault model (Okada, 1985). The effect of the horizontal crustal movement is also considered to calculate the total vertical component (Tanioka and Satake, 1996). The effect of each temporal-spatial slip distribution is incorporated in the tsunami wave propagation by adding the associated sea surface displacement to the current water surface elevation. We use a high-resolution topographic model to represent the surface resistance against the tsunami penetration. The equivalent roughness model (ERM) uses the digital elevation model data and composite equivalent roughness coefficient that is given by Eq. 1 according to land use and building conditions Imai et al. (2013). In addition, in order to evaluate the contribution of the breakwater, which was located at the entrance of Onagawa bay, a second hypothetical topographic model was used. This model was constructed by removing the breakwater's pixel values from the original data.

$$n_{rem} = \sqrt{\frac{100-\theta}{100} n_0^2 + \frac{\theta}{100} \frac{C_D}{2gk} D^{4/3}} \tag{1}$$

where n_0 is the roughness coefficient according to MLIT (2009) (urban areas: n_0 = 0.025, other areas: n_0 = 0.030), θ is the building/house occupancy ratio in the computational grid, C_D is the drag coefficient (C_D=0.5 according to Imai et al. (2013)), g is the gravitational acceleration (9.81 m/s^2), k is the horizontal scale of houses, and D is the computed flow depth.

3. Results and Discussion

3.1. Validation of the models

Figure 1 shows the spatial distribution of the maximum modeled inundation depth from both topographic models where the maximum values are 16.8 and 19.4 m for the ERM and the hypothetical topography model, respectively. The limits of the inundation area from both models are in general equal, which indicates that flooded area was mainly limited by the land elevation of Onagawa town. On the other hand, the inundation depth distribution from the ERM shows lower values than the second model. For instance, in case of the ERM, the maximum inundation depth around Onagawa Hospital varies from 1.0 m to 2.0 m, and in case of the hypothetical topography model the maximum inundation depth varies from 3.0 m to 4.0 m. The tsunami watermark found in one column at the entrance of Onagawa Hospital indicates that the tsunami inundation depth was approximately 1.95 m.

Keywords: 2011 Tohoku Tsunami, Tsunami simulation, Building damages.**Contact address**: Aoba 468-1, Aramaki, Aoba-ku, Sendai 980-0845. (TEL) 022-752-2082

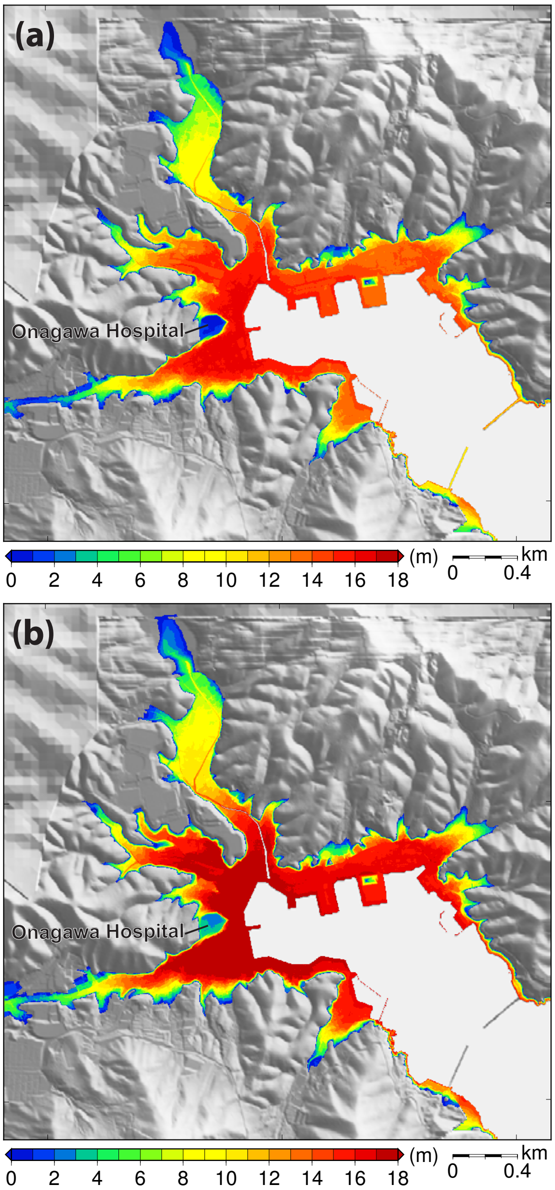

Figure 1: Maximum computed tsunami inundation depth. (a) Numerical result with the breakwater. (b) Numerical result without including the breakwater.

Figure 2 shows the comparison in terms of temporal tsunami flow depth from both topographic models and the video analysis conducted by Koshimura et al. (2013). Although the raising time of the flow depths in the two models started approximately at the same time (15:26 JST), the flow depths of the model which does not include the breakwater was considerably higher than the ERM. For instance, the maximum flow depth is 18.5 m, almost 2 m higher than the ERM. This fact clearly indicates that the breakwater had a positive contribution on reducing the tsunami inundation depth at least on 2.0 m. However, it should be also noted that the inundation results from the ERM considered that the breakwater remains constant during the entire tsunami simulation. According to a testimony of an engineer working as civil servant in Onagawa town, both caissons failed during the tsunami attack (Mikami et al., 2012). The effect of the

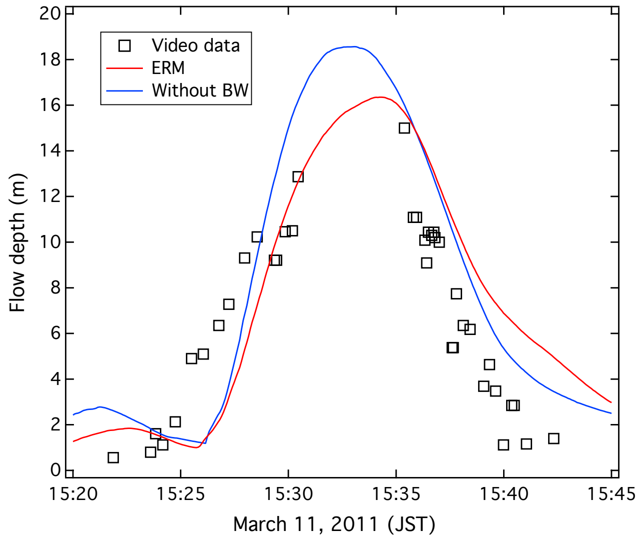

Figure 2: Time series comparison of tsunami flow depth between models results and the video analysis published by Koshimura et al. (2013).

breakwater destruction during the tsunami simulation can be incorporated by estimating the approximately time of destruction of each caisson.

In summary, the result without including the coastal protection revealed that the breakwater did contributed to reduce the tsunami impact, lowering at most 2.0 m of inundation depth. In addition, the tsunami penetration was mainly limited by the land elevation rather than the tsunami energy such as the case of Sendai plain. It also should be noted that our simulation does not incorporate the time when the caissons were destroyed. Therefore, if known, including these factors would increase the reproducibility of the tsunami inundation features observed in Onagawa town.

References

Cabinet Office, G. o. J. (2012). Massive earthquake model review meeting of the Nankai Trough.

Imai, K., Imamura, F., and Iwama, S. (2013). Advanced Tsunami Computation for Urban Regions. *Journal of Japan Society of Civil Engineers*, 69(2):N/A.

Koshimura, S., Hayashi, S., and Gokon, H. (2013). Lessons from the 2011 Tohoku Earthquake Tsunami Disaster. *Journal of Disaster Research*, 8(4):549–560.

Mikami, T., Shibayama, T., Esteban, M., and Matsumaru, R. (2012). Field Survey of the 2011 Tohoku Earthquake and Tsunami in Miyagi and Fukushima Prefectures. *Coastal Engineering Journal*, 54(1):1250011–1.

MLIT (2009). National Land Use Classification (in Japanese), The Minister of Land, Infrastructure, Transport and Tourism (MLIT).

Mori, N., Takahashi, T., and The 2011 Tohoku Earthquake Tsunami Joint Survey Group (2012). Nationwide post event survey and analysis of the 2011 Tohoku Earthquake Tsunami. *Coastal Engineering Journal*, 54(1):1250001–1.

Okada, Y. (1985). Surface deformation due to shear and tensile faults in a half-space. *Bulletin of the Seismological Society of America*, 75(4):1135–1154.

Tanioka, Y. and Satake, K. (1996). Tsunami generation by horizontal displacement of ocean bottom. *Geophysical Research Letters*, 23(8):861.