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SCENARIO TSUNAMI SOURCE MODELING AND PROBABILISTIC TSUNAMI HAZARD ASSESSMENT METHOD

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Abstract

The tsunami caused by the 2011 off the Pacific Coast of Tohoku Earthquake on March 11, 2011 (the 2011 Tohoku Tsunami) led to a severe accident at the Fukushima Daiichi Nuclear Power Plant (NPP) of Tokyo Electric Power Company. The accident revealed the underestimation of the tsunami design level of the power plant, its unpreparedness for tsunamis exceeding the design level, and the importance of awareness of tsunami risks to NPPs.

The tsunami design levels of NPPs in Japan have been estimated based on a report by the Japan Society of Civil Engineers (JSCE). In the JSCE report, a basic tsunami source models which can reproduce tsunamis in the past are established and various tsunami source models based on the basic tsunami source models are provided by changing the positions, strikes, dips, and so on. This estimation method has been applied to address the uncertainty of possible tsunamis in the future. It, however, failed to anticipate a tsunami height comparable to that of the 2011 Tohoku Tsunami. Consequently, the conventional method based on the greatest magnitude of earthquakes in the past proved inadequate in establishing the magnitude of possible earthquakes for the tsunami assumption.

After the 2011 Tohoku Tsunami, Sugino et al.[1] compiled findings on tsunami sources triggered by M_w9-class earthquakes in Japan and abroad (including the 2011 Tohoku Tsunami) to improve scenario tsunami source modeling in future forecasts. The authors then proposed a characterized source model for tsunamis triggered by inter-plate earthquakes by adopting a different concept from the conventional tsunami assumption method based on the greatest scale of tsunami in the past while pointing out the undeniable possibilities of even greater tsunamis in the future.

To improve the probabilistic tsunami hazard assessment method used in an evaluation of the tsunami risks at NPPs, this study applies the characterized source model by Sugino et al.[1] as a new scenario tsunami model to present practical examples of tsunami for the inter-plate earthquakes along the Chishima Trench and Japan Trench. The results are compared with tsunamis assumed by the conventional model (hereinafter called the "old scenario tsunami model") in order to examine the impact of the different approaches in handling uncertainties for tsunami assumption in terms of the results of the probabilistic tsunami hazard assessment.

As a result, the difference of the tsunami hazard curve before the 2011 Tohoku Tsunami was significantly large in a range smaller than 10^{-2} (annual exceedance probability) in case of water level rising. Comparison of the annual exceedance probability in terms of the peak water level based on the simulation analysis of the 2011 Tohoku tsunami demonstrated that the result based on the new scenario tsunami model (about 10^{-3}) is roughly 10^{3} times greater than the result based on the old scenario tsunami model (less than 10^{-6}).

This report is a summary of the studies of Sugino et al.[1,2], which were published in the Japan Association for Earthquake Engineering (JAEE) journal in Japanese.

Keywords: probabilistic tsunami hazard assessment, the 2011 Tohoku Tsunami, scenario tsunami, characterization method for scenario tsunami, nuclear power plant

1. Introduction

The tsunami caused by the 2011 off the Pacific Coast of Tohoku Earthquake on March 11, 2011 (the 2011 Tohoku Tsunami) led to a severe accident at the Fukushima Daiichi Nuclear Power Plant (NPP) of Tokyo Electric Power Company. The accident revealed the underestimation of the tsunami design level of the power plant, its unpreparedness for tsunamis exceeding the design level, and the importance of awareness of tsunami risks to NPPs.

The tsunami design levels of NPPs in Japan have been estimated based on a report [3] by the Japan Society of Civil Engineers (JSCE). According to the JSCE report, basic tsunami source models which can reproduce past tsunamis are established, and various tsunami source models based on basic models are provided by changing the positions, strikes, dips, and so on. This estimation method has been applied to address uncertainties of possible tsunamis in the future. However, it failed to predict a tsunami height comparable to that of the 2011 Tohoku Tsunami. Consequently, the conventional method based on the greatest magnitude of earthquakes in the past proved inadequate in establishing the magnitude of possible earthquakes for the tsunami assumption.

After the 2011 Tohoku Tsunami, Sugino et al. [1] compiled findings on tsunami sources triggered by M_w9-class earthquakes in Japan and abroad (including the 2011 Tohoku Tsunami) to improve scenario tsunami modeling. The authors then proposed a characterization method for scenario tsunamis triggered by inter-plate earthquakes by adopting a different concept from the conventional method while pointing out the undeniable possibilities of even greater tsunamis in the future.

To improve the probabilistic tsunami hazard assessment (PTHA) method used in an evaluation of the tsunami risks at NPPs, Sugino et al. [2] applies the characterization method for scenario tsunami suggested by Sugino et al. [1] as a new model to present practical examples of tsunami for the inter-plate earthquakes along the Chishima Trench and Japan Trench. The results were compared with tsunamis assumption based on the conventional model (hereinafter called the “old model for scenario tsunami”) in order to examine the impact of the different approaches in treating uncertainties of scenario tsunamis in terms of the PTHA results.

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2. Proposal of the new model for scenario tsunami

2.1 Significance of characterization of tsunami source

Tsunami source models fall into two types: models for reproduction and those for prediction. A tsunami source model for reproduction (TSMR) 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 examples of the TSMR [4, 5] of the 2011 Tohoku Tsunami, the source area was divided into sub-faults, and sub-fault-specific parameters such as rupture starting time and 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. Such models, however, are difficult to apply to tsunami prediction problems due to the complexity of parameters.

On the other hand, a tsunami source model for prediction (TSMP) cannot deterministically treat 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, in the “Characterization method for scenario tsunami” proposed by Sugino et al. [1], a model for prediction has the tsunami source characteristics simplified by key parameters to standardize coastal tsunami assessments. In other words, this characterization 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 as same as the characterized seismic source model [6]. When specifying these parameters, however, we should take into account of 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.

2.2 Characteristics analysis of M_w9-class tsunami source models for reproduction

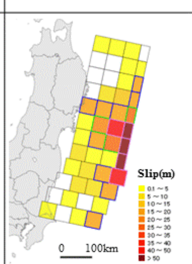
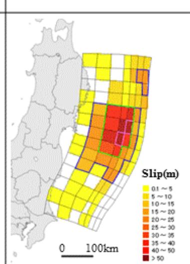
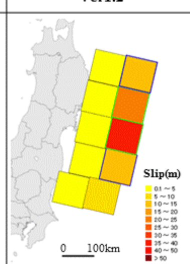
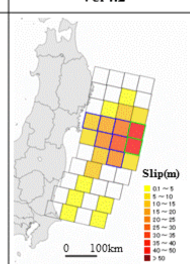
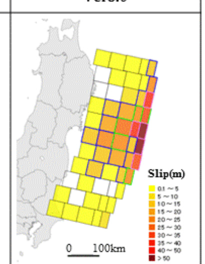
The outer fault parameters of tsunamis caused by inter-plate earthquakes are represented by the following parameters: source location; seismic moment; and average slip. These parameters are applicable to earthquake-induced tsunamis and therefore must be classified as those in common with the Recipe for predicting strong ground motions [6]. Murotani et al. [7] showed that the relationships between seismic moments, fault areas, average slip, etc., extracted from inversion models of tsunami sources caused by M_w9-class inter-plate earthquakes in and outside Japan generally agree with the scaling law for M_w7 to M_w8-class inter-plate earthquakes that occurred near Japan. This result implies that the same scaling law as the Recipe for predicting strong ground motions [6] can be applied to the seismic moment and average slip of an M_w9-class tsunami source model.

Inner fault parameters are represented by the following parameters, thereby showing the heterogeneous slip distribution: (a) the area that gives a slip larger than the average slip; and (b) the slip amount therein. The heterogeneous slip distributions were analyzed based on inversion models of tsunami sources caused by past M_w9-class inter-plate earthquakes in and outside Japan in order to organize the knowledge required for the aforementioned parameter setting.

As for the 2011 Tohoku 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. [4] performed an inversion analysis based on these observation data and proposed a TSMR 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 [8], Imamura et al. [9], Fujii et al. [10] and Satake et al. [5] also proposed TSMRs for 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.

Using these TSMR of the 2011 Tohoku Tsunami, sub-fault areas gradually expand in descending order of slip amount to determine the areas in which the average slips are four times (*4D*), three times (*3D*), or twice (*2D*)

Table 1 – Slip distributions and fault rupture modes of the 2011 Tohoku Tsunami [1]

	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 Slip > 3 x D Slip > 4 x D	 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

the average slip (D) of the whole area. And the ratios of the areas to the whole area (area ratios) were calculated. Table 1 shows the results of slip distribution analysis. As a result, *3D* and *2D* areas showed area ratios of 10 to 20% and 37 to 44%, respectively [1]. Similar analyses were conducted for TSMR of past M_w9-class earthquakes in different parts of the world. As a result of these analyses, *3D* and *2D* areas showed area ratios of 8 to 13% and 28 to 33% [1].

The rupture process parameters are represented by the rupture starting point, the rupture velocity, and the form of rupture propagation, etc. Before the 2011 Tohoku Tsunami, it had been believed that the rupture process parameters had not significant effect on tsunami heights along shorelines. Analyses of the 2011 Tohoku Tsunami, however, revealed that the large source area made it impossible to ignore the effect of these parameters [4]. As shown in Table 1 by the TSMR of the 2011 Tohoku Tsunami, several models reflecting such a rupture process effect were proposed. For these models, the average rupture velocities were calculated to be approximately 1.5 to 2.0 km/s.

In addition, as for the 2011 Tohoku Tsunami, the rupture propagated across the multiple source areas where the past earthquakes occurred. In other cases, multiple source areas of concern for the Nankai Trough may rupture with time lags [11]. The issues related to the future tsunami should include the uncertainties associated with these forms of rupture process.

2.3 Procedure of the new characterization method for scenario tsunami

Sugino et al. [1] proposes the characterization method for scenario tsunami triggered by inter-plate earthquakes based on the results of characteristics analysis in Section 2.2. This is primarily designed for use in the PTHA method. Fig.1 shows the procedure for specifying the outer fault parameters; inner fault parameters; and rupture process parameters. Based upon the experience of the 2011 Tohoku Tsunami, it is necessary to consider the undeniable possibility that future tsunamis may exceed the greatest magnitude of the past tsunamis.

Thus, a departure from the conventional concept based on the greatest recorded magnitude 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 from the greatest recorded seismic moment is selected here.

In terms of the outer fault parameters, much wider seismogenic area is taken into account along the plate boundary without being constrained by the largest magnitude of earthquakes in the past. The source area (S) with

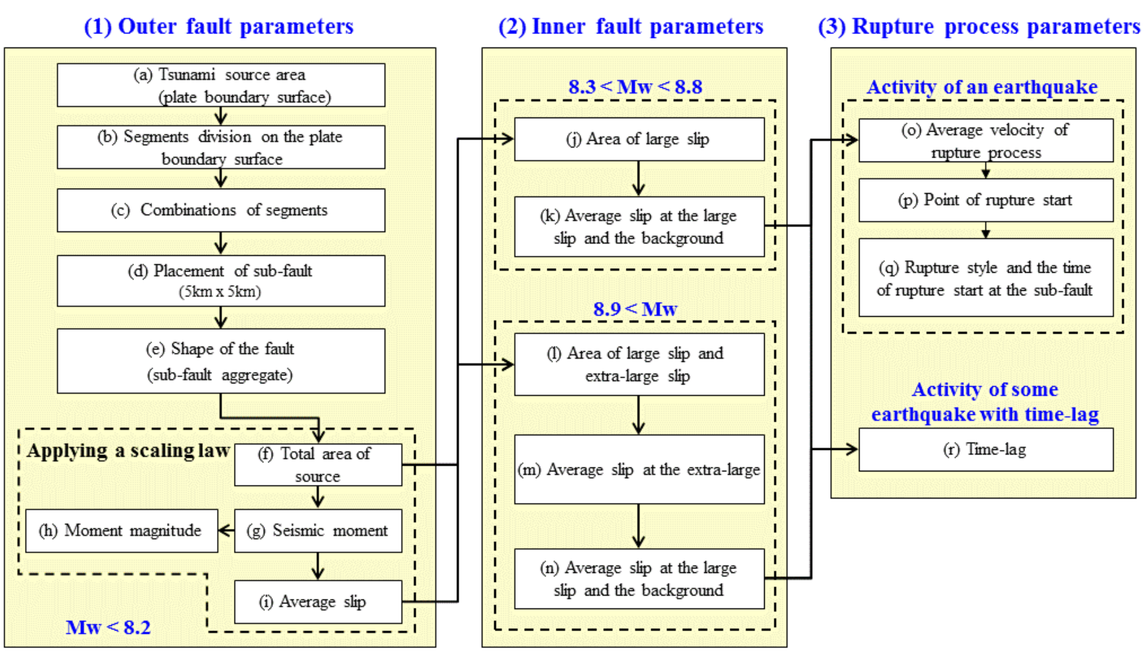


Fig. 1 – Specifying procedure of the characterized tsunami source model for inter-plate earthquakes [1]

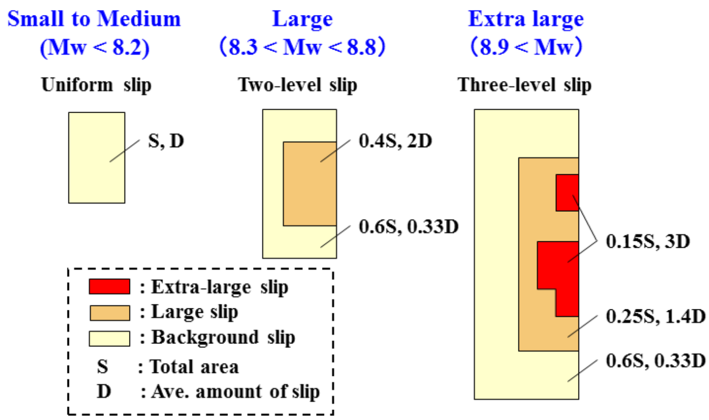


Fig. 2 – Specifying method of slip distributions for the inner fault parameters [1]

multi-segment rupture can be expressed by combination of several adjacent segments. The M_w and average slip (D) in the source area are estimated based on its area by applying the scaling law (M_o~S) [12].

In terms of the inner fault parameters, a rule for heterogeneous slip distribution is applied to the source area. Three classes of M_w are set in this rule as shown in Fig.2. A uniform slip distribution is assigned for small-to-medium-magnitude tsunamis of M_w 8.2 or less. A two-level heterogeneous slip distribution in a large slip area and a background area is set for large-magnitude tsunamis of M_w 8.3 to 8.8. And, a three-level heterogeneous slip distribution in the two areas above and an extra-large slip area is set for extra-large-magnitude of M_w 8.9 or more. The slip and area corresponding to each zone are assigned based on the above-mentioned characteristic analysis of the 2011 Tohoku Tsunami and other M_w 9-class tsunamis around the world. 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 large slip area is twice the average slip and its area ratio is 40% of the total area combining the extra-large slip area and large slip area.

With respect to the rupture process parameters, two patterns of rupture propagation, radial propagation at constant velocity and heterogeneous propagation with time delays between multiple segments, are considered for large-magnitude tsunami of M_w 8.3 or more.

3. Effects of the models for scenario tsunami on the PTHA method

3.1 Outline of PTHA procedure

The PTHA procedure [13] is outlined in Fig.3. The assessment starts from locating the evaluation point and selecting tsunami source areas by taking the impact of tsunamis on the evaluation point into account. In the next step, the tsunami source models (locations and magnitudes) are determined for future tsunami occurrences in the tsunami source area, and the earthquake activities models are determined based on the records of past earthquakes. These models (collectively called “tsunami generation model”) are used to estimate the frequency of tsunami occurrence. Meanwhile, tsunami propagation from the tsunami source to the evaluation point is represented in a model to calculate the tsunami height at the evaluation point (peak and trough).

Then, the uncertainties associated with the above tsunami generation model and tsunami propagation model are classified as aleatory uncertainties associated with the random nature of physical phenomena and epistemic uncertainties associated with insufficient knowledge and recognition.

Lastly, probability distributions of tsunami heights corresponding to all scenario tsunamis are aggregated while assuming a probability distribution in which a calculated tsunami height is the median value used to take account of the uncertainty associated with a tsunami propagation model. In this manner, a tsunami hazard curve (THC) is obtained to represent the relationship between the tsunami height (peak and trough) and the exceedance frequency (or, exceedance probability).

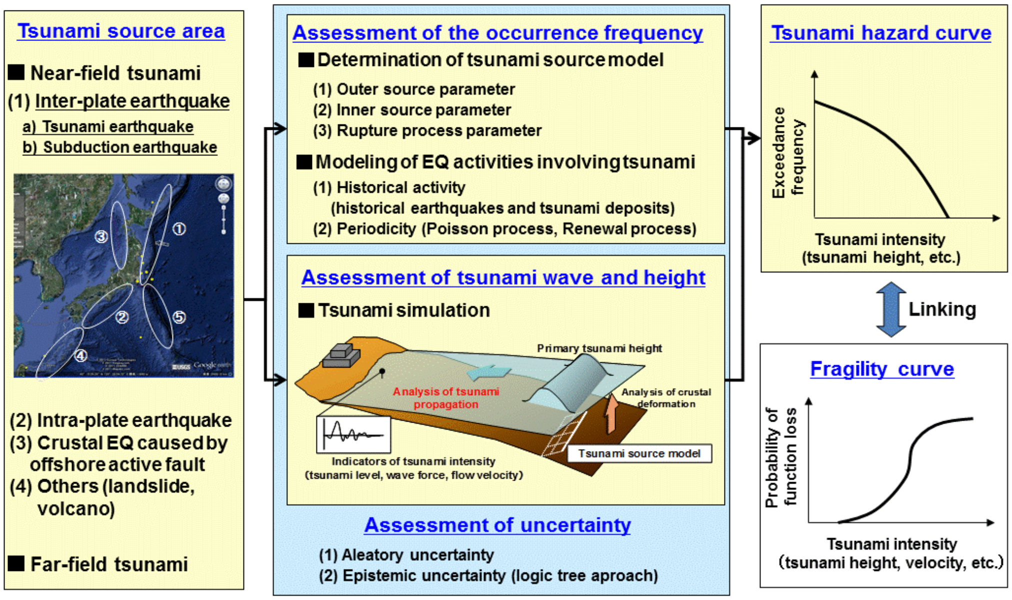
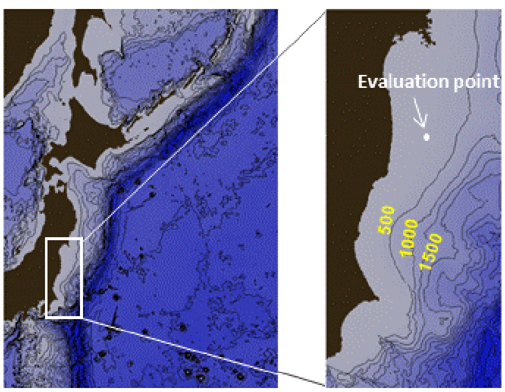


Fig. 4 – Outline of PTHA procedure [13]



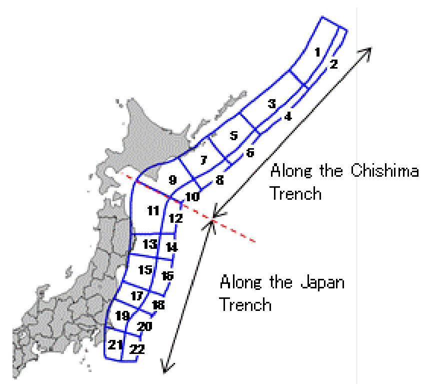


Fig. 3 – Location of evaluation point (depth of 150m) [2]   Fig. 5 – Tsunami source area and segments [2]

A practical way to confirm effects of the new model for scenario tsunami on PTHA is to compare the results using new and old models based on the condition of the day before the 2011 Tohoku Tsunami.

In other words, the new model is employed to assume earthquake tsunamis of unprecedented locations and magnitudes at the time of assessment while bearing in mind the lessons learned from the 2011 Tohoku Tsunami. In contrast, the old model is employed to assume earthquake tsunamis comparable to the largest one in the past in terms of the magnitude based on the knowledge available prior to the 2011 Tohoku Tsunami. The PTHA results using these two models should be compared with respect to that what extent does the difference in knowledge on tsunami assumption before and after the 2011 Tohoku tsunami affect PTHA results.

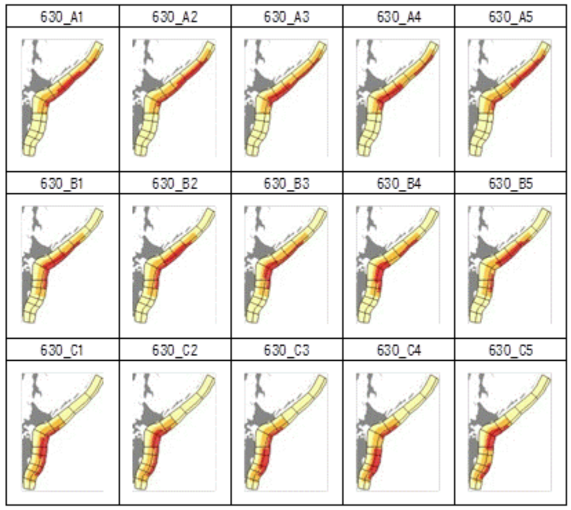
The following sections discuss conducting PTHA by selecting an actual evaluation point to confirm effects of the new model for scenario tsunami.

3.2 PTHA using the “new” model for scenario tsunami

3.2.1 Evaluation point and tsunami sources

The evaluation point was randomly selected from among points with a depth of 150 m off the east coast of Fukushima Prefecture (Fig.4). Considering the location of the evaluation point and the impact of tsunami, tsunami sources were assigned by selecting the largest source area among those established by public institutes.

Table 2 – Patterns of spatially heterogeneous slip distributions (example of No. 630) [2]



They consisted of tsunamis caused by inter-plate earthquakes along the Chishima-Japan Trench as shown in the review guidelines [14] of the Nuclear Regulation Authority and tsunamis caused by oceanic intra-plate (normal-fault) earthquakes that were rarely recorded yet but have a significant impact.

3.2.2 Determining the tsunami source models

The plate boundary along the Chishima-Japan Trench has a complicated three-dimensional structure. The plate boundary was divided into segments with reference to the locations and magnitudes of earthquakes in the past. The tsunami source area and the segments are shown in Fig. 5. Scenario tsunamis were set up by combining the 22 segments as shown in Fig.5. Total number is 93 models with M_w ranging from 7.9 to 9.6 by calculating from each area of scenario tsunamis.

The heterogeneous slip distribution was considered for each scenario tsunami in accordance with the procedure for applying the new model for scenario tsunami as described in Section 2.3. The tsunami height of the evaluation point was expected to be influenced greatly by the heterogeneous slip distribution of a large scenario tsunami of M_w 8.9 or more because of the vast area. However, it is difficult to predict the heterogeneous slip distribution of a future tsunami. Therefore, the heterogeneous slip distribution was included as one of the uncertainty factors for PTHA by preparing different patterns of slip distributions.

The different patterns of heterogeneous slip distributions are shown in Table 2, using the M_w 9.6 scenario tsunami (No. 630) as an example of M_w 8.9 or more. The red zones in the Table represent extra-large slip areas whereas orange zones represent large slip areas, and yellow zones represent background areas. There were three patterns of distributions of large slip areas in the north-south direction and five different patterns of distributions / shapes / numbers of extra-large slip areas for a total of 15 patterns of slip distribution.

3.2.3 Determining the modelings of earthquake activities involving tsunamis

PTHA requires calculation of the occurrence probabilities for all of scenario tsunamis. Considering the difference in the amount and quality of necessary information for calculating the occurrence probabilities of tsunamis when the past seismic activities were known or unknown, the available information was classified.

When the past seismic activities were known, the occurrence probabilities of earthquakes were calculated by applying the Brownian Passage Time (BPT) model (renewal process model) that considered the time elapsed from the latest seismic activity whenever the information of the average interval and the date of the latest seismic activity were available.

On the other hand, if the locations and magnitudes of the past seismic activities were unknown, their probabilities were basically calculated based on an empirical equation or extrapolation to supplement inadequate

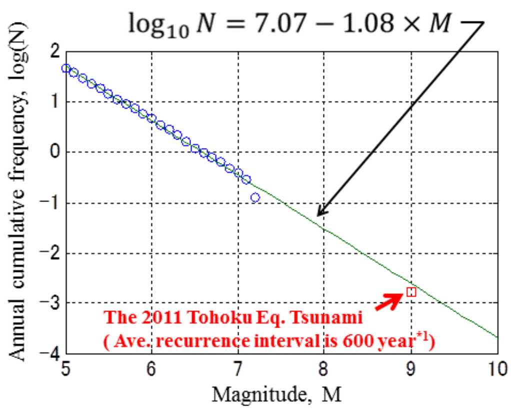


Fig. 6 – Relationship between the annual cumulative frequency and magnitude along the Chishima-Japan Trench (The ○ mark indicates an observation record, the straight line represents the G-R law, and the □ mark corresponds to the 2011 Tohoku Earthquake.) [2]

data. The Gutenberg-Richter (G-R) law [15] is known as an empirical equation of the magnitude and frequency of earthquakes representing the exponential decrease in the frequency of earthquakes against the increase in magnitude. The G-R law is determined by a regression analysis based on observation data mostly corresponding to small and medium earthquakes. There is insufficient observation data of large earthquakes. For this reason, in this study, the frequency of earthquakes of M_w 7 and greater is extrapolated from the G-R law.

Fig. 6 shows the G-R law, which was evaluated based on the earthquake observation data along the Chishima-Japan Trench (integrated epicenter data by the Japan Meteorological Agency). The horizontal axis in this figure represents M_w whereas the vertical axis represents the annual cumulative frequency. The regression analysis was based on data of earthquakes in the area observed from January 1, 1980 to February 28, 2011 with magnitudes ranging from M_J 5.0 to 7.0. The extrapolated G-R law based on the abovementioned conditions was almost consistent with the annual occurrence frequency of 2011 Tohoku Earthquake according to the long-term evaluation by the Headquarters for Earthquake Research Promotion.

3.2.4 Tsunami propagation model

A numerical analysis method is employed to simulate the propagation characteristics and runup characteristics of tsunamis from the source to the evaluation point in order to calculate the tsunami height at the evaluation point. In this study, the same analysis conditions were applied to the tsunami propagation analysis as those applied to reproduce the 2011 Tohoku Tsunami that struck Fukushima Daiichi and validate the characterization method for scenario tsunami [4].

The analysis was based on the non-linear long-wave theory. The equation of motion took the advection term and bottom friction term into account. A Manning's roughness coefficient of 0.025 was applied to the latter term. The horizontal eddy viscous term was not considered. The offshore bathymetry and onshore topography model used for the tsunami propagation analysis consisted of six regions from A to F. Calculation was performed with region A in deep water with a spatial grid interval of 1,350 m to onshore region F with an interval of 5.6 m by gradually reducing the interval by 1/3 and nesting the regions. The boundary conditions were open for region A on the offshore side, perfect reflection for regions from A to C on the onshore side. Regions from D to F were regarded as the runup boundary according to Kotani et al. [16]

3.2.5 PTHA results using the "new" model for scenario tsunami

Tsunami hazard curves (THCs) on the peak side of tsunami waves at the evaluation point are shown in Fig.7. The evaluation reference date for these results was March 10, 2011.

The logic tree was branched by assigning variation β for tsunami heights as a factor of epistemic uncertainty in the tsunami propagation model. In this case, branching was made with three values of 0.20, 0.25,

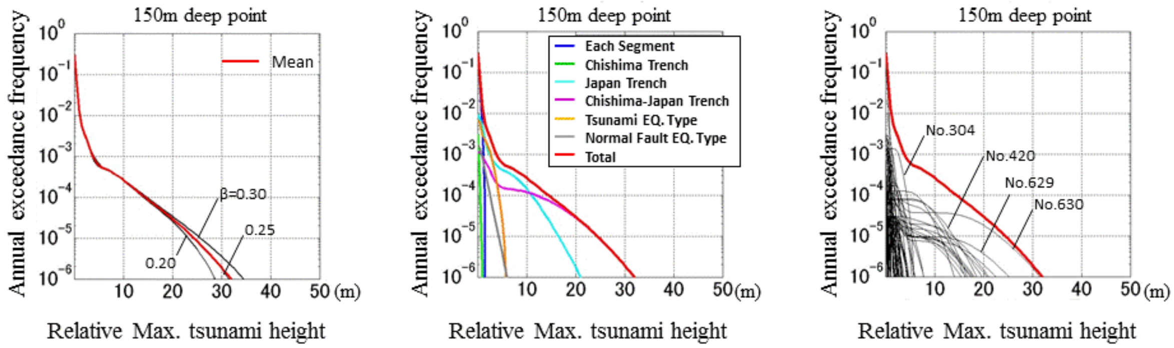


Fig. 7 – Tsunami hazard curves on the peak side using the new model for scenario tsunami [2] (left: all paths and average; center: seismic-area-specific; and right: tsunami-source-specific)

and 0.30 based on the validation results of the characterization method for scenario tsunami by Sugino et al. [1]. The weights were divided equally in the branching for variation β of tsunami heights.

The chart on the left side of the figure shows THCs corresponding to all paths and the average for the logic tree. The one in the center shows seismic-area-specific THCs. The one on the right side shows tsunami-source-specific THCs. In each chart, the horizontal axis represents the relative maximum tsunami height obtained by subtracting the ground deformation (upthrust is positive shift and subsidence is negative shift) from the peak at the evaluation point. The vertical axis represents the annual exceedance frequency. The chart on the left side of the figure shows THCs corresponding to all paths. They converged into three groups when the annual exceedance frequency drops below 10^{-4}. These three groups corresponded to the three values of variation β established for the tsunami propagation model. The conversion was the result of the dominance of the tsunami sources associated with inter-plate earthquakes in the Japan Trench, including tsunami earthquakes, given the annual exceedance frequency was 10^{-3}, and the dominance of the tsunami sources associated with simultaneous ruptures under the two island arcs of the Chishima-Japan Trench given the frequencies of 10^{-4} and 10^{-5}.

Comparison of tsunami sources on the right side of the figure suggested that tsunami earthquake No.304 was dominant among the tsunami source models when the annual exceedance frequency was 10^{-3} while tsunami source model No.630 was dominant among simultaneous ruptures under the two island arcs of the Chishima-Japan Trench when the frequency was 10^{-4} or 10^{-5}. On average, the relative maximum tsunami height corresponding to the annual exceedance frequency of 10^{-3} was roughly 4 m, whereas the relative maximum tsunami heights were about 16 m and 25 m respectively for the frequencies of 10^{-4} and 10^{-5}.

3.3 PTHA using the "old" model for scenario tsunami

3.3.1 Determining the tsunami source models

An old model for scenario tsunami was set up based on the knowledge available prior to the 2011 Tohoku Tsunami as a comparison in order to confirm effects of applying the new model for scenario tsunami to inter-plate earthquakes.

One of the main sources of knowledge on seismic activities along the Chishima-Japan Trench published prior to the 2011 Tohoku Tsunami is the long-term evaluation [17-19] on the possibilities of subduction-zone earthquakes by the Earthquake Research Committee (hereinafter "long-term evaluation"). In addition to the possibilities of earthquakes from a long-term perspective, the magnitudes of the next foreseen earthquakes were also estimated in the long-term evaluation. The magnitudes of earthquakes foreseen along the Chishima Trench at that time were considered that thier impacts were small on the evaluation point (off the east coast of Fukushima Prefecture). Therefore, the scenario tsunamis were estimated based on the long-term evaluation [17-19] of seismic activities from the Sanriku-oki to the Boso-oki (including the earthquake Miyagi-oki) along the Japan Trench.

Table 3 shows the magnitudes of the next foreseen earthquakes in each region as well as main fault parameters for the tsunami source model established based on the magnitude. As the Table indicates, the

Table 3 Long-term evaluation along the Japan Trench and scenario tsunamis [2]

Region No.	Long-term evaluation of Seismic activities around the Japan Trench		Scenario source model based on the Long-term evaluation				
	Region of Earthquake Occurrence	Magnitude of Next EQ.	Mw	Length (km)	Width (km)	Slip (m)	Remarks
1	Northern part of Sanriku-oki (M8 class)	Around M8.0	8.2, 8.3, 8.4	200*1	100*1	2.5, 3.5, 5.0	-
2	Close to the trench from north Sanriku-oki to Boso-oki (Tsunami earthquake)	Around Mt8.2	8.1, 8.2, 8.3	200*2	50*2	4.0, 5.6, 7.9	-
3	Close to the trench from north Sanriku-oki to Boso-oki (normal fault)	Around M8.2	8.4, 8.5, 8.6	200*2	100*2	3.2, 4.5, 6.4	-
4	Northern part of Sanriku-oki (M7 class)	M7.1~M7.6	-	-	-	-	Exclusion because of small influence to the target point
5	Middle part of Sanriku-oki	No evaluation	-	-	-	-	Exclusion because of Long-term evaluation
6	Close to the trench at southern part of Sanriku-oki	Around M7.7	7.9, 8.0, 8.1	200*3	50*3	1.8, 2.5, 3.5	-
7	Miyagi-oki	Around M7.5	7.7, 7.8, 7.9	49*4	130*4	0.9, 1.3, 1.8	-
6+7	Southern part of Sanriku-oki and Miyagi-oki	Around M8.0	8.2, 8.3, 8.4	283*5	71*5	2.5, 3.5, 5.0	-
8	Fukushima-oki	Around M7.4	7.6, 7.7, 7.8	92*6	55*6	1.1, 1.6, 2.2	-
9	Ibaraki-oki	M6.7~7.2	7.0, 7.3, 7.5	43*7	47*7	0.5, 1.5, 3.0	-
10	Boso-oki	No evaluation	-	-	-	-	Exclusion because of Long-term evaluation

magnitude of the next foreseen earthquake according to the long-term evaluation has a certain amount of variation, for example, it is referred to as approximately M 8.0, where "approximately" means a range of ±0.1. The models for scenario tsunamis were set up with the variation in mind. The magnitude of the earthquake denoted as M (M_J) was converted into M_w with the relational equation [20]. Then, the average slip D·(m) was calculated from the relationship [21] between M_J and the earthquake moment M_o·(N·m), and the relationship [22] between M_o and D.

Also, the old models for scenario tsunamis in each region were set up with rectangular fault shapes and uniform slip distributions. The variance in the magnitudes of earthquakes was accounted for by changing the average slip while maintaining the same fault shape. This study followed the assumption of the long-term evaluation used at the time that expected tsunamis earthquakes in any part of region 2 and by intra-plate (normal-fault) earthquakes in any part of region 3 close to the Japan Trench from north part of the Sanriku-oki to the Boso-oki [17].

3.3.2 PTHA results using the "old" model for scenario tsunami

Fig.8 shows THCs when the old model for scenario tsunami based on the long-term evaluation prior to the 2011 Tohoku Tsunami was applied. In this case, the logic tree was branched by assigning β with four values of 0.223, 0.300, 0.372, and 0.438 specified in the JSCE report [3]. The THCs were classified in the same manner as in Fig.7. On average, the relative maximum tsunami height corresponding to the annual exceedance frequency of 10^{-3} was roughly 2 m, whereas the relative maximum tsunami heights were about 3 m and 5 m respectively for the frequencies of 10^{-4} and 10^{-5}. Comparison of seismic-area-specific THCs demonstrated that the coupling of earthquakes of the southern part of Sanriku-oki and Miyagi-oki represented as region 6+7 was dominant when the annual exceedance frequency was 10^{-3}. As the frequency dropped to 10^{-4} then to 10^{-5}, the intra-plate (normal-fault) earthquakes in region 3 grew dominant.

3.4 Effects of the models for scenario tsunami on PTHA

A distinct gap between the average THCs in Fig.7 and 8 was noted in the range of annual exceedance frequency below 10^{-2}. That was to say, given the same annual exceedance frequency, the new model for scenario tsunami resulted in 2 to 5 times larger relative maximum tsunami height. Meanwhile, the relative maximum tsunami height was 6.9 m at the evaluation point (depth of 150 m) according to the reproduced analysis of the 2011 Tohoku Tsunami. The annual exceedance frequency of the relative maximum tsunami height of 6.9 m was less than 10^{-6} in Fig. 8 and approximately 10^{-3} in Fig.7. Thus, the frequency of such a tsunami was roughly 10^{3} times more probable according to the new model for scenario tsunami.

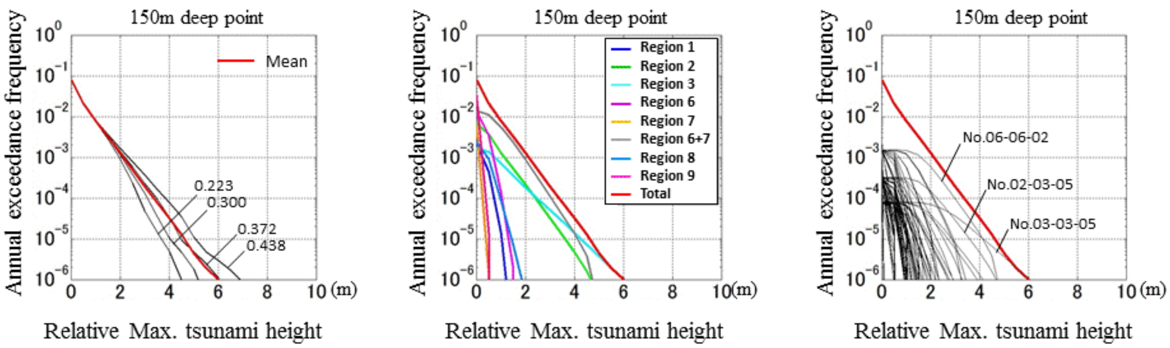


Fig. 8 – Tsunami hazard curves on the peak side using the old model for scenario tsunami [2] (left: all paths and average; center: seismic-area-specific; and right: tsunami-source-specific)

Such distinct effectiveness of the new model for scenario tsunami clearly owes to the tsunami assumption being unconstrained by the largest magnitude of earthquakes in the past. This result implies that the outcome of PTHA depends on the experience and knowledge built up over time.

4. Summary

In pursuit of more advanced methodologies of PTHA for evaluating tsunami risks at NPPs, while taking into account of the experience from the 2011 Tohoku Tsunami, this paper presented a unique application of a new model for scenario tsunamis by considering the possibilities that future tsunamis may exceed the largest recorded magnitude in the past.

The characterization method for scenario tsunami by Sugino et al. [1] was applied to present practical examples of the assumed tsunamis caused by inter-plate earthquakes along the Chishima-Japan Trench. Furthermore, PTHA was conducted with arbitrarily chosen evaluation points off the eastern coast of Fukushima Prefecture to confirm the effects of the new model for scenario tsunami in practice. The findings from these evaluations are presented as follows:

THCs before the 2011 Tohoku Tsunami were compared by applying the new and old models for scenario tsunamis. The difference of the THCs was significant in a range smaller than 10^{-2}(annual exceedance frequency) for the peak side of the tsunami wave.

Comparison of the annual exceedance frequencies of the relative maximum tsunami height estimated by the reproduced analysis of the 2011 Tohoku Tsunami demonstrated that the result based on the new model for scenario tsunami (about 10^{-3}) was roughly 10^{3} times greater than the result based on the old model for scenario tsunami (less than 10^{-6}).

The large difference in the annual exceedance frequencies based on the new and old models for scenario tsunamis and their THCs owed to tsunami sources that were anticipated in the area under the two island arcs of the Chishima-Japan Trench by taking into account their simultaneous ruptures, and in the area along the Japan Trench. This fact indicated the effects of the application of the new model for scenario tsunami.

PTHA extrapolates magnitudes and frequencies of future tsunamis based on scientific findings and experiences of the past. It is important to constantly update the assessment results by incorporating new findings and technologies for observation and analysis. Note that the assessment results in this paper are based on the condition of the day before the 2011 Tohoku Tsunami.

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