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A FRAMEWORK FOR TSUNAMI FRAGILITY ASSESSMENT USING RESPONSE FACTOR

Yoshiyuki Takahashi[1], Naoto Kihara[2], Hideki Kaida[3], and Yoshinori Mihara[4]

[1] Deputy Manager, Kajima Corporation, Tokyo, Japan (takyoshi@kajima.com)
[2] Senior Research Scientist, Central Research Institute of Electric Power Industry, Chiba, Japan
[3] Research Scientist, Central Research Institute of Electric Power Industry, Chiba, Japan
[4] Senior Manager, Kajima Corporation, Tokyo, Japan

ABSTRACT

Several tsunami fragility assessment methods have already been proposed. In Japan, an extremely simplified method, which empirically predicts the magnitude and variation of an inundation depth at a site from the tsunami height directly in front of the site, has commonly been used. On the other hand, it is also common to utilize a method considering the uncertainty of tsunami sources explicitly in tsunami fragility assessments. A method whose accuracy and simplicity are intermediate between the two methods would be effective from the perspective of a graded approach. In this paper, a framework for tsunami fragility assessments using response factors is proposed, and the concept of a methodology for extrapolating the maximum inundation depth is also proposed as an example of a response factor. The framework and methodology have the potential to evaluate tsunami fragility from a limited number of tsunami inundation simulations. This study shows the procedure for evaluating the median value of response factors for maximum inundation depth, but evaluating the variations is a future issue.

INTRODUCTION

It is necessary to evaluate the tsunami impact on facilities and equipment in order to estimate a realistic response for tsunami fragility assessments. Methodologies of tsunami fragility assessments have been developed in the last 15 years (e.g., Sugino et al., 2008). Amplitude and spatial variation of the tsunami profile and impact at a site depend on tsunami sources. In Japan, an extremely simplified method (Haraguchi et al., 2017), which empirically predicts the magnitude and variation of an inundation depth at a site from the tsunami height directly in front of the site, has commonly been used. On the other hand, it is also common to utilize a method considering the uncertainty of tsunami sources explicitly in tsunami fragility assessments (Kihara et al., 2019). In this method, detailed tsunami fragility can be estimated because a tsunami flooding profile for each tsunami source is calculated by tsunami inundation simulations for many tsunami sources. However, this method is expensive in terms of both CPU time and person-hours. Consequently, it is important to expand the simplified method for the first step in a fragility assessment targeted at low-risk sites from the perspective of a graded approach.

In this paper, a framework for tsunami fragility assessments using response factors is proposed in order to improve the simplified methodology. In this methodology, it is assumed that either a realistic capacity and a capacity factor will be used as a capacity of SSCs (structure, system, and component). Preliminary evaluations of response factors are also shown. This study contributes to the development of the graded approach framework of tsunami probabilistic risk assessments (Kihara et al., 2021).

TSUNAMI FRAGILITY ASSESSMENT METHOD

Characteristics of some tsunami fragility assessment methods are depicted in Table 1. The proposed method is positioned intermediately between the extremely simplified method (Haraguchi et al., 2017) and the detailed one (Kihara et al., 2019). The proposed method does not need additional tsunami inundation simulations but evaluates the realistic response by multiplying the existing tsunami inundation simulation results by some coefficients.

Table 1: Characteristics of tsunami fragility assessment method.

Method	Extremely simplified method	Proposed method	Detailed method
Response evaluation	Empirical (No simulations)	Response factor and existent simulations	Realistic response based on new simulations
Evaluation precision	Low	Moderate	High
Resources required	Low	Moderate	High
Example practice	Haraguchi et al. (2017)	This study	Kihara et al. (2019) related to this study

RESPONSE FACTORS

Response factors are coefficients that reflect the uncertainty and conservatism of the response in the fragility assessment. Since the tsunami flooding profile and impact are inherently nonlinear, their nonlinearities must be properly taken into account as a response factor. For example, response factors are divided as shown below.

F1) Response factor for tsunami height time histories at the control point.
F1.1) Sub-response factor for tsunami sources: Period characteristics and temporal characteristics of tsunami source for the fragility assessment.
F1.2) Sub-response factor for tsunami heights: Tsunami height amplitude. It may be the case that it is included in the sub-response factor for nonlinearities of the tsunami profile and impact described below. This sub-response factor is not considered when the fragility assessment is performed using capacity factors.
F2) Response factor for tsunami inundation simulation.
F2.1) Sub-response factor for fundamental theories: Nonlinear shallow water equation model and number of dimensions of space.
F2.2) Sub-response factor for numerical calculations: Space discretization method, time discretization method, and discretization resolution.
F2.3) Sub-response factor for nonlinearities of tsunami profile and impact: Evaluation of tsunami profile and impact at each point at a site from the tsunami height at the control point.

It is assumed that the sub-response factors for tsunami sources (item F1.1) and nonlinearities of the tsunami profile and impact (item F2.3), among the response factors, have the strongest influence on the overall fragility. The response factors shown above are only examples. It is necessary to examine whether there are any factors that should be considered as sub-response factors by referring to existing tsunami propagation analyses and tsunami inundation simulations. For the sub-response factors, which have a large influence on fragility assessments, it is important to propose a calculation procedure and to validate the procedure through trial calculations.

ESTIMATION OF RESPONSE FACTOR

The estimation of the sub-response factor for nonlinearities of the tsunami profile and impact (item 2.3) is illustrated based on tsunami inundation simulations for many tsunami sources at a virtual site. Examples are given for a maximum inundation depth.

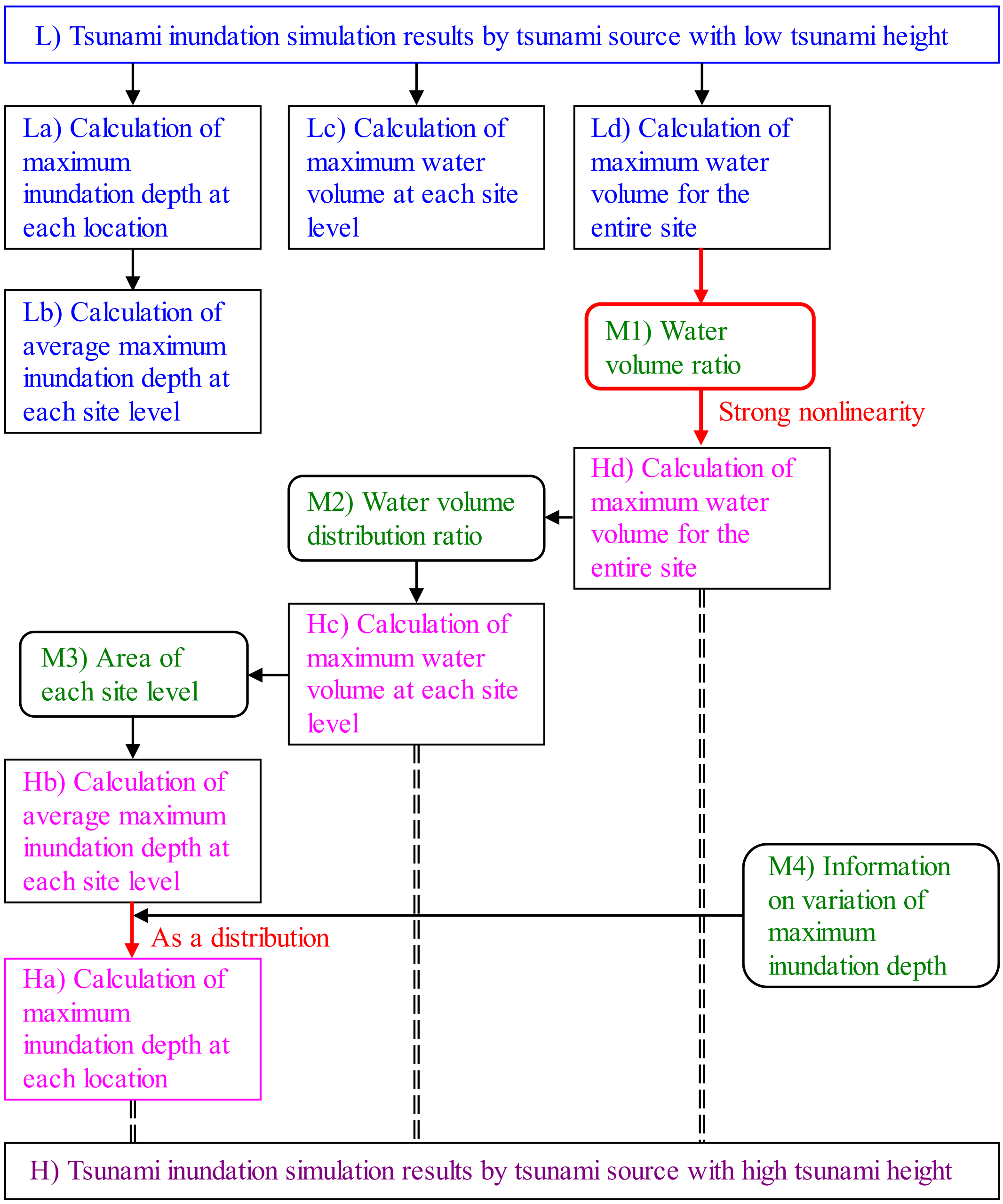


Figure 1. Concept of a methodology for extrapolating maximum inundation depth.

Concept of a Methodology for Extrapolating Maximum Inundation Depth

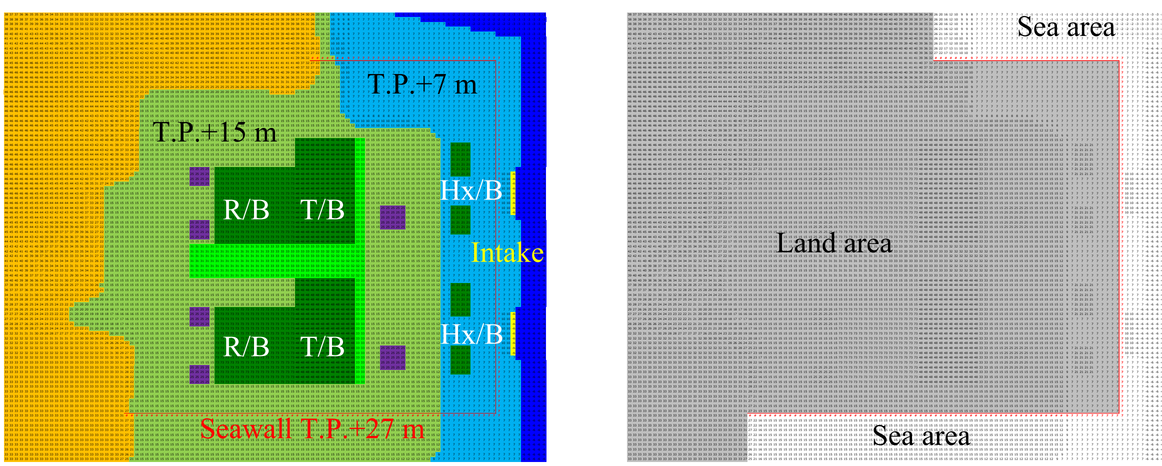
Here, the proportionality factor is evaluated based on the following assumptions.

1) The tsunami is assumed to overflow the seawall. The volume of outflow from the site to the sea is not considered to be large, so it is ignored in this study for the sake of simplicity.
2) The overflow volume is estimated from the water level in front of the seawall. The water level inside the seawall is assumed to be much lower than the water level in front of the seawall, so the state of complete overflow is assumed for the sake of simplicity.
3) The water volume is estimated from the inundation depth at the site, and its maximum value is assumed to be approximately equal to the overflow volume.

Concept of a methodology for extrapolating the maximum inundation depth under a high tsunami height condition from that under a low tsunami height condition is depicted in Figure 1.

M0) Calculate the maximum water volume for the entire site based on the tsunami inundation simulation results by a tsunami source with low tsunami height.
M1) Calculate the maximum water volume for the entire site corresponding to a tsunami source with high tsunami height from that with low tsunami height based on the information of the tsunami source with high tsunami height.
M2) Calculate the maximum water volume at each site level based on the water volume distribution ratio from the maximum water volume for the entire site.
M3) Calculate the average maximum inundation depth based on the area of each site level from the maximum water volume at each site level.
M4) Calculate the maximum inundation depth at each location taking into account the information on the variation of the maximum inundation depth from the average maximum inundation depth.

Although the applicability of the processes M1–M4 should be checked, the processes of M1–M3 are investigated by using the results of tsunami inundation simulations as examples.



(a) Site levels (b) Inundation depth and water volume

Figure 2. Area to be evaluated at the virtual site.

Summary of Investigation Conditions

This study uses the tsunami inundation simulation results for a virtual site that is located on the Pacific coast of Tohoku as conducted by Kihara et al. (2019). The site has two ground levels of 7 m and 15 m mainly and a 27 m seawall, and the intake is near the seawall. The area to be evaluated at the site is shown in Figure 2. The area from 7 m to 11 m in elevation is defined as site level 7 m (light blue area in Figure 2(a)) and the area from 11 m to 21 m in elevation as site level 15 m (yellow-green area in Figure 2(a)). The area to be evaluated for inundation depth and water volume is the land area (gray area in Figure 2(b)), excluding the sea area (white area in Figure 2(b)) in front of the seawall.

Estimation of Maximum Water Volume for the Entire Site

The following is the procedure for predicting the maximum water volume for the entire site V_H at a given tsunami height H_H for a specific tsunami source. The maximum representative water level ${}_{rep}\eta_{L\max}$, the time history of the water level in front of the seawall η_L, the time history of the inundation depth at the site h_L, and the maximum water volume for the entire site V_L at the tsunami height H_L ($H_L<H_H$) are assumed to be available for the prediction.

M1.1) Set the tsunami height H_H or the maximum representative water level ${}_{rep}\eta_{H\max}$. The representative water level can be the water level in front of the intake.

M1.2) Calculate the coefficient for water level k_η from the tsunami heights H_L and H_H or the maximum representative water levels ${}_{rep}\eta_{L\max}$ and ${}_{rep}\eta_{H\max}$ at the tsunami height,

$$k_\eta = \frac{H_H}{H_L}\text{, or} \tag{1}$$

$$k_\eta = \frac{{}_{rep}\eta_{H\max}}{{}_{rep}\eta_{L\max}}. \tag{2}$$

M1.3) Calculate the time history of the water level in front of the seawall η_H at the tsunami height H_H based on the η_L at the tsunami height H_L and the coefficient for water level k_η.

$$\eta_H = k_\eta \eta_L \tag{3}$$

M1.4) Calculate the time histories of the overflow per unit width from the seawall q_L and q_H based on the time histories of the water level in front of the seawall η_L and η_H at the tsunami height H_L and H_H, respectively, using the Homma formula assuming the state of complete overflow. Where g is the acceleration of gravity, μ is the flow coefficient (0.35), and z_{sw} is the height of the seawall.

$$\begin{aligned} q_L &= \mu(\eta_L - z_{sw})\sqrt{2g(\eta_L - z_{sw})} & \eta_L &\geq z_{sw} \\ q_L &= 0 & \eta_L &< z_{sw} \end{aligned} \tag{4}$$

$$\begin{aligned} q_H &= \mu(\eta_H - z_{sw})\sqrt{2g(\eta_H - z_{sw})} & \eta_H &\geq z_{sw} \\ q_H &= 0 & \eta_H &< z_{sw} \end{aligned} \tag{5}$$

M1.5) Calculate the cumulative overflows of the entire seawall Q_L and Q_H by integrating in the length direction of the seawall (ds) and in the time direction (dt) based on the time histories of the overflow per unit width from the seawall q_L and q_H at the tsunami height H_L and H_H, respectively.

$$Q_L = \iint q_L dsdt \tag{6}$$

$$Q_H = \iint q_H dsdt \tag{7}$$

M1.6) Calculate the coefficient for overflow k_Q from the cumulative overflows of the entire seawall Q_L and Q_H at the tsunami height H_L and H_H.

$$k_Q = \frac{Q_H}{Q_L} \tag{8}$$

M1.7) Calculate the maximum water volume for the entire site V_H at the tsunami height H_H based on the V_L at the tsunami height H_L and the coefficient for overflow k_Q.

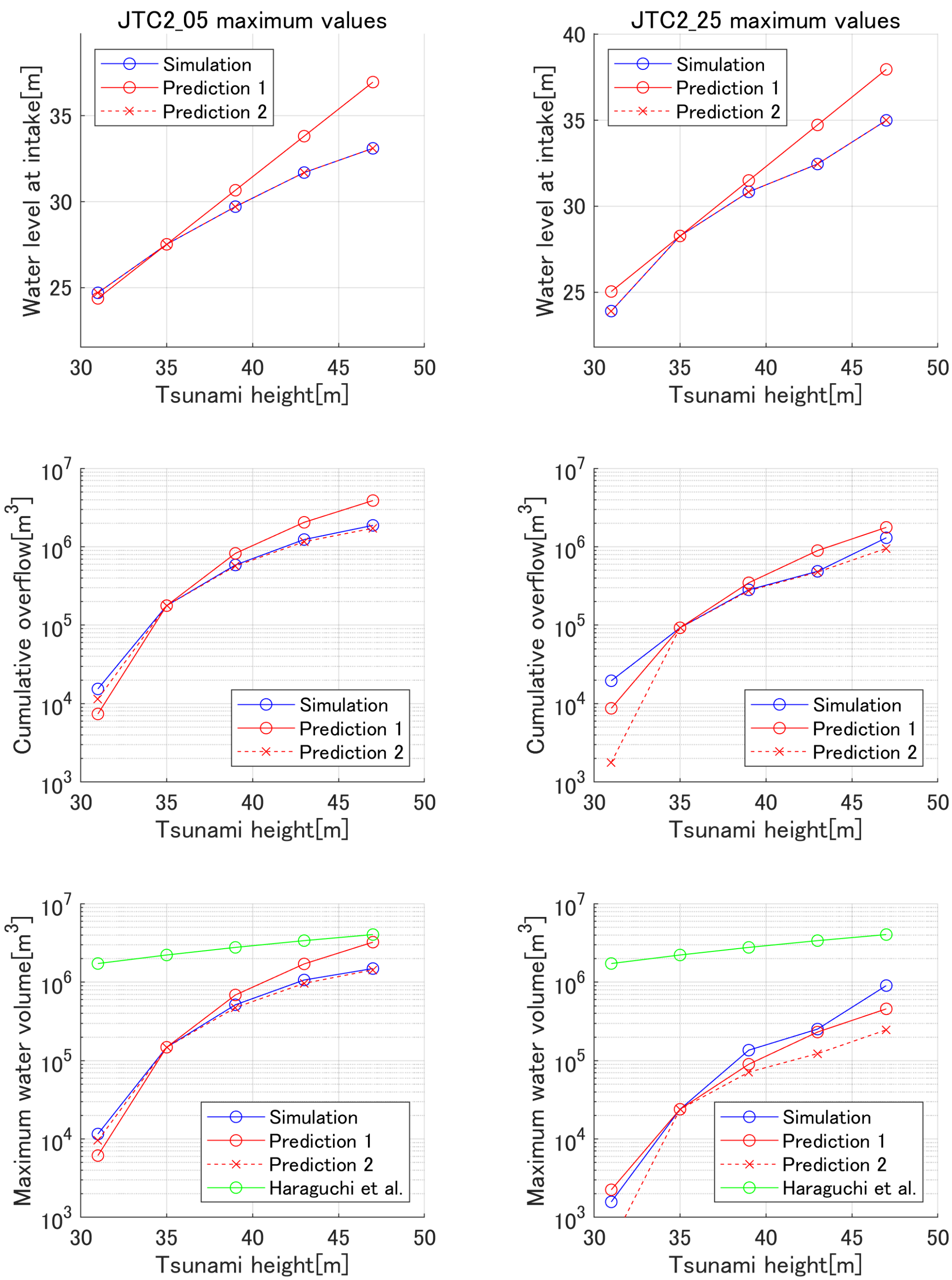
$$V_H = k_Q V_L \tag{9}$$

Figure 3 show the predicted results by using numerical results for a tsunami height of 35 m for two tsunami sources. It shows the maximum hydraulic quantities obtained from the tsunami inundation simulations and the predicted values for them where the blue circle line represents the tsunami inundation simulation results and the red circle line and red x line represent the predicted values. As hydraulic quantities, the upper row shows the average water level in front of the intake, the middle row shows the cumulative overflow, and the lower row shows the maximum water volume for the entire site. The maximum water volume for the entire site is shown by the green circle line, which is the water volume when the water level at the site is assumed to be equal to the tsunami height (Haraguchi et al., 2017). The red circle line (Prediction 1) corresponds to the predicted value when the coefficient for the water level is calculated from the tsunami height, and the red x line (Prediction 2) corresponds to the predicted value when the coefficient for the water level is calculated from the maximum average water level in front of the intake. (This means the prediction in case the water level is known.)

The predicted maximum average water level in front of the intake agrees with the simulation results in the case of Prediction 2, since the coefficient for the water level is calculated based on the maximum average water level in front of the intake. In the case of Prediction 1, the relationship between the maximum average water level in front of the intake and the tsunami height, which differs for each tsunami source, is expressed in the predicted values. (Tsunami heights do not match the maximum water levels in front of the seawall.)

The predicted cumulative overflow, regardless of tsunami source and tsunami height, generally captures the simulation results in the case of Prediction 2. The relationship between the maximum average water level in front of the intake and the tsunami height depends on the tsunami source, but the relationship between the maximum water level in front of the seawall and the maximum average water level in front of the intake is assumed to be constant regardless of tsunami source and tsunami height. In the case of Prediction 1, the same effect as the maximum average water level in front of the intake is carried over.

In the case of Prediction 2, the predicted maximum water volume at tsunami source JTC2_05 generally captures the simulation results, but at tsunami source JTC2_25, the predicted value underestimates the simulation results because the cumulative overflow is overestimated at JTC2_25 because of the time interval of the output of the cumulative overflow and the maximum water volume. In the case of Prediction 1, the same effect as the maximum average water level in front of the intake is carried over. In any case, both predictions capture the simulation results more appropriately than Haraguchi et al. (2017). Given that the cumulative overflow is evaluated larger than the maximum water volume, the cumulative overflow may be conservatively considered the maximum water volume.



(a) JTC2_05 (b) JTC2_25

Figure 3. Example predictions of maximum water volume for the entire site.

Estimation of Maximum Water Volume at Each Site Level

M2.0) Definition of parameters

The water volume at each site level is defined as the area-integrated value of the inundation depth at each site level, and the maximum value is the maximum water volume at each site level (see Figure 4(a)). The equivalent maximum inundation depth is defined as the maximum water volume divided by the area at each site level (see Figure 4(b)). The water volume distribution ratio is defined as the ratio of the maximum water volume at each site level to that for the entire site (see Figure 4(c)). The pseudo water volume distribution ratio is defined as the ratio of the maximum water volume at each site level to that for the entire site, including the volume of terrain at site level 15 m with respect to site level 7 m (see Figure 4(d)).

M2.1) Pseudo-water volume distribution ratio

Formulate the pseudo water volume distribution ratio using the site information. The formulated pseudo water volume distribution ratios for site levels 7 m and 15 m are shown in Figure 4(d) with gray lines and in Equations (10)–(11). Where V is a variable representing the maximum water volume for the entire site, A_7 and A_{15} are the respective areas at site levels 7 m and 15 m, V_{15} is the volume of terrain at site level 15 m with respect to site level 7 m, and c_7 is the correction factor (water volume distribution ratio at site level 7 m) discussed below in Equation (12).

$$a_7(V) = \min\left(\frac{c_7 V}{V + V_{15}},\ \frac{A_7}{A_7 + A_{15}}\right) \tag{10}$$

$$a_{15}(V) = 1 - a_7(V) \tag{11}$$

The first item in the minimum function in Equation (10) indicates that site level 7 m will be inundated first when the water volume is low. However, site level 15 m is inundated simultaneously with site level 7 m, so the effect is represented by a correction factor. The second item indicates inundation regardless of the elevation of the site when the water volume is high. Equation (11) assumes that an inundation occurs only at site levels 7 m and 15 m, and that the sum of their respective pseudo water volume distribution ratios is 1.

M2.2) Water volume distribution ratio

Formulate the correction factor using the site information and the assumed water level. The formulated correction factor is shown in Equation (12). Where z_7 and z_{15} are the respective site levels and $\Delta\eta$ is the rise in water level due to a simultaneous inundation.

$$c_7 = \frac{(z_{15} - z_7 + \Delta\eta)A_7}{(z_{15} - z_7 + \Delta\eta)A_7 + \Delta\eta A_{15}} \tag{12}$$

Equation (12) represents a simultaneous inundation of site levels 7 m and 15 m from zero inundation depth to a certain water level that takes into account the water level rise, which is equal to the water volume distribution ratio at site level 7 m. Figure 4(c) shows that the water volume distribution ratio varies with the maximum water volume. However, based on the fact that the effect on the pseudo water volume distribution ratio is small in the range of small maximum water volume, that the water volume distribution ratio is about a certain value up to about full water volume at site level 7 m (red dashed line), and that it is difficult to express the water volume distribution ratio as a function of the maximum water volume in practice, the water volume distribution ratio is made independent of the maximum water volume. According to Figure 4(b), the water level rise due to simultaneous inundation is about 1 m in this study. Although $\Delta\eta$ is assumed to be an index that varies depending on sites, a rise of 1 m in water level is generally considered reasonable given the characteristic of water flowing into a lower location.

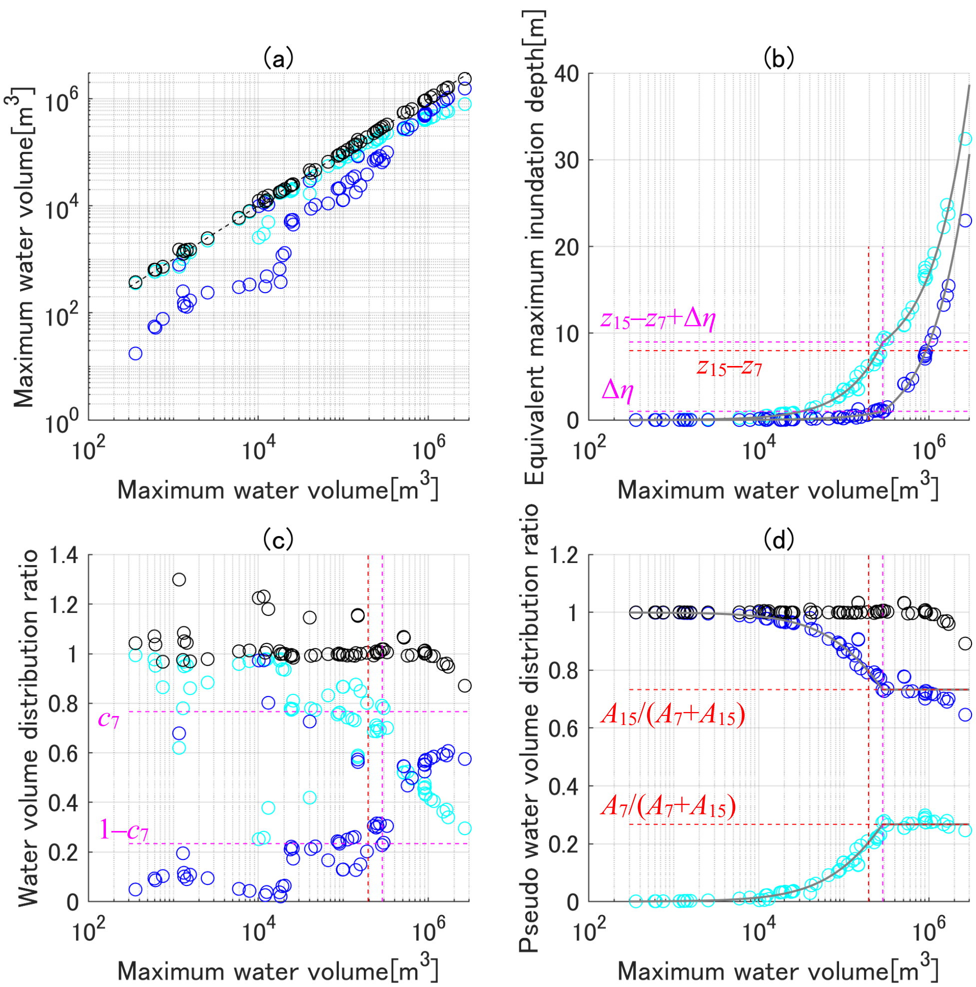
M2.3) Equivalent maximum inundation depth

Formulate the maximum water volume at each site level as the equivalent maximum inundation depth using the above Equations (10)–(12). The formulated equivalent maximum inundation depths are shown in Figure 4(b) with gray lines and in Equations (13)–(14).

$$h_7(V) = \frac{a_7(V) \cdot (V + V_{15})}{A_7} \tag{13}$$

$$h_{15}(V) = \frac{a_{15}(V) \cdot (V + V_{15}) - V_{15}}{A_{15}} \tag{14}$$

Equation (13) finds the maximum water volume at the site level according to the definition of the pseudo water volume distribution ratio and converts it to the equivalent maximum inundation depth divided by the area. Equation (14) does the same, but subtracts the volume of terrain at site level 15 m with respect to site level 7 m.



Cyan: site level 7 m, Blue: site level 15 m, Black: sum of site levels 7 m and 15 m
Vertical red dashed line: full water volume at site level 7 m, Vertical pink dashed line: full water volume at site level 7 m considering the water level rise due to simultaneous inundation

Figure 4. Relationship between various parameters and maximum water volume for the entire site.

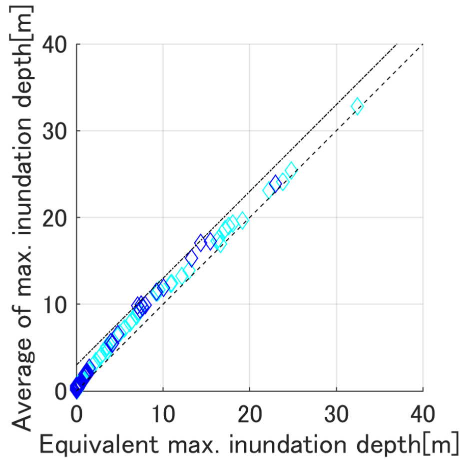


Figure 5. Relationship between average of maximum inundation depth and equivalent maximum inundation depth.

Estimation of Average Maximum Inundation Depth at Each Site Level

Figure 5 shows the relationship between the average of maximum inundation depth and the equivalent maximum inundation depth. The equivalent maximum inundation depth is the value smoothed at each site level, but the average of the maximum inundation depths includes the local effects of the site. Both values are generally comparable, and the difference is within 3 m.

CONCLUSION

In this paper, the framework for tsunami fragility assessments using response factors is proposed, and the concept of the methodology for extrapolating the maximum inundation depth is also proposed as an example of a response factor. The framework and methodology have the potential to evaluate tsunami fragility from limited tsunami inundation simulation results. The example of response factors for the maximum inundation depth shows the procedure for evaluating the mean value, but evaluating the variation is a future issue. For response factors, which have a large influence on fragility assessments, it is important to propose a calculation procedure and to validate the procedure through trial calculations, and it is necessary to investigate continually.

REFERENCES

Sugino, H., Iwabuchi, Y., Nishio, M., Tsutsumi, H., Sakagami, M. and Ebisawa, K. (2008). "Development of probabilistic methodology for evaluating tsunami risk on nuclear power plants," *The 14th World Conference on Earthquake Engineering*.

Haraguchi, R., Togashi, T., Kunimasa, T. and Maehara, K. (2017). "Development of a Fragility Evaluation Methodology for the Tsunami PRA," *ASRAM2017*, ASRAM2017-1051.

Kihara, N., Kaida, H., Takahashi, Y., Nishi A., Kimura, T., Fujii, N., Fujioka, B., Oda, S., Ohtori, Y. and Mihara, Y. (2021). "Tsunami flooding analysis graded-approach framework for tsunami probabilistic risk assessment, *Journal of Nuclear Science and Technology*," xxxxxx. (under review)

Kihara, N., Kaida, H., Kimura, T., Nishi, A., Masuko, M. and Fujii, N. (2019). "A Tsunami Scenario Determination Methodology for Risk Assessment of Coastal Industrial Facilities." *The Proceedings of the 29th International Ocean and Polar Engineering Conference*, 3292-3296.