*Coastal Dynamics 2017*
*Paper No. 238*

# ANALYSIS OF TSUNAMI VARIABILITY AND BREAKWATER STABILITY CONSIDERING UNCERTAINTY OF TSUNAMI SOURCE FOR THE 2011 TOHOKU EARTHQUAKE

Daiki Tsujio[1], Katsuichiro Goda[2], Tomohiro Yasuda[3] and Nobuhito Mori[4]

**Abstract**

Most of breakwaters destroyed by the 2011 Tohoku tsunami have been reconstructed against the $M_w$9.0-class tsunamis to prevent similar tsunami damage. However, future tsunamis which will occur in this region can be different from the 2011 tsunami. This study aims at clarifying the variability of tsunami profiles and breakwater stability against uncertain tsunami source in the Tohoku region. The analysis of the tsunami profiles in six ports located in Tohoku area demonstrated that the locations relative to epi center and the topography of these ports strongly influence the variability of the maximum tsunami wave height. The results of the stability analysis clarified that the breakwater stability in five ports depends on tsunami profiles affected by regional features. These results implied that future tsunami defense strategy requires consideration of uncertainty in tsunami wave profiles and regional features.

**Key words:** tsunami variability, breakwater stability, stochastic tsunami source model, 2011 Tohoku tsunami, uncertainty and sensitivity analysis of tsunami hazards

## 1. Introduction

The 2011 off Pacific coast of Tohoku earthquake (the 2011 Tohoku earthquake), moment magnitude ($M_w$) 9.0, caused a great number of fatalities and damage to buildings and infrastructures, leading to huge economic loss (Mori & Takahashi, 2012; Mori et al., 2011). The tsunami caused by the 2011 Tohoku earthquake devastated various kinds of infrastructures, including bridges, quays, floodgates, and roads (Suppasri et al., 2013). Particularly, several breakwaters for tsunami defense in this region had suffered from major damage (Kazama et al., 2012) (e.g. Kamaishi, Ofunato, and Soma ports). The damage to breakwaters is critical be-cause it increases tsunami hydrodynamic force to facilities inside harbors and lands; the damage also delays recovery of transport functions, such as importing relief supplies by ships. Therefore, an integrated strategy regarding breakwater functionality and recovery is essential for tsunami risk management.

Several tsunami breakwaters and harbor entrance breakwaters have been constructed in the Tohoku region before the 2011 Tohoku earthquake to mitigate tsunamis and storm waves inside ports and coastal zones. The main external force for break-water design is tsunamis or storm waves. Generally, most of breakwaters located in the Tohoku region are designed against wind wave forces. After this disaster, most of breakwaters destroyed by the 2011 Tohoku tsunami are redesigned and reconstructed against the $M_w$9.0-class tsunamis to prevent tsunami damage due to similar repeating events.

Although the reconstruction and recovery policy is understandable for residents and stakeholders, future tsunamis which will occur in this region can be different from the 2011 Tohoku tsunami. Accordingly future tsunami defense strategy needs to take into account variability in major tsunami characteristics, such as geometry, asperity, and slip distribution. Goda et al. developed the stochastic random-field slip models for the 2011 Tohoku earth-quake to consider numerous possible tsunami scenarios and conducted a sensitivity analysis of tsunami waves and inundation heights along the Tohoku

[1]Disaster Prevention Department, Pacific Consultants Co., Ltd., Japan. daiki.tsujio@os.pacific.co.jp
[2]Department of Civil Engineering, University of Bristol, United Kingdom. katsu.goda@bristol.ac.uk
[3]Department of Civil, Environmental and Applied System Engineering, Kansai University, Japan. tomo@oceanwave.jp
[4]Disaster Prevention Research Institute, Kyoto University, Japan. mori@oceanwave.jp

coast. Such hazard variability affects breakwater stability, and the uncertainty should be quantified for effective tsunami defense planning.

This study aims at clarifying the variability of tsunami profiles and breakwater stability against uncertain tsunami source in the Tohoku region. The paper begins with a description of the stochastic tsunami source models followed by discussion of the distributions of the maximum tsunami wave height in target ports. Then, the methods of breakwater stability analysis are explained. Finally, the paper concludes with a discussion of the analysis results using model breakwaters and future investigations for strategic breakwater planning.

## 2. Stochastic Tsunami Model for the 2011 Tohoku Earthquake

### 2.1. *Stochastic Tsunami Source Models*

This study employs the stochastic tsunami waves generated by Goda et al. (2014) for the breakwater stability analysis. This section describes the stochastic tsunami source modeling.

The stochastic modeling procedure is based on spectral analysis of an inversion-based earthquake slip distribution proposed by Mai & Beroza (2002). A number of possible initial tsunami profiles for the 2011 Tohoku earthquake have been proposed by many researchers. In particular, Goda et al. (2014) used 11 inversion models for the stochastic modeling as shown in Figure 1 and Table 1. For each of the 11 inversion-based models, Goda et al. (2014) generated 66 slip models: an original model, 5 models with different top-edge depths, 5 models with different strike angles, 5 models with different dip angles, and 50 models with different slip distributions. The depth to the top of the fault plane, strike angle, and dip angle are varied with respect to the original inversion models. Using a total of 726 (= 11×66) initial tsunami distributions, Goda et al. (2014) simulated tsunami profiles along the Tohoku coast. This study utilizes the results of tsunami wave heights at target ports (shown in Table 2) as external load for breakwater stability analysis.

Table 1. Eleven slip models.

| Model ID and reference | Seismic moment (Nm) | Length (km) | Width (km) | Data type |
|---|---|---|---|---|
| 1: Fujii et al. (2011) | $3.8\times10^{22}$ | 500 | 200 | Tsunami |
| 2: Satake et al. (2013) | $4.2\times10^{22}$ | 550 | 200 | Tsunami |
| 3: Shao et al. (2011) [Ver1] | $5.6\times10^{22}$ | 500 | 200 | Teleseismic |
| 4: Shao et al. (2011) [Ver2] | $5.8\times10^{22}$ | 475 | 200 | Teleseismic |
| 5: Shao et al. (2011) [Ver3] | $5.8\times10^{22}$ | 475 | 200 | Teleseismic |
| 6: Yamazaki et al. (2011) | $3.2\times10^{22}$ | 340 | 200 | Teleseismic & tsunami |
| 7: Ammon et al. (2011) | $3.6\times10^{22}$ | 600 | 210 | Teleseismic & geodetic |
| 8: Gusman et al. (2012) | $5.1\times10^{22}$ | 450 | 200 | Tsunami & geodetic |
| 9: Hayes (2011) | $4.9\times10^{22}$ | 625 | 260 | Teleseismic |
| 10: Iinuma et al. (2011) | $4.0\times10^{22}$ | 600 | 240 | Geodetic |
| 11: Iinuma et al. (2012) | $4.0\times10^{22}$ | 620 | 260 | Geodetic |

Table 2. Location of target ports.

| Port Name | Latitude (°) | Longitude (°) | Depth (m) |
|---|---|---|---|
| 1. Miyako | 39.6393 | 141.9821 | 23 |
| * Kamaishi | 39.2598 | 141.9308 | 62 |
| 2. Ofunato | 39.0176 | 141.7326 | 22 |
| 3. Ishinomaki | 38.3885 | 141.2725 | 14 |
| 4. Sendai | 38.2602 | 141.0616 | 20 |
| 5. Soma | 37.8547 | 140.9713 | 13 |

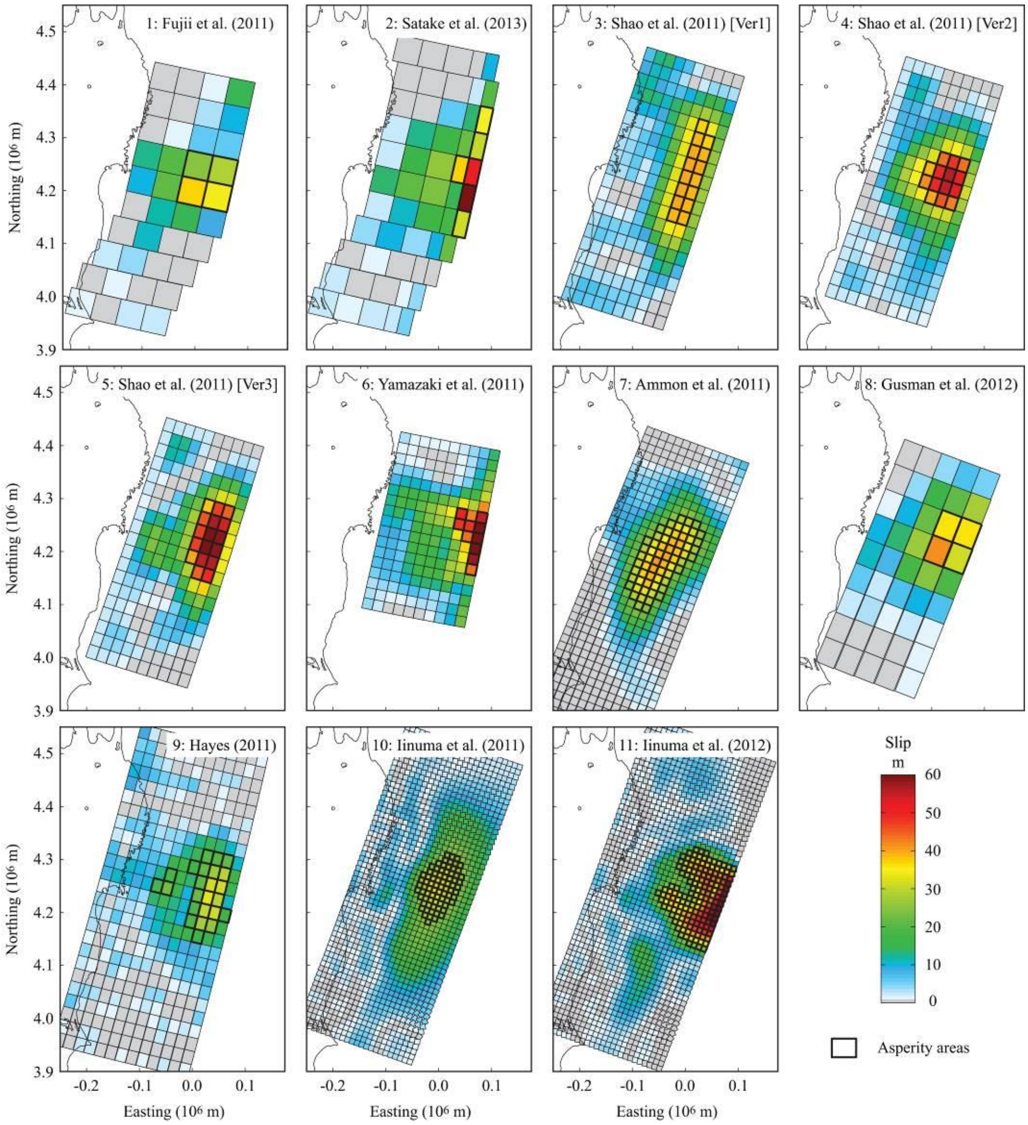


Figure 1. 11 Inversion-based source models.

## 3. Tsunami Profile

### 3.1. *Distributions of Tsunami Wave Heights*

This study aims at understanding the failure modes and their likelihoods of breakwaters against tsunamis in the Tohoku region. Accordingly, to grasp the characteristics of the tsunami profiles in Tohoku region, north to south around epicenter, five primary ports are selected for the investigation: (1) Miyako, (2) Ofunato, (3) Ishinomaki, (4) Sendai, and (5) Soma as shown in Table 2. The main factor of breakwater stability is maximum tsunami wave height. To grasp the characteristics of the tsunami profiles in these ports the distributions of the maximum tsunami wave heights at the breakwaters in these ports are examined. Figure 2 shows the histograms of the maximum tsunami wave heights in five ports. For reference, the histogram of tsunami heights at Kamaishi breakwater is also shown in this figure (note: the Kamaishi breakwater is not use in the stability analysis because it is installed at relatively deep seabed, about 60 m depth.

The features of the tsunami wave height distributions can be divided into three categories: symmetrical, right-heavy tail, and left-heavy tail distributions as shown in Figure 2. The Miyako and Kamaishi ports belong to the left-heavy tail group; a large part of the maximum wave heights in the two ports are relatively small and the peak values are between 5 to 10 m, while the distributions have a long tail in a higher range of tsunami height. The locations and topography of these ports can explain the features; these ports are located in the northern part of the Tohoku region and comparably far from the main rupture area (or asperity) of the 2011 Tohoku earthquake. Therefore, if the main rupture area shifts to south of the region in the stochastic source models, the maximum tsunami heights in the ports would de-crease. Furthermore, as the port mouths are open to northeast, large tsunamis from south are unlikely to be amplified.

Second, the histogram of Ofunato is symmetrical, having an average tsunami height of 20 m. This port is located in the central part of the Tohoku region and faces the main rupture area of the 2011 Tohoku earthquake. In addition, the ria coastline around this area amplifies tsunami waves at a maximum of more than 40 m. Ofunato is one of the most affected areas in the Tohoku region because of its geographical features.

Third, the wave height distributions in Ishinomaki, Sendai, and Soma ports have a right-heavy tail. Although these ports are relatively close to the main rupture area, the maximum wave height in this region ranges from 15 to 20 m and is smaller than that of Ofunato port. The reason for the low maxi-mum wave heights is because the flat plain terrain of the coast prevents an increase of tsunami wave heights in these ports. However, it should be noted that tsunami heights of 10 to 15 m are generally expected in these ports, comparing with the other ports.

Thus, tsunami waves propagated to the Tohoku coast have a variety of features and future defense planning should consider such features for effective tsunami hazard management. The following section analyzes the breakwater stability using these tsunami waves.

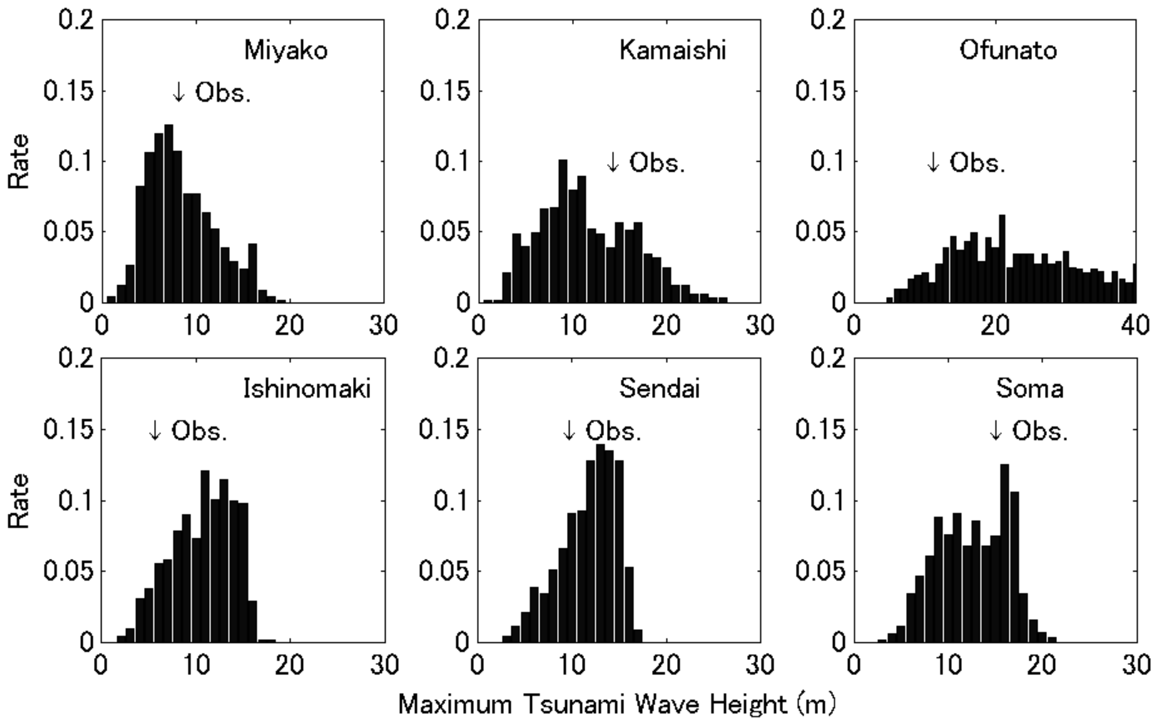


Figure 2. Probabilistic tsunami wave heights in front of breakwaters in Miyako, Kamaishi, Ofunato, Ishinomaki, Sendai and Soma.

## 4. Breakwater Stability Analysis

### 4.1. *Stability Analysis Methods*

A guideline (MLIT, 2013) of breakwater design against tsunami in Japan requires stability analysis of three main failure modes: sliding, overturning, and foundation failures. Although most of the failure modes during the 2011 Tohoku tsunami were a combination of these three, present foundation failure analysis involves uncertainty in various significant elements. For example, tsunami-seabed-structure interaction (Sassa, 2014) and the effects of differential water levels at the seaward and the landward sides of breakwaters (Takahashi et al., 2014) have not been fully understood. Future research should cover these effects for breakwater stability. Thus, this study focuses on the sliding and overturning failure modes. The guideline (MLIT, 2013) employs the following equations for the stability analysis:

For sliding:

$$f(W - P_B - P_U) \geq \gamma P_H \tag{1}$$

For overturning:

$$a_1 W - a_2 P_B - a_3 P_U \geq \gamma a_4 P_H \tag{2}$$

where $f$ is the friction coefficient, $W$ is the weight of breakwater, $P_B$ is the buoyancy (kN/m), $P_U$ is the uplift tsunami force (kN/m), $P_H$ is the horizontal tsunami force (kN/m), $\gamma$ is the structural analysis factor and $a_1$ to $a_4$ are the lengths of action arms. The guideline (MLIT, 2013) also proposed three estimation methods of tsunami horizontal and uplift forces considering the effects of wave breaking and tsunami overflow. According to the guideline (MLIT, 2013), time dependent water levels at the seaward and the landward sides of breakwaters are necessary for calculation of the tsunami overflow effect. This method is computationally expensive for hundreds of tsunami simulations. Thus, this study neglects the overflow effect and covers only the effect of wave breaking. As for estimation of wave pressure, Tanimoto's formula (Tanimoto et al., 1984) are employed in compliance with the guideline (MLIT, 2013).

Specification of breakwaters depends on local design conditions, such as wind wave height, tsunami height, and water depth. To equally assess the breakwater stability against tsunami profiles in the five ports, this study assesses the stability of model breakwaters. To cover multiple environmental conditions, this study designs model breakwaters using three different maximum wind wave heights ($H$): 5, 7, and 9 m. The widths ($Bc$) and other specification of the model breakwaters are determined such that the safety factors for both sliding and overturning failures exceed 1.2. Figure 3 shows a cross section of a model breakwater, and Table 3 summarizes the main parameters of the model breakwaters. For simplification, the high water levels (HWL) and low water levels (LWL) are assumed to be the same for all ports: HWL is 2.0 m above LWL. This study adopts the mean sea levels (i.e. 1.0 m above LWL) as the reference water level in the stability analysis.

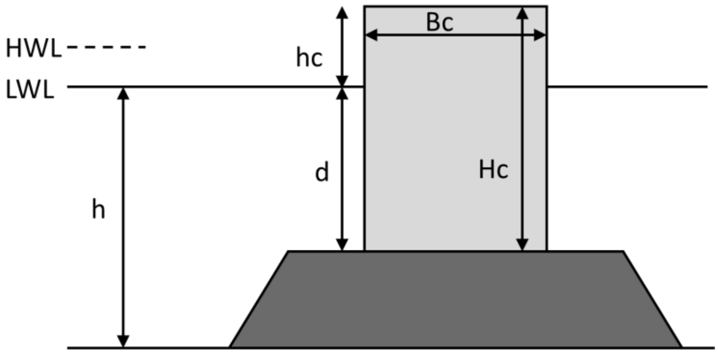


Figure 3. Cross section of modeled breakwater.

Table 3. Model breakwaters.

| Design wave height (m) | *Hc* (m) | *Bc* (m) | *d* (m) | Safety factor | |
|---|---|---|---|---|---|
| | | | | Slide | Overturn |
| 5 | 13.7 | 8.4 | 10 | 1.27 | 1.21 |
| 7 | 14.4 | 15.1 | 10 | 1.21 | 2.06 |
| 9 | 15 | 22.4 | 10 | 1.21 | 2.98 |

### 4.2. *RESULTS AND DISCUSSIONS*

4.2.1. *Histograms of Safety Factors*

This study conducts the stability analysis of three different model breakwaters in the five Tohoku ports using the 726 cases of tsunami profiles. As a result of the calculations, this analysis focuses on variability of structural analysis factors (i.e. safety factors) for both sliding and overturning. Figure 4 shows histograms of sliding and overturning safety factors of three breakwaters in the Sendai port. The modes of all histograms of sliding safety factors are less than 1.0 and the histogram has a long tail in a higher range of safety factors. Generally, the safety factors for sliding are smaller than those for overturning in all ports. However, in some cases of breakwaters designed for $H$ = 5 m, the overturning safety factors are quite close to those for sliding. As sliding is a critical failure mode in this study, the following analysis concentrates on the sliding stability results.

4.2.2. *Probability of Sliding Failure*

To understand the differences of sliding stability within the five ports, the probabilities of sliding failure are investigated. Figure 5 illustrates change of failure probability relative to latitudinal locations of all ports because the breakwaters are unable to withstand against $M_w$9.0 tsunami waves. The failure probabilities in the five ports become more variable with the increase of H. For instance, the failure probability in the Miyako port is significantly de-creased with the increase of H: from 0.8 to 0.16 for H = 5 m to 9 m. On the other hand, the Ofunato port has little change in the failure probability even if the breakwater is increased to H = 9 m. The distributions of the maximum tsunami wave height (Figure 2) can explain this. The histogram of tsunami wave heights arriving at the Miyako port is a back shift of distribution. Therefore, enhancement of the breakwater stability can simply lead to a reduction of the failure probability. Meanwhile, because Ofunato has a wide range of tsunami height distribution, marginal in-crease in design height is ineffective for reducing the failure probability. As for Ishinomaki, Sendai, and Soma, the failure probabilities decrease particularly in case of H = 9 m although the effects of Miyako surpass those of the three ports.

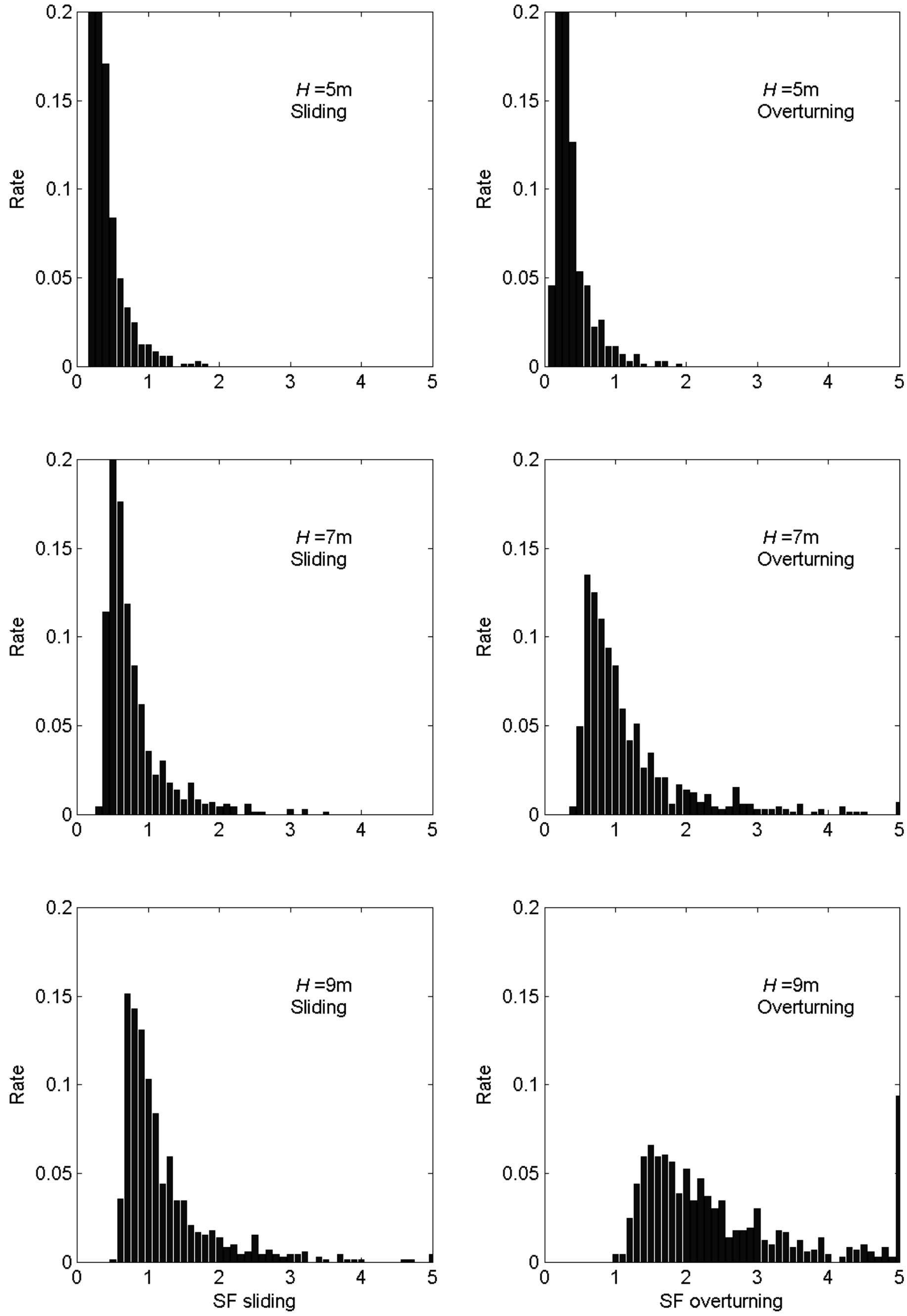


Figure.4. Histogram of safety factors of sliding (left) and overturning (right) in Sendai port (top: $H$ = 5 m, middle: $H$ = 7 m and bottom: $H$ = 9 m).

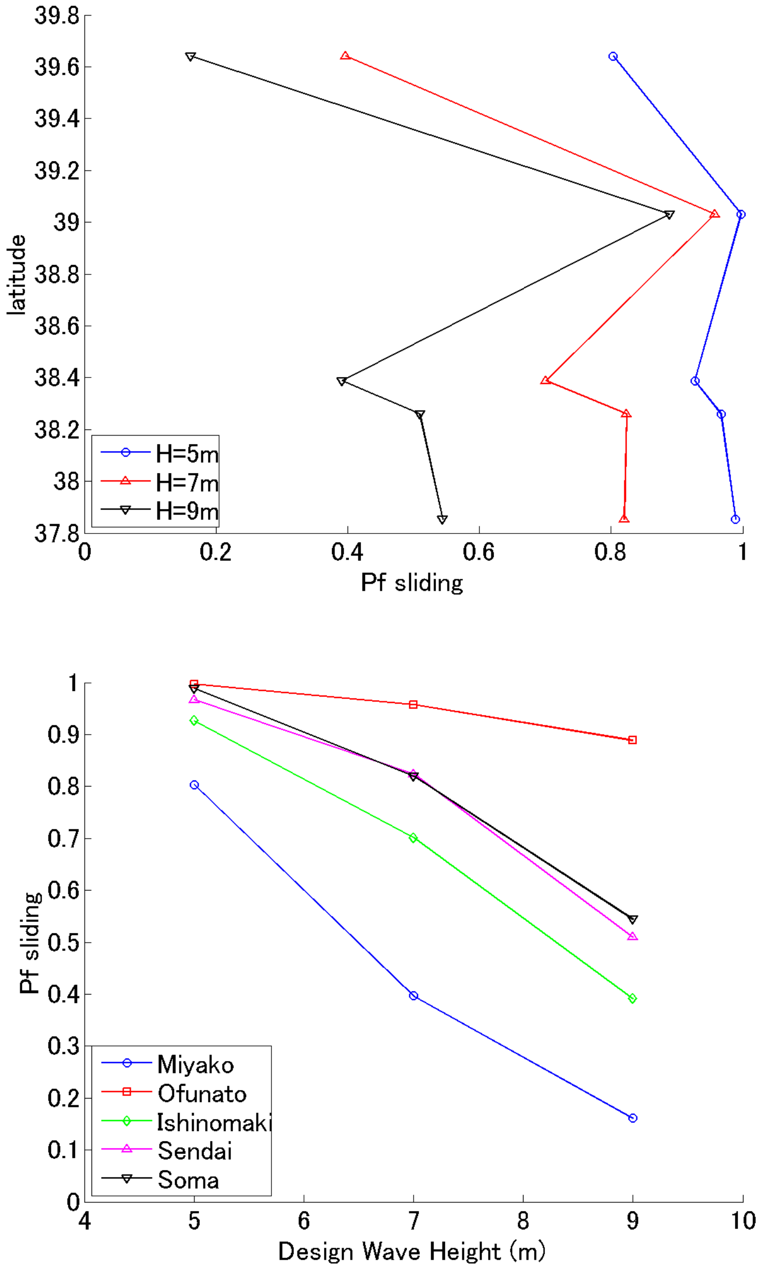


Figure 5. Probability of sliding failure against latitudinal location (top) and design wave height (*H*) (bottom).

4.2.3. *Histograms of Safety Factors*

To investigate the sensitivity of breakwater stability, the occurrence probabilities of sliding safety factors are analyzed. Figure 6 shows the results for the Miyako and Ofunato ports. The slopes of the probability curves for Miyako are relatively gentle, while Ofunato has steep gradients in the probability curves. Figure 7 shows the medians, 5th and 95th per-centiles of the sliding safety factors in the two ports. The range between 5th and 95th percentiles in the Miyako port is 1.4 for H = 5 m, while that for Ofunato is a half of Miyako's. The ranges in both ports become greater with the increase of H, although the ranges in Ofunato are still a half of Miyako's: e.g. 1.5 and 4.1 for H = 9 m. Thus, even if the earthquake magnitudes are the same as $M_w$9.0, the mean values and ranges of the breakwater stability can be quite variable with spatial features and tsunami profiles.

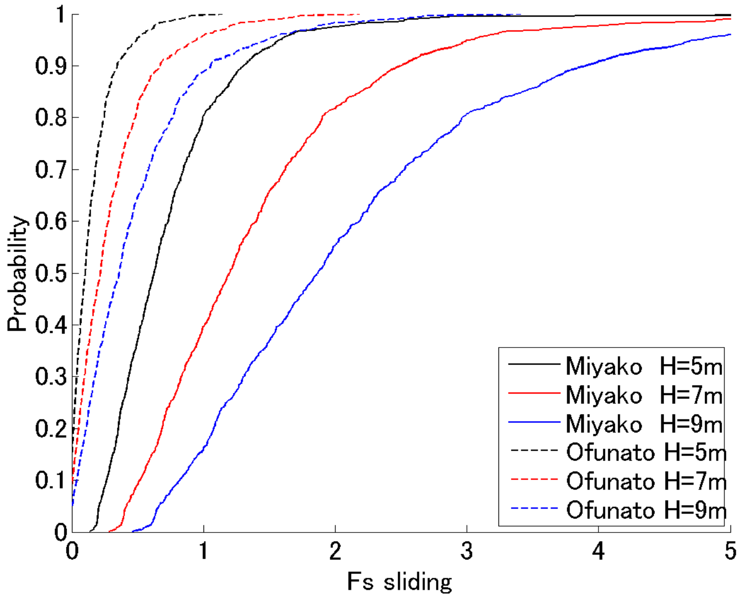


Figure 6. Occurrence probability of sliding safety factor in Miyako and Ofunato port.

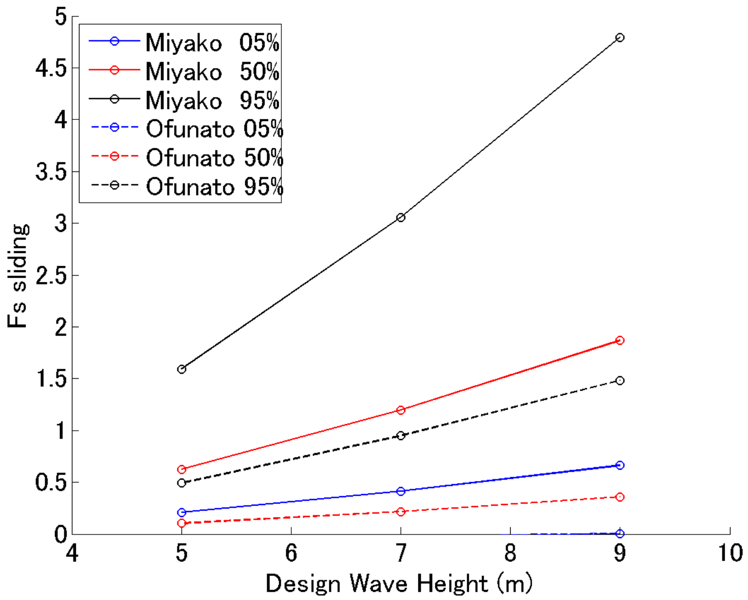


Figure 7. Occurrence probability of sliding safety factor in Miyako and Ofunato port.

## 5. Conclusion

This study assessed the breakwater stability due to uncertain tsunami loading in the Tohoku ports. This paper analyzed the tsunami profiles generated by the stochastic tsunami source models (Goda et al., 2014) for the 2011 Tohoku earthquake. The stability analysis of three model breakwaters was carried out in five ports, and the sensitivity of breakwater stability for probabilistic tsunami wave profiles was discussed. The major findings are as follows:

1) The distributions of the maximum tsunami wave height are quite variable in the five ports. The port locations and topography strongly influence the features of the tsunami height distributions.
2) The stability analysis confirms that breakwater stability in the target ports depends on tsunami wave profiles affected by regional features.
3) The breakwater stability in the Ofunato port is sensitive to the tsunami wave characteristics.
4) The results implied that future tsunami defense policy requires consideration of uncertainty in tsunami wave profiles and regional features.

As this paper focused only on the inversion-based source models for the 2011 Tohoku earthquake, further study would require consideration of variability in source models: e.g. major shift of the main rupture area and asperity. Such investigations are also necessary for hazard management of future possible earthquakes, such as the Tokai- Tonankai-Nankai scenarios. The developed methodology can promote effective defense strategy for tsunami disasters.

## References

Mori N., Takahashi T., The 2011 Tohoku Earthquake Tsunami Joint Survey Group: Nationwide post event survey and analysis of the 2011 Tohoku earthquake tsunami, Coastal Eng. J., 54:1250001-1-27, 2012.

Mori N., Takahashi T., Yasuda T., Yanagisawa H.: Survey of 2011 Tohoku earthquake tsunami inundation and run-up, Geophys. Res Lett, 38: L00G14, 2011.

Suppasri A., Mas E., Charvet I., Gunasekera R., Imai K., Fukutani Y., Abe Y., and Imamura F.: Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan tsunami, Nat. Haz., 66:319–341, 2013.

Kazama M., Noda T.: Damage statistics (Summary of the 2011 off the Pacific Coast of Tohoku Earthquake dam-age), Soils and Foundations, 52, 5, pp.780–792, 2012.

Goda K., Mai P. M., and Yasuda T., Mori N.: Sensitivity of tsunami wave profile and inundation simulations to earthquake slip and fault geometry for the 2011 Tohoku earthquake. Earth Planets Space, 66:105, 2014.

Mai P. M., Beroza G.C.: A spatial random field model to characterize complexity in earthquake slip, J. Geophys. Res., 107(B11), 2308, 2002.

Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan: A guideline of breakwater design for tsunami stability, 2013 (in Japanese).

Sassa, S.: Tsunami-Seabed-Structure Interaction from Geotechnical and Hydrodynamic Perspectives, Geotechnical Eng. Jour., 45(4), Special Issue on Offshore and Coastal Geotechnics, 102–107, 2014.

Takahashi, H., Sassa, S., Morikawa, Y., Takano, D., Maruyama, K.: Stability of caisson-type breakwater foundation under tsunami-induced seepage, Soils and Foundations, 54(4), 789–805, 2014.

Tanimoto, K., Tsuruya, K., Nakano, S.: Tsunami Force of Nihonkai-Chubu Earthquake in 1983 and Cause of Revetment Damage, Proc. of the 31st Japanese Conf. on Coastal Eng., JSCE, 1984.