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THE CHARACTERIZING MODEL FOR TSUNAMI SOURCE REGARDING THE INTER-PLATE EARTHQUAKE TSUNAMI

Hideharu SUGINO[1], Yoko IWABUCHI[2], Norihiko HASHIMOTO[3], Kazuyuki MATSUSUE[4], Katsumi EBISAWA[5], Hiroyuki KAMEDA[6] and Fumihiko IMAMURA[7]

[1] Member of JAEE, Director, Japan Nuclear Energy Safety Organization, Tokyo, Japan, sugino-hideharu@jnes.go.jp
[2] Chief Researcher, Japan Nuclear Energy Safety Organization, Tokyo, Japan, iwabuchi-yoko@jnes.go.jp
[3] Itochu Techno-Solutions Corporation, Tokyo, Japan, norihiko.hashimoto@ctc-g.co.jp
[4] General Manager (Special Assignment), OYO Corporation, Tsukuba, Japan, matusue-kazuyuki@oyonet.oyo.co.jp
[5] Member of JAEE, Vice President, Japan Nuclear Energy Safety Organization, Tokyo, Japan, ebisawa-katsumi@jnes.go.jp
[6] Honorary member of JAEE, Emeritus Professor, Kyoto Univ., Technical Advisor, Japan Nuclear Energy Safety Organization, Tokyo, Japan, kameda2@minuet.plala.or.jp
[7] Member of JAEE, Professor, Tohoku Univ. IRIDeS., Sendai, Japan, imamura@irides.tohoku.ac.jp

ABSTRACT: The 2011 Tohoku Earthquake which exceeds the maximum magnitude of historical earthquake records could not be predicted. Which means, in the probabilistic tsunami hazard assessment for the future prediction, it is necessary to apply a different concept from the existing scenario tsunami assessment based on the maximum magnitude of historical earthquake tsunami. As a new modeling method for scenario tsunami, we propose a characterized tsunami source model which indicates setting method of the area of tsunami source and slip distribution by the inter-plate earthquake.

Key Words: The 2011 Tohoku Earthquake, Tsunami, Nuclear Power Plant, Characterized tsunami source model, Heterogeneous slip distribution

1. INTRODUCTION

A severe accident occurred at the Fukushima Daiichi Nuclear Power Plant due to the tsunami caused by the Off the Pacific Coast of Tohoku Earthquake on March 11, 2011 (hereafter "Tohoku Earthquake Tsunami"). This accident revealed the underestimation of the tsunami design level of the power plant, its unpreparedness for tsunamis exceeding the tsunami design level, and the importance of awareness of tsunami risks to nuclear power plants. In light of the lessons learned from this accident, a government report[1)] stated that measures should be taken such that facilities maintain critical safety functions at the occurrence of a tsunami exceeding the design level and risk management should be conducted based on the Probabilistic Risk Assessment (PRA) method.

The Tohoku Earthquake Tsunami occurred due to a mega-earthquake on the plate boundary along the Japan Trench. According to the seismological knowledge before the occurrence of this tsunami, an inter-plate earthquake was regarded as a so-called characteristic earthquake, i.e., a "maximum-scale earthquake that recurs within individual areas which are zoned[2)]" on the basis of the records of past known earthquakes. Consequently, the tsunami assumption (scenario tsunami sources specifying) for determining tsunami design levels for nuclear power plants was also developed based on the largest recorded earthquake magnitude (Japan Society of Civil Engineers, JSCE[3)]) and failed to foresee the occurrence of the Tohoku Earthquake Tsunami.

Taking the lessons learned from the Fukushima Daiichi Nuclear Power Plant Accident caused by the Tohoku Earthquake Tsunami, the Nuclear Regulation Authority (NRA) and the Secretariat of NRA established and implemented new regulatory standards and review guidelines in July 2013. The "Review Guidelines for Design Basis Tsunami and Tsunami-Resistant Design Principles,"[4)] in particular, emphasize that the following points should be considered among others: (a) when specifying scenario tsunami sources, similarities between tsunami occurrence mechanisms or between tectonic backgrounds should be considered based on cases of large-scale tsunamis experienced in and outside Japan; and (b) if an earthquake or tsunami occurrence area and magnitude are predicted entirely based on past cases, the possibility of the occurrence of an earthquake or tsunami exceeding the past cases should not be excluded .

The design and risk assessment of a nuclear power plant are issues related to the prediction of future tsunami occurrences. Now that we experienced the Tohoku Earthquake Tsunami, it is necessary to seriously recognize the limits of the scientific knowledge based on historical records confined to the last several hundred years and to address these issues with scientific imagination.[5)]

Included among tsunami risk assessment methods for nuclear power plants is the Implementation Standard Concerning the Tsunami PRA of Nuclear Power Plants (AESJ).[6)] Tsunami PRA uses a Probabilistic Tsunami Hazard Analysis method[7)] for assessing the relationship between the height of a tsunami attacking the relevant facility and its exceedance frequency. Here again, a tsunami assumption for future prediction is required. The tsunami assumption by this method relies on a specialist questionnaire to define a certain range of magnitude for the largest recorded earthquake in order to allow for the uncertainty of future tsunami occurrences. This magnitude range is, however, limited and set basically based on the largest recorded earthquake magnitude.

As part of the effort to identify the cause of the Fukushima Daiichi Nuclear Power Plant Accident, Sugino et al.[8)] investigated the occurrence mechanism of the Tohoku Earthquake Tsunami to help improve the safety of future nuclear power plants. Their main achievements include: (a) creation of tsunami source models for simultaneously simulating the tsunami at the four tsunami-damaged nuclear power plants, and an estimation of the consequent slip distribution; (b) clarification of the fact that the dominant regions strongly influential on the tsunami levels for the nuclear power plants all concentrate in "the tsunami earthquake" occurrence area near the Japan Trench in the entire tsunami source area; and (c) the discovery of the fact that the earthquake source model estimated from the observed long-period earthquake ground motions agrees with the tsunami source above in that large slips concentrate near the Japan Trench.

Meanwhile, Wu et al.[9)] showed the strong motion generation areas of the earthquake source estimated from the observed short-period earthquake ground motions during the Tohoku Earthquake. This area, however, clearly differs from the slip concentration area of the tsunami source above.

In the field of strong motion prediction, the Recipe[10)] of the Headquarters for Earthquake Research Promotion is widely used. This recipe uses a "Characterized Seismic Fault Model" with key parameters to represent source characteristics based on the empirical relationship between the seismic moment and the area of earthquake faults, etc., to standardize the strong ground motion assessment procedure. This model consists of three kinds of parameters, namely outer fault parameter representing the geometry and size of the whole fault, inner fault parameter representing the heterogeneity of the fault, and other parameters representing the rupture process. For the inner fault parameter and the rupture process parameter in particular, it is clear from the example above of analysis of the Tohoku Earthquake that the Characterized Seismic Fault Model intended for the short-period component of earthquake ground motions cannot be applied directly to prediction of earthquake-induced tsunami.

To establish a tsunami assumption method based on the premise that future tsunamis may exceed the largest recorded scale, this paper first analyzes the earthquake magnitudes, the areas and slip distributions, and rupture process characteristics of tsunami sources due to mega-earthquakes around the world, including the Tohoku Earthquake Tsunami. Then, for the purpose of tsunami assessment (runup height and/or inundation depth calculation) on coasts, based on the above-mentioned analysis results, a "Characterized Tsunami Source Model" is proposed for which the key parameters represent the tsunami source parameters of a tsunami caused by an inter-plate earthquake. Then, this characterized tsunami source model is made for the Tohoku Earthquake Tsunami to study the variation of its simulated tsunami height as compared with its tsunami trace height and examine the effect of characterizing tsunami source.

2. SIGNIFICANCE OF CATEGORIZATION AND CHARACTERIZATION OF TSUNAMI SOURCE MODELS

Tsunami source models largely fall into two types: models for reproduction and those for prediction.

A tsunami source model for reproduction (TSM_R) is required to reproduce an actual tsunami phenomenon as truly as possible. For this purpose, the addition or refinement of parameters necessary for modeling is allowed. In an example of the TSM_R[8] of the Tohoku Earthquake Tsunami, the tsunami source area was divided into sub-faults, and sub-fault-specific parameters such as the rupture starting time and the rupture duration were refined to consider the spatial-temporal heterogeneity of slip distribution, thereby contributing to improvements in the reproducibility of tsunami waveform observed offshore, etc. Inconveniently, however, such a model is difficult to apply to future-prediction problems due to the complexity of parameters.

A tsunami source model for prediction (TSM_P), used for future-prediction problems, cannot deterministically handle detailed values or spatial-temporal distribution of parameters which are used to deal with the complexity of actual phenomena, and consequently needs simplification, including the omission (or averaging) of parameters. Naturally, the degree of uncertainty will increase depending on the degree of simplification and must be quantitatively grasped.

Therefore, the "Characterized Tsunami Source Model" proposed in this study is a model for prediction with the tsunami source characteristics simplified by key parameters to standardize coastal tsunami assessments. Similarly to the Characterized Seismic Source Model, this model uses the following three kinds of parameters of characteristics: outer fault parameters representing the geometry and size of the whole fault; inner fault parameters representing the heterogeneity of the fault; and fault rupture process parameters. When specifying these parameters, however, consideration must be made for the common points between a tsunami and an earthquake arising from the same fault and their dissimilarities reflecting the differences in the phenomena to be assessed, such as tsunami heights at shorelines and short-period earthquake ground motions (strong ground motion).

3. TSUNAMI SOURCE CHARACTERISICS ANALYSIS BASED ON M9-CLASS TSUNAMI

3.1 Outer fault parameters

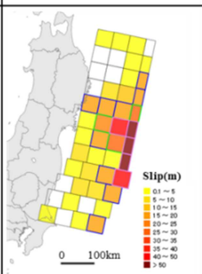
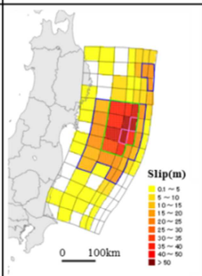
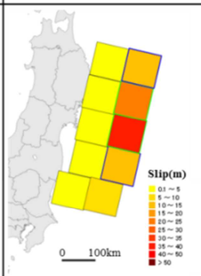
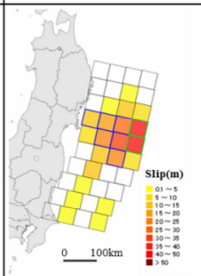
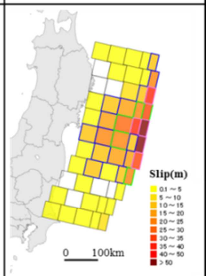
The outer fault parameters of a tsunami caused by an inter-plate earthquake are represented by the following parameters: source location; seismic moment; and average slip. These parameters are applicable to earthquake-induced tsunamis and therefore must be classified as those in common with the Recipe for predicting strong motions[10].

Murotani et al.[11] showed that the relationships between seismic moments, fault areas, average slip, etc., extracted from inversion models of tsunami sources caused by M9-class inter-plate earthquakes in and outside Japan generally agree with the scaling law for M7 to M8-class inter-plate earthquakes that occurred near Japan. This result implies that the same scaling law as the Recipe for predicting strong

Table 1 List of mega-tsunamis of Mw 9.0 or more in and outside Japan

Name of earthquake tsunami	Mw
1952 Kamchatka EQ.	9.0
1960 Chile	9.5
1964 Alaska EQ.	9.2
2004 Sumatra-Andaman EQ.	9.1
2011 Tohoku EQ.	9.0

Table 2 Slip distributions and fault rupture modes of the Tohoku EQ. Tsunami

	Sugino et al.[8]	CAO[12]	Imamura et al.[13] Ver1.2	Fujii et al.[14] Ver4.2	Satake et al.[15] Ver8.0
Slip > 2 x D (blue); Slip > 3 x D (green); Slip > 4 x D (pink)	 Dynamic rupture (0-300s)	 Dynamic rupture (0-300s)	 Static rupture	 Static rupture	 Dynamic rupture (0-300s)
Ave. slip (D)	14.6 m	11.7m	9.5m	14.5m	10.8m
＞2 x D	37%	40%	40%	38%	44%
＞3 x D	18%	15%	20%	10%	16%
＞4 x D	11%	2%	—	—	6%
Ave. rupture vel.	1.52 km/sec	2.04 km/sec	∞	∞	1.47 km/sec

motions[10] can be applied to the seismic moment and average slip of an M9-class tsunami source model. For more details, see Section 4.1.

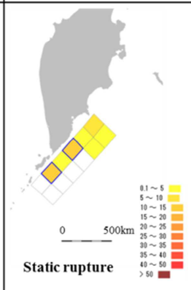
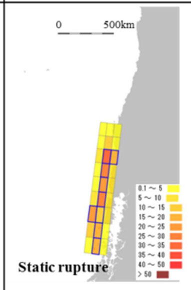
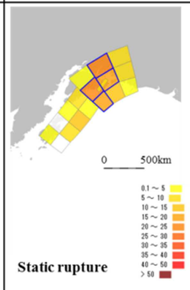
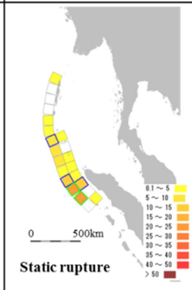
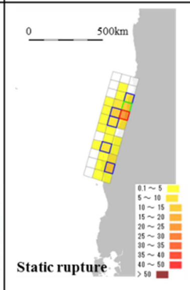
3.2 Inner fault parameters

Inner fault parameters are represented by the following parameters, thereby showing the heterogeneity of slip distribution: (a) the area that gives a slip larger than the average slip; and (b) the slip amount therein. A method different from the Recipe for predicting strong motions[10] is considered necessary to specify these parameters, as is clear from the aforementioned cases of seismic fault/tsunami source analysis of the Tohoku Earthquake.

Therefore, analyses are made of the heterogeneity of slip distributions based on inversion models of tsunami sources caused by past M9-class inter-plate earthquakes in and outside Japan in order to organize the knowledge required for the aforementioned parameter setting. Table 1 shows the past tsunamis to be analyzed.

As for the Tohoku Earthquake Tsunami, research institutions in and outside Japan collected high-precision observation data, including tsunami waveforms, trace heights, and amounts of crustal movements. Sugino et al.[8] performed an inversion analysis based on these observation data and proposed a TSM_R of tsunami waveforms observed by GPS wave gauges and the trace heights of four nuclear power plants including the Fukushima Daiichi Nuclear Power Plant. In addition, the Cabinet Office[12], Imamura et al.[13], Fujii et al.[14], and Satake et al.[15] also proposed TSM_R of the same tsunami. Each of these models consists of sub-faults, a slip amount is estimated for each sub-fault, and the slip distribution is given for the tsunami source model as a whole.

Table 3 Slip distributions and fault rupture modes of the world's Mw 9.0-class mega-tsunamis

	1952 Kamchatka [16]	1960 Chile [17]	1964 Alaska [18]	2004 Sumatra-Andaman [19]	2010 Chile [17]
Slip > 2 x D Slip > 3 x D Slip > 4 x D					
Ave. slip (D)	5.5m	10.6m	9.9m	7.5 m	5.4m
> 2 x D	29%	33%	28%	31%	28%
> 3 x D	—	—	—	13%	8%
> 4 x D	—	—	—	—	4%
Ave. rupture vel.	∞	∞	∞	∞	∞

Using these models for reproduction, sub-fault areas gradually expand in descending order of slip amount to determine the areas in which the average slip are four times (*4D*), three times (*3D*), or twice (*2D*) the average slip (*D*) of the whole area, the ratios of the areas to the whole area (area ratios) is calculated. Table 2 shows the results of slip distribution analysis. As a result, in the case of the Tohoku Earthquake Tsunami, *3D* and *2D* areas showed area ratios of 10 to 20% and 37 to 44%, respectively.

Similar analyses were conducted for tsunami source models of past M9-class earthquakes in different parts of the world.[16)-19)] Table 3 shows the results of these analyses. In this table, *3D* and *2D* areas showed area ratios of 8 to 13% and 28 to 33%. Note, however, that the *3D* data were obtained from two models out of five and the other three models failed to produce *3D* or greater data. From these results, it is impossible to assert whether no *3D* or greater slip actually occurred or the sub-fault area (100 km^2) used for this tsunami source modeling was too much larger than those in other models to obtain a resolution sufficient to extract *3D* or greater slip areas. Yet, the data on the heterogeneity of slip distribution obtained from the aforementioned analyses are important to specify the inner fault parameters.

3.3 Rupture process parameters

The rupture process parameters of a tsunami source are represented by the rupture starting point, the rupture propagation velocity, and the form of rupture propagation, etc.

Until the occurrence of the Tohoku Earthquake Tsunami, it was assumed that the rupture process parameters of a tsunami source had only an insignificant effect on tsunami heights along shorelines. Analyses of the Tohoku Earthquake Tsunami, however, revealed that the large source area made it impossible to ignore the effect of these parameters.[8)] As shown in Table 2 by the wave source models for the reproduction of the Tohoku Earthquake Tsunami, several models reflecting such a dynamic rupture effect have been proposed. For these models, from the rupture propagation velocity obtained by dividing the distance of the rupture starting point to the center point of each sub-fault by the time required until each sub-fault starts to slip, the average rupture propagation velocity is calculated to be approximately 1.5 to 2.0 km/s.

In addition, as in the case of the Tohoku Earthquake Tsunami, a fault rupture may propagate across the multiple source areas that the past earthquakes occurred. In other cases, multiple source areas of concern for the Nankai Trough may rupture with time lags[20)]. The issues related to the future prediction of tsunami occurrence should consider the uncertainties associated with these modes of rupture process.

4. METHOD OF CHARACTERIZING MODEL FOR TSUNAMI SOURCE

Based on the analysis results in Chapter 3, this chapter proposes a method of characterizing tsunami source models for inter-plate earthquakes. This is primarily designed for use in the Probabilistic Tsunami Hazard Analysis method for future prediction purposes. Figure 1 shows the procedure for specifying the outer fault parameters; inner fault parameters; and rupture process parameters. Based upon the experience of the Tohoku Earthquake Tsunami, particular consideration was taken into the undeniable possibility that future tsunamis may exceed the largest recorded scale. Thus, a departure from the traditional concept based on the largest recorded seismic moment is intended as an important part of the framework. In other words, a method of determining the seismic moment from a tsunami source area with uncertainties taken into account instead of determining parameters from the largest recorded seismic moment is selected here. The following sections describe the parameter-specifying procedures.

4.1 Specifying procedure of outer fault parameters

1) A tsunami source area is set on the plate boundary surface, taking into consideration the possibility that an earthquake may occur with a tsunami. When doing so, this area is set that is not limited to the largest recorded seismic moment in the relevant sea area. A model of this area is created as a three-dimensional plate boundary model that covers from the lower limit of the earthquake occurrence to the depth of the trench axis, based on the contour data of the plate boundary surface. When setting the range of this area, the Nuclear Regulation Authority's Review Guidelines[4] will be of informative (Step (a) in Figure 1).
2) Based on the locations and seismic moments of past earthquakes, the aforementioned tsunami source area is divided into segments. As for these segments division method, the long-term assessment of inter-plate earthquakes[21] by the Headquarters for Earthquake Research Promotion will be informative (Step (b) in Figure 1).

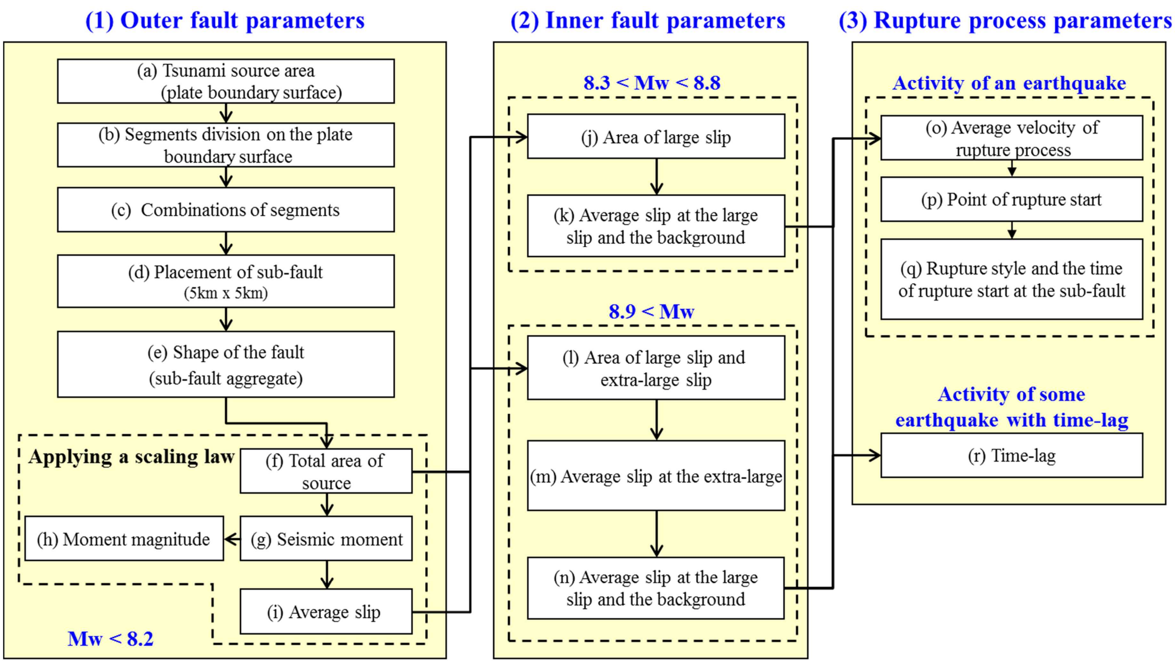


Figure 1 Specifying procedure of the characterized tsunami source model for inter-plate earthquakes

3) Mutually neighboring segments of the above are combined to consider the uncertainty of location and source area of the tsunami source (Step (c) in Figure 1).
4) In the area consisting of the combinations of the above, a multiple number of sub-faults (each approximately 5 km x 5 km) are arranged to aggregate into a whole source model (Steps (d) and (e) in Figure 1).
5) The scaling law[22)] is applied to the area S of the entire tsunami source consisting of the combinations of the segments above, and the following equations are used to calculate the moment magnitude Mw and the average slip D (m) (Steps (f) to (i) in Figure 1):

$$Mw = (\log M_o - 9.1)/1.5 \quad (1)$$
$$D = M_o/(\mu \cdot S) \quad (2)$$
$$M_o = 16/\left(7\pi^{3/2}\right) \cdot \Delta\sigma \cdot S^{3/2} \quad (3)$$

in which M_o stands for the seismic moment (Nm), μ for the shear modulus (N/m^2), S for the area of the entire tsunami source (m^2), and $\Delta\sigma$ for the average stress drop of the entire tsunami source (N/m^2), respectively.

4.2 Specifying procedure of inner fault parameters

6) The heterogeneity of the slip distribution is set appropriately based on Mw. As shown in Figure 2, a uniform slip distribution is set for small-to-medium-scale tsunamis of Mw 8.2 or less. A two-level heterogeneous slip distribution in a large slip area and a background area is set for large-scale tsunamis of Mw 8.3 to 8.8. A three-level heterogeneous slip distribution in the two areas above and an extra-large slip area is set for extra-large-scale tsunamis of Mw 8.9 or more. These slip distributions are specified to take into consideration the effect on tsunami heights along the shoreline. As for tsunamis of Mw 8.2 or less, past tsunami source models represented by rectangular uniform average slip are referred to, while reference is made to the analysis results in Section 3.2 for tsunamis of Mw 8.9 or more. In addition, tsunamis of Mw 8.3 to 8.8 are in the middle of the three classes above. Hence, consideration is made for the continuity of the slip distribution specifying method. The number of the large slip area is one, and the number of the extra-large slip area is one, two or more. This is based on the slip distribution analysis results in Section 3.2 showing that *2D* and *3D* areas concentrate in one or two areas. In cases of tsunamis of Mw 8.9 or more in particular, a source area larger than that of the Tohoku Earthquake Tsunami will be covered. Therefore, it is necessary to allow for a large uncertainty for the number of extra-large slip areas.
7) The slip amounts and areas of the respective areas shall be as follows, based on the analysis results in Section 3.2. In the case of a two-level slip distribution, the slip amount in the large slip area is

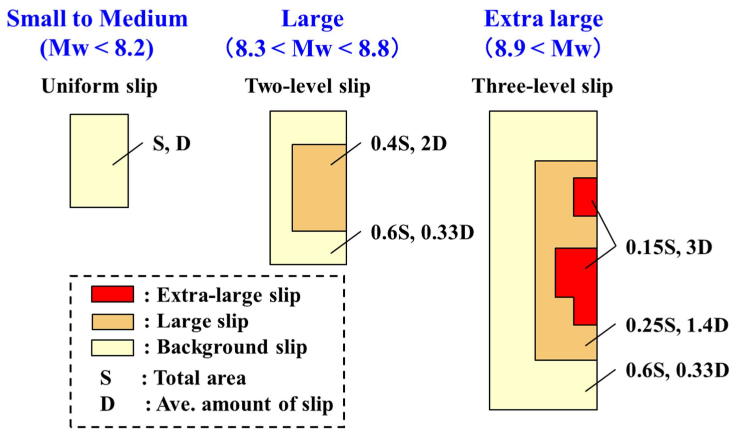


Figure 2 Specifying method of slip distributions for the inner fault parameters

twice the average slip and its area ratio is 40% of the total area (Steps (j) and (k) in Figure 1). In the case of a three-level slip distribution, the slip amount in the extra-large slip area is three times the average slip and its area ratio is 15% of the total area. The large slip area is regarded as the background area of the extra-large slip area, the average slip in the combined area consisting of the large slip area and the extra-large slip area is twice the average slip in the whole tsunami source, and the area ratio of the combined area is 40%. Therefore, the slip amount and area ratio of the large slip area for a three-level heterogeneous slip distribution is calculated from the following equation to be 1.4 times the average slip and 25% of the total area, respectively (Steps (l) to (n) in Figure 1, and Figure 2).

Let the seismic moments of the extra-large slip area, its background area (large slip area), and their combined area be M_{o3}, M_{o3b}, and M_{o2}, respectively. Then, the following relational equation will hold for these:

$$M_{o2} = M_{o3} + M_{o3b} \quad (4)$$

$$\begin{aligned} D_{3b} &= (D_2 S_2 - D_3 S_3)/S_{3b} \\ &= (2D \times 0.4S - 3D \times 0.15S)/(0.4S - 0.15S) \\ &= 1.4D \end{aligned} \quad (5)$$

in which D_{3b} is the slip amount (m) in the large slip area (background area of extra-large slip area), S_{3b} is the area (m^2) of the large slip (background area of extra-large slip), D_3 is the slip amount (= $3D$) (m) in the extra-large slip area, S_3 is the area (= $0.15S$) (m^2) of the extra-large slip, D_2 is the average slip (=$2D$) (m) in the combined area consisting of the large slip area and the extra-large slip area, and S_2 is the area (= $0.4S$) (m^2) of the combined area consisting of the large slip area and the extra-large slip area.

8) Because no slip distribution arrangement patterns can be handled deterministically in a future-prediction problem, multiple patterns of slip distribution with the extra-large slip area and the large slip area variably arranged are used in the tsunami source area. Even in this case, if the tsunami source area is extend to the trench axis, it is reasonable to arrange the extra-large slip area or the large slip area along the trench axis based on the knowledge from the Tohoku Earthquake. Figure 3 shows multiple patterns of typical slip distribution.

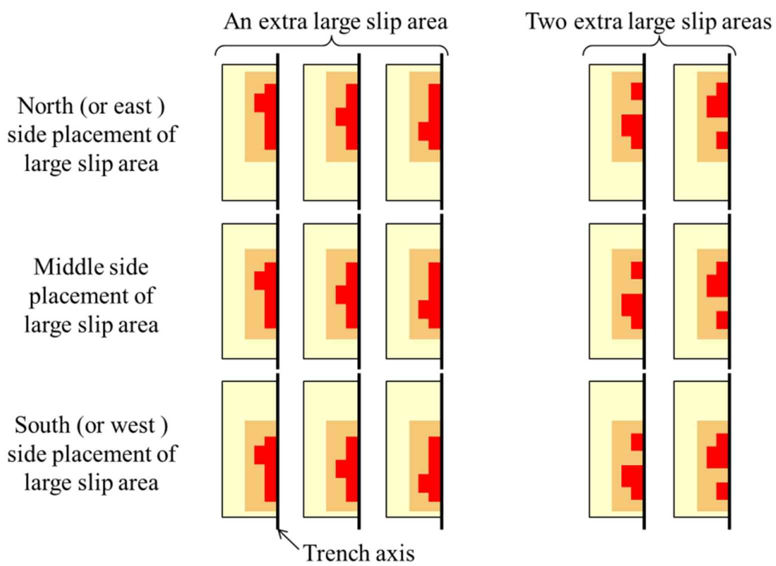
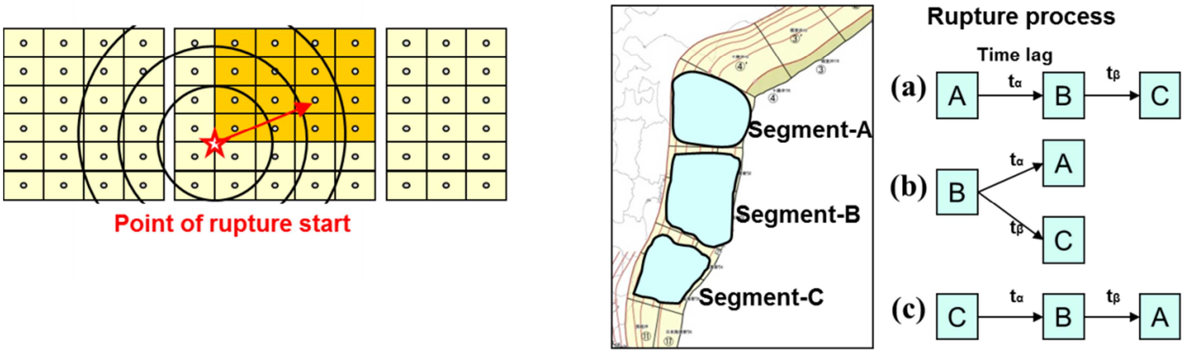


Figure 3 Multiple patterns of typical slip distribution (Mw 8.9 or more)

4.3 Specifying procedure of rupture process parameters

9) For extra-large-scale tsunami sources of *Mw* 8.9 or more, two different modes of rupture are considered because the tsunami source has a large area. One is a mode that assumes only one rupture process even though the tsunami source covers a multiple number of segments as shown in Figure 4(a). In this case, concentric circular rupture propagation is assumed with parameters of the rupture starting point and the average rupture velocity (Steps (o) to (q) in Figure 1). The other is a mode that assumes rupture process in consideration of time lags between ruptures of multiple segments as shown in Figure 4(b). In this case, the parameters are the order of rupture of each segment and the time lags between their ruptures. As for a specific setting method, the one in Sugino et al.[20] is helpful (Step (r) in Figure 1).

For large-scale tsunami sources of *Mw* 8.3 to 8.8, the method of specifying the rupture process parameters are basically the same as above. If the tsunami source is represented by a single segment, however, the method applies only to the case of Figure 4(a) among the cases above. For small-to-medium-scale tsunami sources of *Mw* 8.2 or less, reference was made to the fact that past tsunami source models assumed static rupture process conditions and showed sufficient reproducibility. In future-prediction problems except for static ruptures of *Mw* 8.2 or less, the rupture starting point, the average rupture velocity, the order of rupture of each segment, and the time lags between their ruptures cannot be handled deterministically. Therefore, multiple patterns are used.



(a) A concentric circular rupture propagation pattern (b) Rupture process with time lags

Figure 4 Specifying methods of rupture process parameters

5. VALIDATION OF CHARACTERIZED TSUNAMI SOURCE MODEL BY THE 2011 TOHOKU EARTHQUAKE TSUNAMI

Chapter 4 described the procedure of dividing the seismic scale for tsunamis caused by inter-plate earthquakes into three classes and specifying parameters for the tsunami source in each class. This chapter validates the characterized tsunami source model for the extra-large-scale category by comparison with the trace heights due to the Tohoku Earthquake Tsunami.

5.1 Validation method

The tsunami height variation (β) obtained using the tsunami propagation model is assessed in terms of the variation of the ratio K_i of trace height to simulated tsunami height at a multiple number of locations hit by past tsunamis. Here, β is the natural logarithm of the geometric standard deviation κ used as the indicator for judging the reproducibility obtained using the tsunami propagation model of Aida[23] intended for past tsunamis and is defined by the following equation:

$$\beta = \ln(\kappa) = \left[\frac{1}{n}\{\sum_{i=1}^{n}(\ln K_i)^2 - n(\ln K)^2\}\right]^{1/2} \quad (6)$$

$$\ln K = \frac{1}{n}\sum_{i=1}^{n}\ln K_i \quad (7)$$

$$K_i = R_i/H_i \quad (8)$$

in which R_i is the trace height, H_i is the simulated tsunami height, and i shows the each point of observation.

As shown in Figure 5, this tsunami propagation model is the general term for the models of the following three characteristics: tsunami source, tsunami propagation including sea bathymetry effects, and runup including land topography effects. Therefore, the tsunami height variation β obtained using the tsunami propagation model includes variations associated with the modeling of these three characteristics. Moreover, uncertainties of trace information, i.e., tsunami height, or positional information are also included. The effect of characterizing tsunami source to be examined in this chapter is one of these variation factors but is difficult to quantitatively evaluate by breaking it down into the β of individual characteristics. Hence, this chapter comprehensively investigates these variation factors as a single whole.

As stated earlier, Sugino et al.[8)] proposed a TSM_R of the Tohoku Earthquake Tsunami. While TSM_R and TSM_P are intrinsically different from each other, they are both tested and evaluated for reproducibility of past tsunamis. Then, the effect of the characterization of a tsunami source is examined by comparison with β obtained using the tsunami propagation model used for the reproduction analysis of the Tohoku Earthquake Tsunami.

Figure 6 shows the framework of the validation method. This validation proceeds in two steps. First of all, the TSM_R is estimated for reproduction at the four nuclear sites (Fukushima Daiichi, Fukushima Daini, Onagawa and Tokai Daini). Hence, with expanding the scope of reproduction to a multiple number of general sites to enhance the generality and explanatory ability of the TSM_R, the tsunami height variation β_{rep} obtained using this model is evaluated. Next, based on the tsunami source location or the slip distribution heterogeneity of the TSM_R, a characterized tsunami source model is created in accordance with the steps in Figure 1. Then, the same propagation and runup models as those for β_{rep} are used to evaluate β_{cha}.

It is expected that, when the aforementioned procedure is used, β_{cha} will be greater than β_{rep}. In other words, the switch from the TSM_R to the characterized tsunami source model, the only different

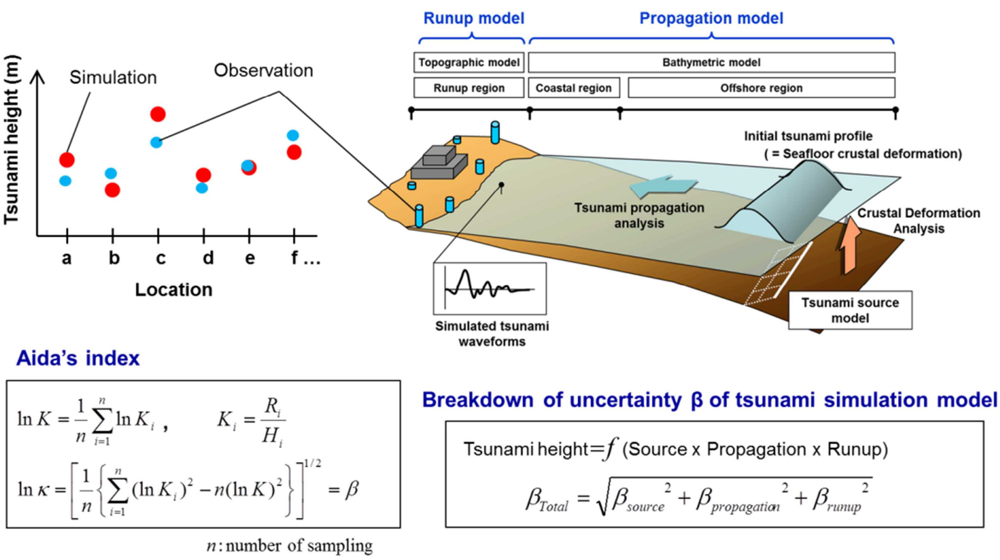


Figure 5 Configuration of the tsunami propagation model and tsunami level variation factors

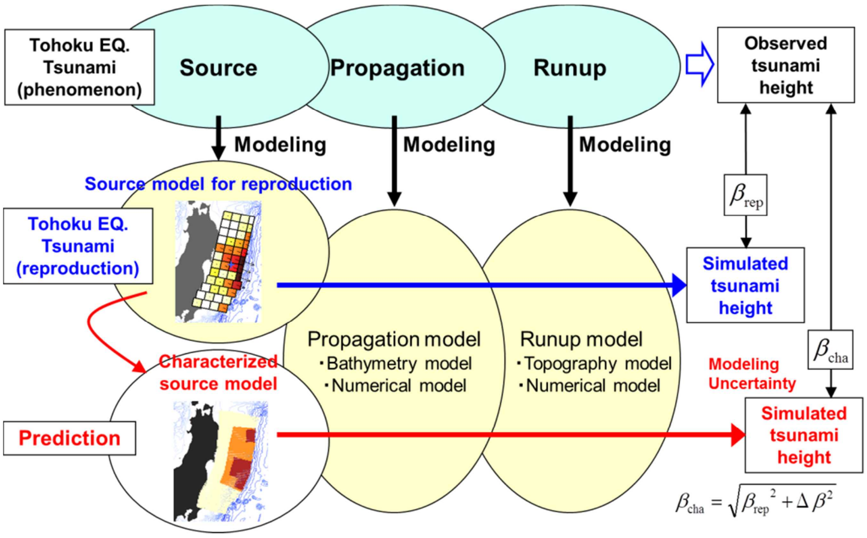


Figure 6 Examination framework for variations of tsunami propagation models

factor among the variation factors, places more weight on an engineering availability through the model simplification than the detailedness of the parameters featured by the TSM_R, thereby resulting in an increase in β. Furthermore, because all conditions other than the tsunami source model are the same, the increment from β_{rep} to β_{cha} is considered to be the effect of the characterization of the tsunami source.

What follows describes the selection criteria for general sites. Criterion 1 is that a candidate site is one for which the high-resolution altitude data were developed before the occurrence of the Tohoku Earthquake Tsunami and are available, because it is required to ensure a level of analysis precision equivalent to that achievable by a topography model with a spatial grid size of approximately 5 meters recommended[4)] for tsunami assessment at nuclear sites. Criterion 2 is that a candidate site is topographically similar to nuclear sites that are often cliff features backed by mountains. Criterion 3 is the avoidance of bias to certain sites or trace heights.

Where Criterion 1 applies, the airborne laser survey-based "3D Digital Coastal Map"[24)] is useful which was developed by the Geospatial Information Authority of Japan (GSI) before the occurrence of the Tohoku Earthquake Tsunami, and 50 or more candidate sites were selected from the scope of the coverage of the map. Then, under Criterion 2, these candidate sites were narrowed down to 18 sites. Finally, under Criterion 3, based on the trace data[25)] created by the Joint Research Group for the Tohoku Earthquake Tsunami, 0-to-40-meter heights were classified into four categories in 10-m increments, and 11 sites were selected so that at least one or more sites were included in each category and spatially dispersed.

Table 4 shows the 18 candidate sites above, 11 selected sites, and 4 nuclear sites. Moreover, Figure 7 shows the GSI high-precision altitude data coverage used as the selection criterion for general sites, the trace data from the Tohoku Earthquake Tsunami, and the selected general sites. As for the trace heights compared with the tsunami heights in the analysis results, data on locations that can be regarded as natural topographic features/cliffs are selected as far as possible from the data contained in the 11 sites above. In the case of Onagawa-cho in particular, a lot of trace data left on town-area buildings are available. These data are excluded because the topography model created for the present validation is not detailed down to individual buildings.

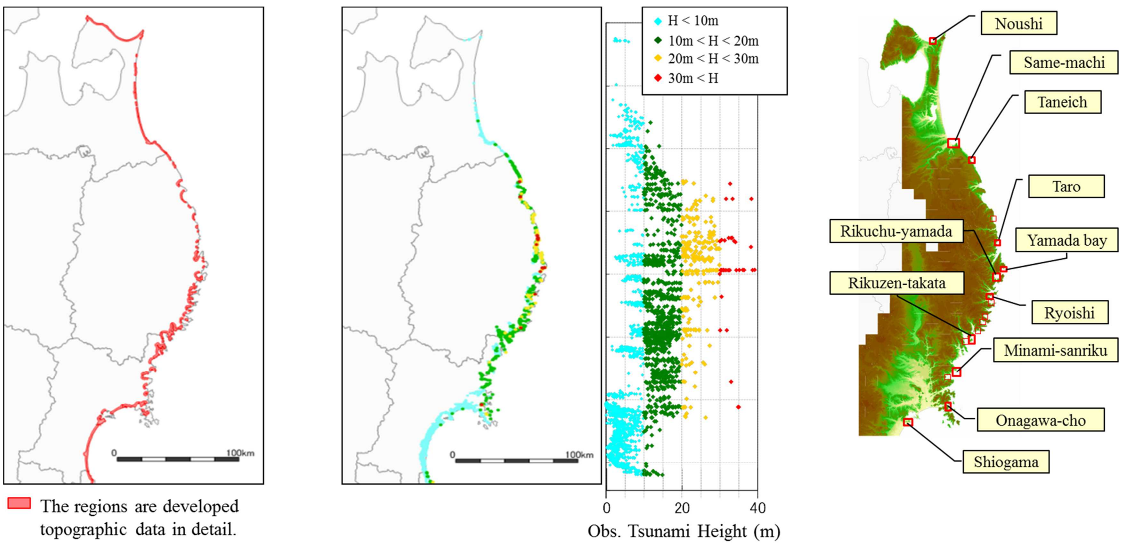
5.2 Creation of a characterized tsunami source model for the Tohoku Earthquake Tsunami

In accordance with Specifying Steps 1) to 9) in Chapter 4, a characterized tsunami source model for the Tohoku Earthquake Tsunami is created. Note, however, that because the characterized tsunami

Table 4 Candidate general sites and selection results

Obs. Height	0 -10 m	10 - 20 m	20 - 30 m	30 - 40 m
Aomori	**Noushi**			
	Same-machi	**Same-machi**		
Iwate	**Taneichi**			
		Tanohata	Tanohata	
	Taro	**Taro**	**Taro**	**Taro**
		Yamada bay	**Yamada bay**	**Yamada bay**
	Rikuchu-yamada	**Rikuchu-yamada**		
		Ryouishi	**Ryouishi**	
	Kamaishi	Kamaishi		
		Yoshihama		
		Okirai bay		
		Ryori		
		Rikuzentakata		
		Dairiseki beach		
Miyagi	**Minami-sanriku, utatsu**	**Minami-sanriku, utatsu**		
		Minami-sanriku, tsugawa		
		Onagawa-cho	**Onagawa-cho**	**Onagawa-cho**
		Onagawa NPP		
	Shiogama			
Fukushima		**Fukushima daiichi NPP**		
	Fukushima daini NPP	**Fukushima daini NPP**		
Ibaraki	**Tokai daini NPP**			

: Selected Sites



(a) High-precision altitude data[24] (b) Trace data of Tohoku EQ. Tsunami[25] (c) Selected sites

Figure 7 Selection criteria and selection results for general sites

source model is a TSM_P, the source area and location are basically the parameters with uncertainties.

The present purpose is, however, validation based on the Tohoku Earthquake Tsunami. Hence, it is premised that the area and location of the tsunami source for the characterized model are handled as known information, similarly to the case with the tsunami source model of Sugino et al.[8] for the reproduction of the Tohoku Earthquake Tsunami.

(1) Specifying outer fault parameters

In accordance with Step 1), a plate boundary model is created, based on the figure of contour maps reported by the Central Disaster Prevention Council[26], for the plate boundary surfaces of the complicated three-dimensional structures along the Japan Trench. The plate boundary model is created to cover a tsunami source area almost equivalent to that in the TSM_R of the Tohoku Earthquake Tsunami. Note that the segment setting in Step 2) and the segment combinations in Step 3) are omitted based on the premise above. Next, in accordance with Step 4), sub-faults, each with an area of approximately 5 km × 5 km, are arranged in the aforementioned plate boundary model. Then, in accordance with Step 5), Mw and the average slip D are calculated using Equations (1) to (3). For the calculation of these values, let the average stress drop $\Delta\sigma$ be 3.1 MPa.[10] In addition, because the tsunami source area of the Tohoku Earthquake Tsunami extends from the shallow depths along the trench to the deep area with a depth of approximately 60 km, let the depth of the boundary between the shallow and deep area with a depth of approximately 18 km, and let the shear modulus[3] of each area be 3.5×10^{10} N/m^2 at the shallow depths and 5.0×10^{10} N/m^2 at the deep depths. In this case, the average slip D is calculated by the following equation to be 10.4 m:

$$\mathrm{D} = M_o/\left(\mu_{shallow} \times S_{shallow} + \mu_{deep} \times S_{deep}\right) \tag{9}$$

in which $\mu_{shallow}$ and μ_{deep} are the shear modulus at the shallow depths and that at the deep depths, respectively, while S_{shallow} and S_{deep} are the area of the tsunami source at the shallow depths and that at the deep depths, respectively. Table 5 shows the areas of the tsunami source thus set, the number of sub-faults, and the average slip, among other things.

(2) Specifying inner fault parameters

In accordance with Steps 6) and 7), the slip distribution is set up taking the heterogeneity in the tsunami source area into consideration. From the outer fault parameters previously described, Mw is 9.1. Accordingly, a three-level heterogeneous slip distribution is set here. From Equations (4) and (5), the slip amount D_3 (= $3D$) of the extra-large slip area is calculated to be 31.2 m, D_{3b} of the large slip area to be 14.6 m, and D_{2b} of the background area to be 3.5 m, respectively. In addition, Table 5 shows the areas of the respective areas. It is assumed that there are two extra-large slip areas. The rationale is that the results of the tsunami source estimation by Sugino et al.[8] show that the slip was concentrated near the rupture starting point and along the trench during the first half to the middle stage of the fault rupture process and that the slip concentrated along the trench slightly shifted to the north during the final stage. Note that variations in the slip distribution arrangement patterns in Step 8) are omitted based on the premise above.

(3) Specifying rupture process parameters

It is considered likely that, in the Tohoku Earthquake Tsunami, a fault rupture propagated across a multiple number of segments in a relatively short period of several minutes. Then, the average rupture propagation velocity and the concentric circular rupture propagation mode in consideration of different rupture starting point are used in Step 9). Let the average rupture propagation velocity be 1.5km/s[8] and the rupture starting point be the observed hypocenter.

Table 5 Parameters of the characterized tsunami source model for the Tohoku Earthquake Tsunami

Region		Number of sub-fault	Area (km^2)	Slip (m)	Moment magnitude Mw
Total region		5147	134593	10.4 (average)	9.1
Break-down	Extra large slip	792	20189	31.2	—
	Large slip	1312	33648	14.6	—
	Background	3043	80756	3.5	—

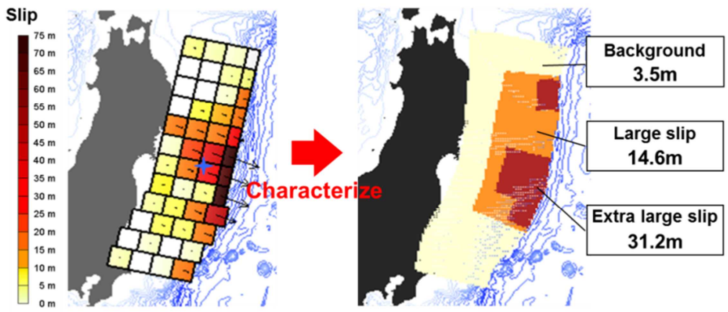


Figure 8 TSM_R (left) and the characterized model (right) of the Tohoku Earthquake Tsunami

Table 6 Calculation conditions for tsunami propagation/runup analysis for the validation of the characterized tsunami source model

<table>
<tr><th>Item</th><th>Specifying</th></tr>
<tr><td>Condition of each region</td><td>
<table>
<tr><td colspan="2">Region</td><td>A</td><td>B</td><td>C</td><td>D</td><td>E</td><td>F</td></tr>
<tr><td colspan="2">Mesh size (m)</td><td>1350</td><td>450</td><td>150</td><td>50</td><td>17</td><td>5.6</td></tr>
<tr><td colspan="2">Time step (sec)</td><td>2.43</td><td>0.81</td><td>0.27</td><td>0.09</td><td>0.03</td><td>0.01</td></tr>
<tr><td colspan="2">Equation</td><td colspan="6">Non linear long wave</td></tr>
<tr><td colspan="2">Topography model</td><td colspan="3">Only sea area</td><td colspan="3">Sea and land</td></tr>
<tr><td rowspan="2">Boundary condition</td><td>Land side</td><td colspan="3">Total reflection</td><td colspan="3">Runup model due to Kotani et al.[27]</td></tr>
<tr><td>Offshore side</td><td>Open</td><td colspan="5">Water level and flux are connected to the outside region</td></tr>
</table>
</td></tr>
<tr><td>Initial tsunami profile</td><td>By the method of Mansinha and Smylie (1971)[28]</td></tr>
<tr><td>Bottom friction factor</td><td>Manning number, n=0.025$m^{-1/3}s$ (Goto and Sato (1993)[29], JSCE(2002)[3])</td></tr>
<tr><td>Horizontal eddy viscosity</td><td>No consideration</td></tr>
<tr><td>Duration time for tsunami simulation</td><td>Six hours after tsunami generation</td></tr>
</table>

Figure 8 shows the characterized tsunami source model of Tohoku Earthquake Tsunami created in accordance with these steps.

Table 6 shows the main calculation conditions for the numerical tsunami analysis of the Tohoku Earthquake Tsunami performed to validate the characterized tsunami source model. The nonlinear long wave theory was used for numerical tsunami analysis. For the equation of motion, an advection term and a bottom friction term were taken into consideration. A Manning's roughness coefficient of 0.025 was applied to the latter term. The finite difference method was used for the numerical calculations, and the nesting calculations was performed using a topography model consisting of six regions (A to F) covering a sea area and a land area with the spatial grid interval gradually reduced by the dividing factor of 3 from 1,350 meters in Region A down to 5.6 meters in Region F. Figure 9 shows these calculation domains. The boundary conditions are open for Region A on the offshore side, perfect reflection for Regions A to C on the shore side, and the runup boundary of Kotani et al.[27] for Regions D to F.

5.3 Validation results

Figure 10 shows the results of the comparison of the trace heights at the four nuclear sites and 11 general sites with the corresponding simulated tsunami heights. In this figure, trace heights (runups

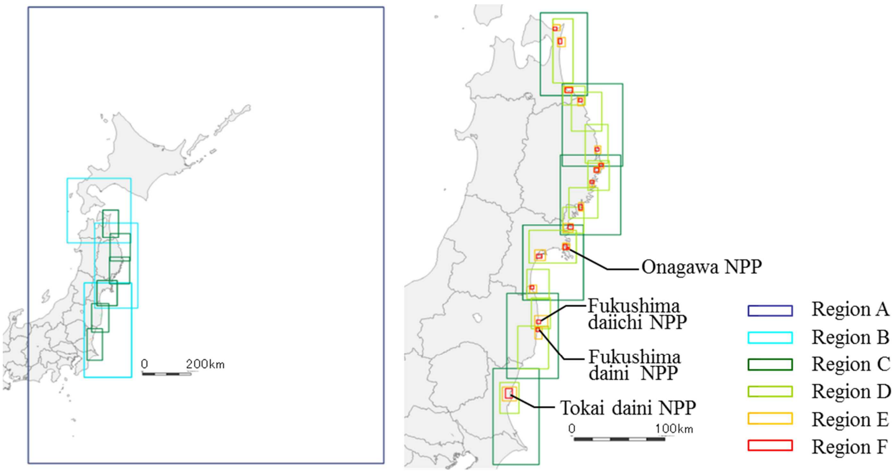


Figure 9 Calculation domains of numerical tsunami analysis

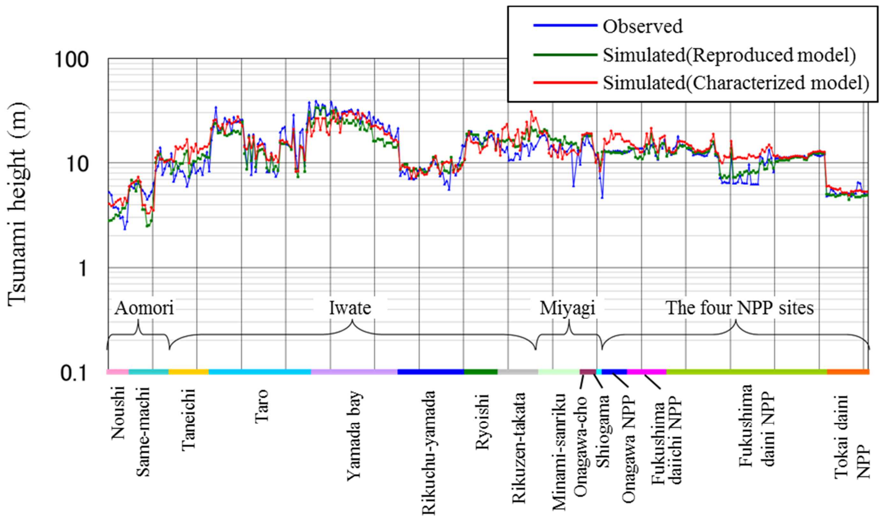


Figure 10 Comparison of the trace heights and simulated tsunami height of the Tohoku Earthquake Tsunami

and inundation heights) measured in field investigations are shown in blue line, simulated tsunami heights obtained by numerical analysis using the TSM_R are shown in green line, and those obtained by numerical analysis using the characterized tsunami source model are shown in red line. The degree of reproducibility achievable by the TSM_R can be expressed, using the Aida's index[23)], as K = 1.01, κ = 1.24 (β_{rep} = 0.22), and n = 339 points. These values sufficiently meet the standard for good reproduction [0.95 < K < 1.05 and κ = < 1.45].[3)] On the other hand, when the characterized tsunami source model is used, K = 0.91, κ= 1.30 (β_{cha} = 0.26), and n = 337 points. Thus, while the value of K is slightly below the standard above, the reproduction is almost successful. In addition, the value of β_{cha} is greater than that of β_{rep}, as expected. The difference between the two values is approximately 0.04.

These results show an average tendency for all relevant trace heights but do not show the details of their relationship with tsunami heights. Therefore, focusing on β_{rep} and β_{cha}, their relationships with simulated tsunami heights were examined. The results are shown respectively in Figures 11 and 12.

The upper panels of these figures show the distribution of the ratio of trace height to simulated tsunami height, while the lower panels show the values of β calculated from these distributions. In all these figures, the x-axis stands for the simulated tsunami height. Note, however, that the simulated

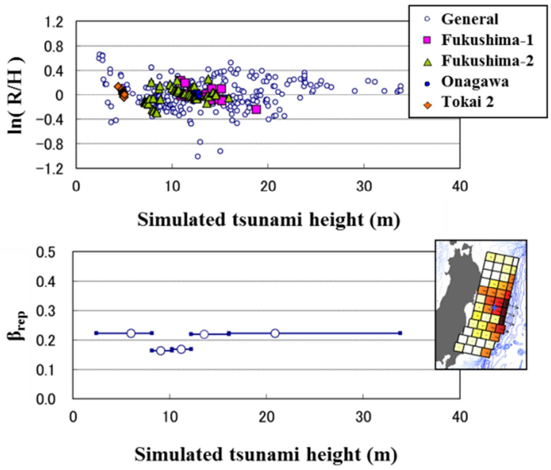


Fig. 11 Relationship between β_{rep} and the simulated tsunami height

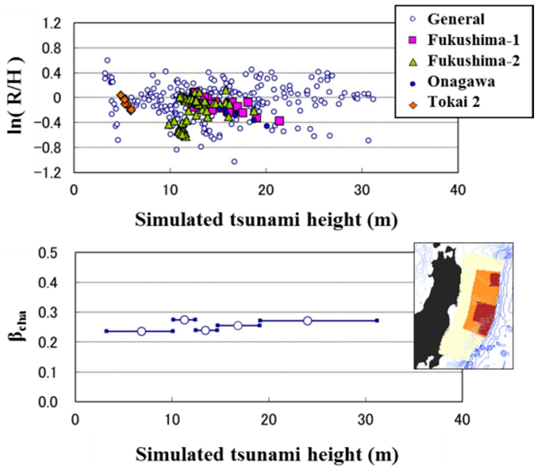


Fig. 12 Relationship between β_{cha} and the simulated tsunami height

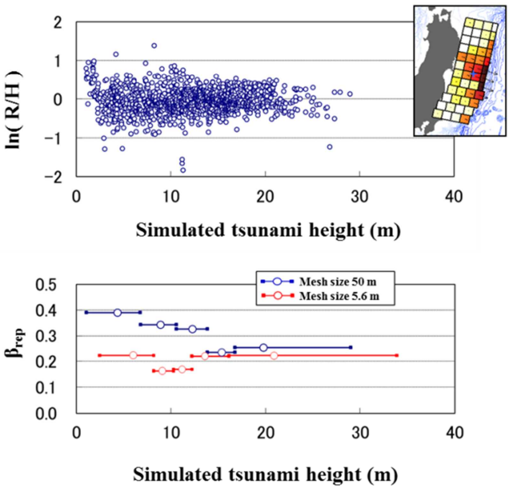


Fig. 13 Effect of spatial grid on the relationship between β_{rep} and the simulated tsunami height

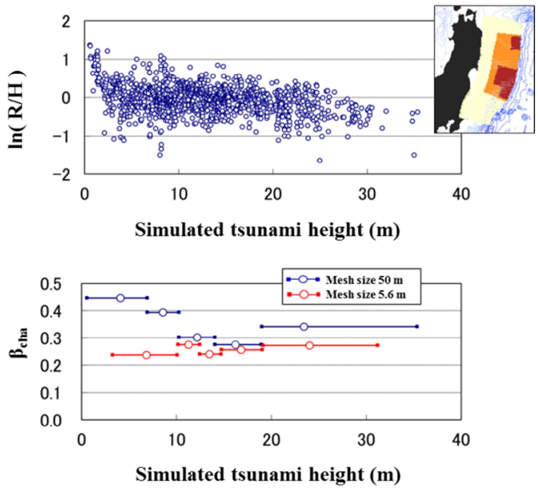


Fig. 14 Effect of spatial grid on the relationship between β_{cha} and the simulated tsunami height

tsunami height along the x-axis of the lower panels was divided into five sections, for each of which β was calculated. When doing so, the widths of these sections were set so that each section would contain approximately the same number of samples. Then, in the figures, the widths of the respective sections are indicated by the lengths of solid lines, and the average values of simulated tsunami heights and the values of β in the respective sections are marked with circles. Figure 11 shows β_{rep} ranging from 0.16 to 0.22, while Figure 12 shows β_{cha} ranging from 0.24 to 0.27. In either case, the value of β remains almost constant regardless of the simulated tsunami height.

Incidentally, the simulated tsunami height value obtained by a tsunami propagation model significantly depends on the spatial mesh size of the topography model. Then, naturally, it easily follows that the value of variation β will also change accordingly. Therefore, to understand the relationship between β and the spatial mesh size, a comparative analysis is performed with a variable spatial mesh size and the investigation is performed in the way similar to Figure 11 and 12.

The tsunami source models used for comparative analysis are the TSM_R and the characterized tsunami source model same to those used in the above. In addition, the locations of the 11 general sites and four nuclear sites shown in Fig. 9 are discrete in spatial distribution. Therefore, to compensate

Table 7 Tsunami propagation model-based comparison with existing knowledge on variation β

	1) Source model	2) Propagation model	3) Runup model	4) Trace height	Uncetainty β (κ)
JSCE [7] 2011.9	• Uniform slip model	• Bathymetry model	• Mesh size 100~200m • Total Reflection	• Precision of location info.- Low	Japan Trench: 0.34~0.37 (1.40~1.45) Nankai trough: 0.30~0.47 (1.35~1.60)
	• Heterogeneous slip model	• Bathymetry model	• Mesh size 50m • Total Reflection	• Precision of location info.- Low	Japan Trench: 0.31~0.37 (1.37~1.45) Nankai trough: 0.28~0.39 (1.32~1.48)
Tohoku EQ. Tsunami (This study)	• Characterized source model (Heterogeneous slip model)	• Bathymetry model	• Mesh size 5.6m • Runup • Building	• Precision of location info.- High	Japan Trench: 0.24~0.27 (1.27~1.31)

Improvement precision of several modeling

discreteness, this investigation covers trace heights in a wide range extending from Hokkaido to Ibaraki Prefecture. The finest spatial mesh size is set to 50 m to obtain simulated tsunami heights. These results are shown in Figures 13 and 14. In these figures, the results are shown overlapped, for comparison, with β_{rep} and β_{cha} with a spatial mesh size of 5.6 m shown in Figures 11 and 12.

Figure 13 shows β_{rep} ranging from 0.23 to 0.39, while Figure 14 shows β_{cha} ranging from 0.28 to 0.45. In either case, the value of β tends to decrease as the simulated tsunami height increases, thus showing a result different from when the spatial mesh is size 5.6 meters. In other words, the effect of the spatial mesh size increases as the simulated tsunami height decreases. The difference between β_{rep} and β_{cha} is approximately 0.05, which is similar to the value obtained when the spatial mesh size is 5.6 meters.

5.4 Discussions based on the validation results

As shown in Section 5.3, the tsunami height variation β_{cha} based on the characterized tsunami source model was quantitatively obtained. A comparison between the variation β_{cha} and existing knowledge is conducted in this section.

The existing knowledge on tsunami height variations obtained using tsunami propagation model is summarized in a report of Japan Society of Civil Engineers[7]. Based on this information, a comparison is made with the results of the validation in this paper from the perspective of the four factors of the variations, i.e., source model, propagation model, runup model, and trace information. Table 7 shows the results of the comparison.

The table reveals that, while the value of β based on the existing knowledge ranges from approximately 0.28 to 0.47, the variation β_{cha} in this paper ranges from 0.24 to 0.27, thus showing a significant decrease. This is the result of combinations of various factors such as the incorporation of heterogeneous slip distributions into the inner fault parameters of the characterized tsunami source model; the refinement of the spatial mesh size of the land topography model based on the altitude data obtained by airborne laser surveying; and the Tohoku Earthquake Tsunami trace information treated in this paper which contains GPS survey-based detailed positional information while the traditionally-known trace information is based on historical records. In other words, the increased accuracy of various models and trace information are considered instrumental to the reduction of variation β.

Furthermore, the results of the validation in this paper reveal that the spatial mesh size of the topography model is influential in the relationship between variation β and the simulated tsunami height and the influence will intensify as the simulated tsunami height decreases. In other words, it follows that the lower trace heights to be reproduced need the higher accuracy for topography modeling. It is considered that this is because a small tsunami is easily influenced by topographical ups and downs in runup areas while a big tsunami spreads all over the place regardless of topographical ups and downs. An additional likely factor is that the variation β calculation method uses the ratio of trace height to simulated tsunami height in the first place, which means that the ratio of a trace height of 2m to a simulated tsunami height 4m is handled as a sample value equivalent to the ratio of a trace height of 20m to a simulated tsunami height of 40m. Note, however, that the present study tested the effectiveness of our model for only one case, namely, the *Mw* 9.0 Tohoku Earthquake Tsunami, which is classified as an extra-large-scale tsunami of *Mw* 8.9 or more. Cases of other *Mw* also require a similar validation and should be addressed in future studies.

6. SUMMARY

In order to contribute to the advancement of the Probabilistic Tsunami Hazard Analysis method for nuclear power plants, existing knowledge and lessons learned from M9-class earthquake tsunami sources in and outside Japan, including the Tohoku Earthquake Tsunami, were summarized for predicting future tsunami. Based on the obtained results, this study proposed the specifying methods for the characterized tsunami source model for the inter-plate earthquakes-induced tsunami. In addition, taking the Tohoku Earthquake Tsunami as an example, a tsunami propagation model using the characterized tsunami source model was employed to examine the tsunami height variation β in order to validate the usefulness of the characterized tsunami source model. What follows summarizes the features of the characterized tsunami source model and the results of our validation:

1) Analyses of slip distributions obtained from tsunami source models for reproduction intended for past tsunamis caused by M9-class earthquakes in and outside Japan revealed that the area ratio of an area with three times the average slip of the whole ranged from 8 to 20% (three tsunami cases analyzed) and that the area ratio of an area with twice the average slip of the whole ranged from 28 to 40% (six tsunami cases analyzed). Thus, new knowledge was obtained on the heterogeneity of slip distribution.

2) Taking into consideration the undeniable possibility that future tsunamis may exceed the largest recorded scale, a “Characterized Tsunami Source Model” was proposed that uses a concept different from the conventional tsunami assumption based on the largest recorded scale and standardizes the methods of specifying the tsunami source area, slip distribution, etc., of an inter-plate earthquake-induced tsunami.

3) In the specifying method of a characterized tsunami source model, the tsunami source characteristics are represented in three steps and as outer fault parameters, inner fault parameters and rupture process parameters. As for the outer fault parameters, a tsunami source area that is not limited to the largest recorded earthquake scale and allows for the possibility of exceedance in the target area, and its segments are combined to set the seismic moment. As for the inner fault parameters, three classes are used as appropriate for *Mw*. For small-to-middle-scale sources of *Mw* 8.2 or less, a uniform slip distribution is set. For large-scale sources of *Mw* 8.3 to 8.8, a two-level heterogeneous slip distribution consisting of a large slip area and a background area is specified. For extra-large-scale sources of *Mw* 8.9 or more, a three-level heterogeneous slip distribution consisting of the two areas above and an extra-large slip area is used. As for the slip amount and area of these sources, based on 1) above, the slip amount in the extra-large slip area is three times the average slip and its area ratio is 15% of the total area. The slip amount in the combined area consisting of an extra-large slip area and a large slip area is twice the average slip and its area ratio is 40% of the total area. For tsunami sources of *Mw* 8.3 or more with a large source area, rupture process parameters are used, taking into consideration two different modes of rupture propagation, one that assumes concentric circular rupture propagation and the other that assumes time lags between multiple segments.

4) The characterized tsunami source model was made for the Tohoku Earthquake Tsunami, and it was revealed that the model can generally reproduce trace heights of the Tohoku Earthquake

Tsunami and that its specifying method is effective. In addition, it was shown that the tsunami height variation β_{cha} obtained from the tsunami propagation model using the characterized tsunami source model depends on the spatial mesh size of the topography model used for numerical tsunami analysis. Therefore, when the characterized tsunami source model is used for probabilistic tsunami hazard analysis, the value of β_{cha} can be reduced to approximately 0.20 to 0.30 under the condition of a spatial mesh size of approximately 5 meters. Note, however, that the present study validated the effectiveness of the model only for extra-large-scale tsunamis of *Mw* 8.9 or more and the validation of its effectiveness for other classes of tsunamis is left for future studies.

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