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## Development of a Probabilistic Tsunami Hazard Analysis in Japan

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### ABSTRACT.

It is meaningful for tsunami assessment to evaluate phenomena beyond the design basis as well as seismic design. Because once we set the design basis tsunami height, we still have possibilities tsunami height may exceeds the determined design tsunami height due to uncertainties regarding the tsunami phenomena.

Probabilistic tsunami risk assessment consists of estimating for tsunami hazard and fragility of structures and executing system analysis. In this report, we apply a method for probabilistic tsunami hazard analysis (PTHA). We introduce a logic tree approach to estimate tsunami hazard curves (relationships between tsunami height and probability of excess) and present an example for Japan. Examples of tsunami hazard curves are illustrated, and uncertainty in the tsunami hazard is displayed by 5-, 16-, 50-, 84- and 95-percentile and mean hazard curves. The result of PTHA will be used for quantitative assessment of the tsunami risk for important facilities located on coastal area.

Tsunami hazard curves are the reasonable input data for structures and system analysis. However the evaluation method for estimating fragility of structures and the procedure of system analysis is now being developed.

### 1. INTRODUCTION

It is meaningful for tsunami assessment to evaluate phenomena beyond the design basis. Because once we set the design basis tsunami height, we still have possibilities that tsunami height exceeds the determined design tsunami height due to uncertainties regarding the tsunami

phenomena. It is apparent that probabilistic risk assessment (PRA) gives an effective clue.

A probabilistic seismic hazard analysis (PSHA) is much more common than a probabilistic tsunami hazard analysis (PTHA). The PSHA is a methodology for estimating the probability that specified levels of earthquake ground motions will be exceeded at a given location in a given future time period by combining the probabilistic models of earthquake occurrence and earthquake-caused ground motion (WGCEP, 2002 [1]; Power et al., 2005 [2]). PSHA can give fruitful information for evaluation of PTHA.

Probabilistic tsunami risk assessment (PTRA) consists of estimating for tsunami hazard and fragility of structures and executing system analysis. Annaka et al. (2005) [3] proposed a method for probabilistic tsunami hazard analysis (PTHA), where a logic tree approach (e.g. Pacific Gas and Electric Company, 1988 [4]) was introduced to estimate tsunami hazard curves (relationships between tsunami height and probability of excess).

The objective of this report is to apply a method for probabilistic tsunami hazard analysis (PTHA) for Japan based on the achievement in the field of the PSHA. In this report, we select coast of Fukushima Prefecture, which is located at Northeast of Japan, as an example target site.

The result of PTHA will be used for quantitative assessment of the tsunami risk for important facilities located on coastal area. Tsunami hazard curves are the reasonable input data for structures and system analysis.

### 2. OVERVIEW OF THE METHOD

A probabilistic model for estimating tsunami hazard curves consists of a tsunami source model and a tsunami height for



estimation model. The logic tree model is an effective tool for estimation (Annaka et al.). It consists of tsunami source zones, size and frequency of tsunamigenic earthquakes, fault models used in numerical simulation, and standard error of estimated tsunami height. Numerical simulation rather than empirical relation is used for estimating the median tsunami height.

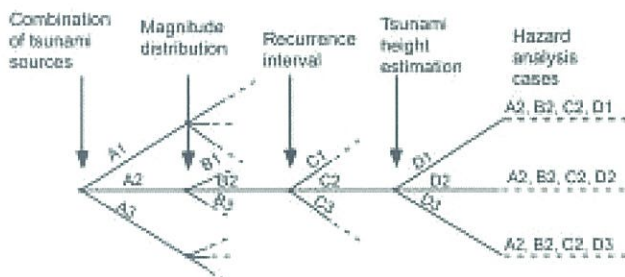
When we are considering the uncertainty in natural phenomenon, two kinds of uncertainty, aleatory and epistemic, are distinguished. Aleatory uncertainty is due to the random nature of earthquake occurrence and its effects. Epistemic uncertainty is due to incomplete knowledge and data about the earthquake process. A hazard curve is obtained by the integration over the aleatory uncertainties. And a large number of hazard curves are obtained by the combinations of the model parameters that represent epistemic uncertainty using the logic tree approach.

Weights of discrete branches that represent alternative hypotheses and interpretations are determined by the questionnaire survey, whereas those that represent the error of estimated value are determined based on the error evaluation. Examples of tsunami hazard curves are illustrated, and uncertainty in the tsunami hazard is displayed by 5-, 16-, 50-, 84- and 95-percentile and mean hazard curves.

### 3. LOGIC-TREE APPROACH

The logic-tree approach is used for evaluating uncertainty in tsunami hazard. When the uncertainty in natural phenomenon is considered in the PSHA, two kinds of uncertainty, aleatory and epistemic, are generally distinguished. Aleatory uncertainty is due to the random nature of earthquake occurrence and its effects. Epistemic uncertainty is due to incomplete knowledge and data about the earthquake process. A hazard curve is obtained by the integration over the aleatory uncertainties and a large number of hazard curves are obtained by the combinations of the model parameters that represent epistemic uncertainty using the logic-tree approach.

Figure\_1 shows an outline of the logic-tree used in this report. Combination of tsunami sources, magnitude



FIGURE\_1. Logic-tree representation of uncertain parameters

distribution of tsunami-generating earthquakes, recurrence interval of them, and tsunami height estimation procedure based on a numerical simulation are defined as the nodes in the logic-tree.

## 4. TSUNAMI SOURCE MODEL

### 4.1 SELECTION OF TARGET TSUNAMI SOURCE

The islands of Japan lie mainly on the Eurasia and Okhotsk plates. The Pacific and Philippine Sea plates subduct beneath the islands towards the west-northwest and northwest, respectively. The seismic activities in and around Japan are controlled by the interaction of the four plates.

The segmentation for assuming a source region is based on the idea of seismotectonics. In the Japanese archipelago and surrounding areas, various segmentation charts that show seismotectonics on the basis of varying viewpoints have been proposed. One of the widely used charts is the segmentation chart of the seismotectonics edited by Hagiwara (1991) [5] in which the segmentation covers over the entire sea area; this chart can be applied to the tsunami evaluation. The segmentation chart of seismotectonics edited by Hagiwara (1991) was compiled using comparatively large tectonic segments on the basis of topographical, geological, or geophysical similarities. In this report, not only tsunami source along trenches but also inland shallow earthquake in continental plate are considered.

As for trench area, which means plate boundary, the location of tsunami source can be specified. The tsunami source zones along the coast of Northeast Japan in Figure\_2 are mainly identified from the fault models of historical large earthquakes generating significant tsunamis (Tsunami Evaluation Subcommittee, Submitting [6]). For evaluation on Fukushima, JTTs, JTNRs, JTS1, JTN2 and JTN3 are dominant because of their location and magnitude. Therefore JTTs, JTNRs, JTS1, JTN2 and JTN3 are considered as near-field tsunami source zones in this report. Among the circum-Pacific distant tsunami sources, the tsunami source zones in Figure\_3 are selected because the impacts of their tsunamis on the Japanese Northeast coasts are predominant.

### 4.2 SETTING CONDITIONS FOR PLATE BOUNDARY

The logic-tree models are made for the combination of tsunami source zones and the size and frequency of earthquakes for each zone. Some examples of nodes in the logic-tree are illustrated as follows.

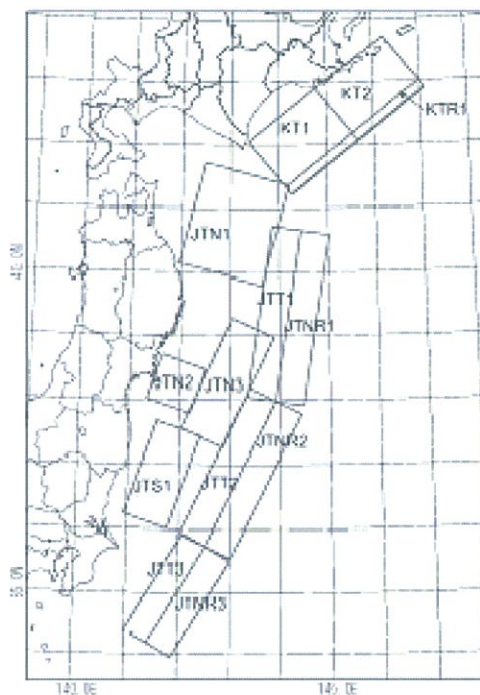
An example branch for the combination of active source zones is shown in Figure\_4. Historical tsunamis for JTTs are known only at JTT1 and JTT3; the one at JTT1 is



Meiji Sanriku Tsunami in 1896, and the one at JTT3 is Enpo Boso Tsunami in 1677. It may be assumed that tsunami earthquakes occur in all JTTs along the Japan trench, because all JTTs are located along similar subducting condition. On the other hand, it may be assumed that tsunami earthquakes occur in only JTT1 and JTT3, because no historical tsunami in JTT2 is identified. Subducting deformation may be absorbed by the activity in JTS1, JTN2

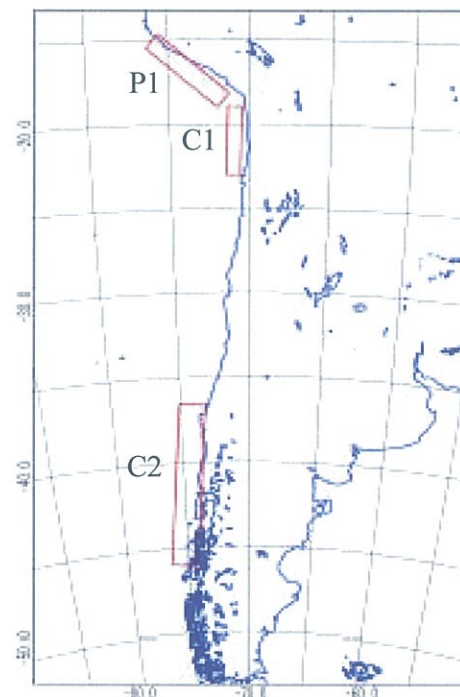
**TABLE\_1.** The maximum  $M_w$  in the past

		The maximum $M_w$ in the past	Year in which the tsunami occurred
Near-field Tsunami	JTT1	8.3	1896
	JTT2	There is no historical record. It may be assumed to be the same $M_w$ as JTT1.	
	JTT3	There is no historical record. It may be assumed to be the same $M_w$ as JTT1.	
	JTNR1	8.6	1611
	JTNR2	There is no historical record. It may be assumed to be the same $M_w$ as JTNR1.	
	JTNR3	8.2	1677
	JTS1	7.9	1938
	JTN2	7.7	1978
	JTN3	8.2	1793
Far-field Tsunami	P1	9.0	1868
	C1	8.8	1877
	C2	9.3	1960

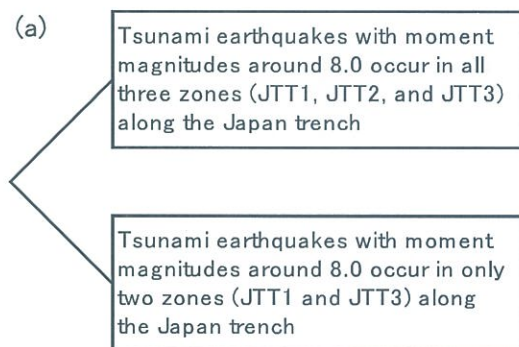


**FIGURE\_2.** Distribution of near-field tsunami source zones

and JTN3. Therefore, the branch shown in **Figure\_4** is considered. Characteristic tsunami-generating earthquakes are assumed to occur repeatedly in each tsunami source zone. The magnitude in each event can be different. In this paper, the bandwidth of magnitude is assumed to be either 0.5 or 0.3. Moment magnitude ( $M_w$ ) scale is used because  $M_w$  scale is considered to be most appropriate for tsunami generation. The maximum  $M_w$  in the past at each region is shown in **Table\_1**. An example branch for magnitude ranges



**FIGURE\_3.** Distribution of far-field tsunami source zones



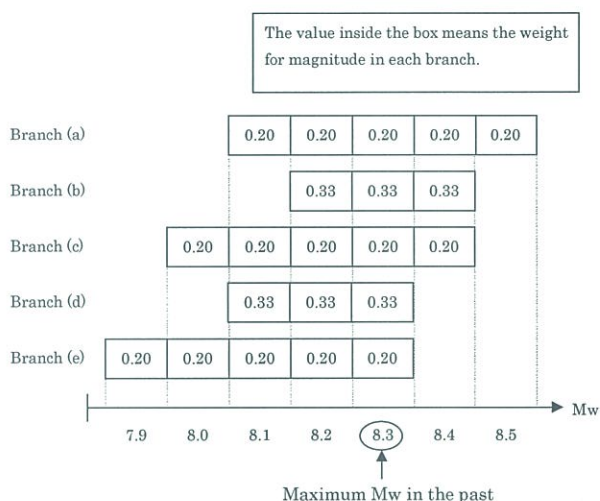
**FIGURE\_4.** Example of Nodes for Combination of Tsunami Source

is shown in *Figure 5*. The maximum magnitude for historical tsunamis in JTT1 is  $M_w=8.3$  of Meiji Sanriku Tsunami in 1896; however, there is a possibility the maximum  $M_w$  in the past is not the possible maximum  $M_w$  in JTT1. For the purpose of taking this possibility into account, branch (a) and (b) are set. Because the maximum  $M_w$  in the past is 8.3, the possible maximum magnitude is assumed  $M_w=8.5$  in this paper.

For evaluating instantaneous tsunami hazard, recurrence intervals are modeled by a BPT (Brownian Passage Time) distribution (Ellsworth et al., 1999 [7]). Uniform distribution is used for the magnitude-frequency distribution of characteristic earthquakes. An example branch for recurrence interval is shown in *Figure 6*. In this example case, Keicho Sanriku Tsunami in 1611 is assumed to be reverse faulting. Then historical tsunamis in JTNR1 are Meiji Sanriku Tsunami in 1896 and Keicho Sanriku Tsunami in 1611. The interval of these tsunamis is 285 years on condition that historical records are provided for these 400 years. Here a branch for recurrence interval can be set as 210, 285 and 380 years.

#### 4.3 SETTING CONDITIONS FOR INLAND EARTHQUAKE

As for shallow crustal tsunamigenic earthquakes in shallow sea area along the coast, it is difficult to specify the location of tsunami source. Thus the tsunami source zone along the coast of Fukushima prefecture shown in *Figure 7* is defined based on Hagiwara (1990). Tsunami source is assumed at anywhere inside the area, and the maximum  $M_w$  is set as 6.6. Distribution of tsunami sources with  $M_w=6.6$  in *Figure 7* was used for tsunami height estimation.

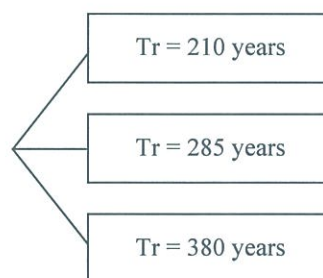


**FIGURE\_5.** Example of Nodes for Magnitude Distribution at JTT1

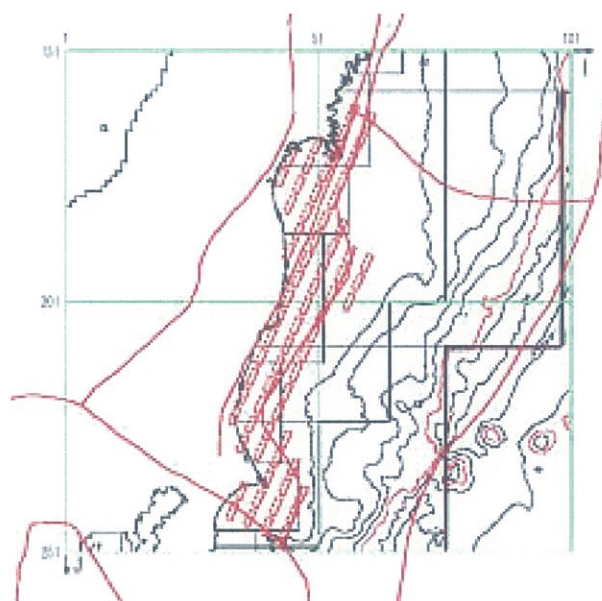
#### 5. TSUNAMI HEIGHT ESTIMATION MODEL

Numerical simulation would be better for estimating the median tsunami height than empirical relation. Fault models used for numerical simulation are determined by scaling relations from the optimal fault models of the historical tsunami-generating earthquakes. We can determine the optimal fault model with reproducing tsunamis from tsunami run-up height data for the sea area along the Japan and southern Kurile Trenches (Yanagisawa et al., 2005 [8]).

The logic-tree for tsunami height estimation is shown in *Figure 8*. Two methods, method 1 and method 2, are used for numerical simulation. For method 1, single fault model, a reference fault model, is used for given location



**FIGURE\_6.** Example of Nodes for Recurrence Interval at JTNR1



**FIGURE\_7.** Distribution of tsunami source zones in continentalplate (The line is defined by Hagiwara(1990))



and magnitude. For method 2, multiple fault models taking account of the variability of the parameters such as strike for a reference fault model are used. The distribution of tsunami height around the median value is assumed to be log-normal. Four values are selected as the branches for standard deviation of log-normal distribution. Parameter  $\beta$  is related with often referred as Aida's  $\kappa$  in Japan, as  $\kappa = \exp(\beta)$  (Aida, 1978 [9]). The log-normal distribution is truncated at either  $\pm 2.3 \beta$  or  $\pm 10 \beta$  (actually no truncation).

## 6. TSUNAMI HAZARD CALCULATIONS

By combining the tsunami source model and the tsunami height estimation model mentioned above, we can calculate tsunami hazard curves. Long-term stationary tsunami hazard as well as instantaneous tsunami hazard is evaluated. For evaluating long-term stationary tsunami hazard, a Poisson process is assumed. Generally for evaluating instantaneous tsunami hazard, the tsunami source zones are divided into two groups by the temporal models. One is modeled by a BPT distribution and another is modeled by the Poisson process. Uncertainty in the tsunami hazard is displayed by fractile hazard curves. The probability level for each fractile value can be determined by cumulative weight curve.

Weight of each hazard curve is given by the product of the weights of all nodes in the logic-tree. Weights (probabilities) of discrete branches represent alternative hypotheses and interpretations. In this report weights are estimated tentatively. For assessing tsunami hazard for a specified important facility, the weights should be determined more carefully by the questionnaire survey of tsunami and earthquake experts and the manner in which expert opinions are elicited and interpreted.

Variation of tidal stage is incorporated into the calculation by the convolution of tsunami height distribution.

## 7. TSUNAMI HAZARD CURVES

Tsunami hazard curves are evaluated for an example site at Fukushima, and uncertainty in the tsunami hazard was displayed by 0.05-, 0.16-, 0.50-, 0.84- and 0.95-fractile and mean hazard curves. The numerical tsunami simulation cases for near-field and far-field tsunami sources were about 1000 and 75 respectively.

The long-term stationary fractile and mean hazard curves obtained from near-field and far-field tsunami sources are shown in *Figure 9(a)* and those obtained from only near- and far-field tsunami sources are shown in *Figure 9(b)* and *\_(c)* respectively. And the instantaneous tsunami hazards for coming 50 years are shown in *Figure 9(d)*. The probability levels for the coming 50 years and the long-term are almost the same at this example site.

## 8. CONCLUSIONS

Tsunami hazard curves are the reasonable input data for structures and system analysis. However the evaluation method for estimating fragility of structures and the procedure of system analysis is now being developed. We are also studying tsunami hazard to be rationalized.

Probabilistic hazard analysis is commonly used for seismic hazard analysis, but rarely used for tsunami hazard. We applied a logic-tree approach to estimate tsunami hazard curves (relationship between tsunami height and probability of excess) and present an example for Japan.

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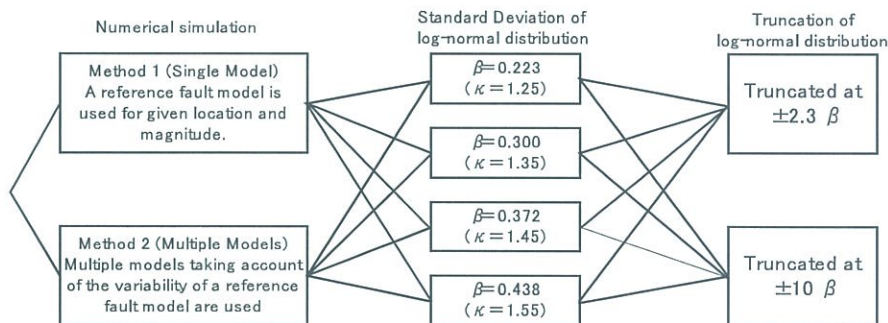
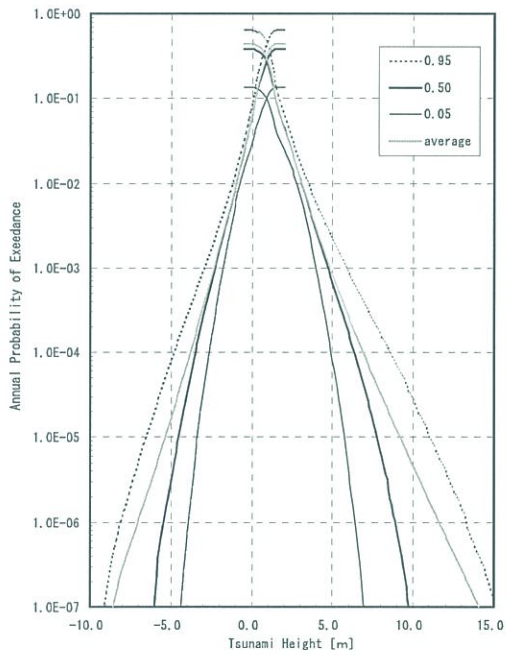
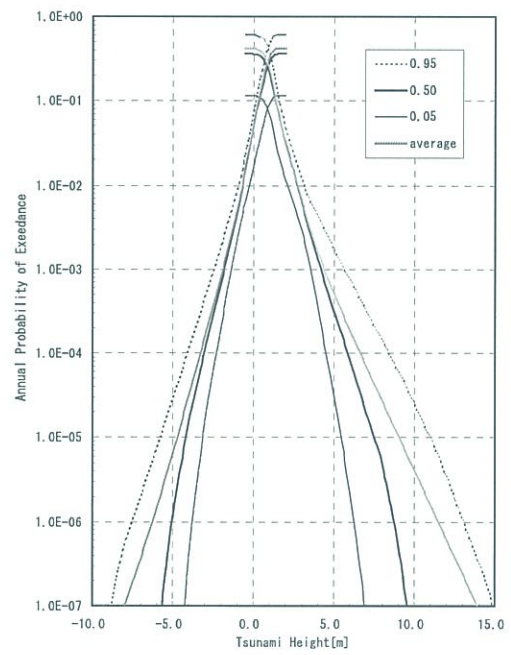


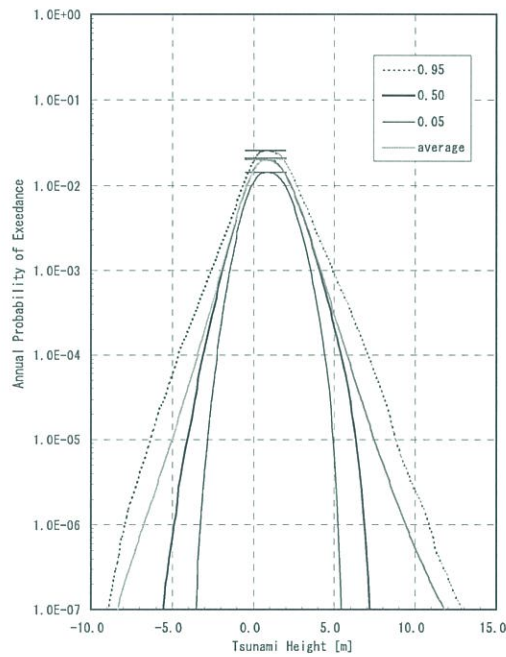
FIGURE 8. Nodes in logic-tree for tsunami height estimation



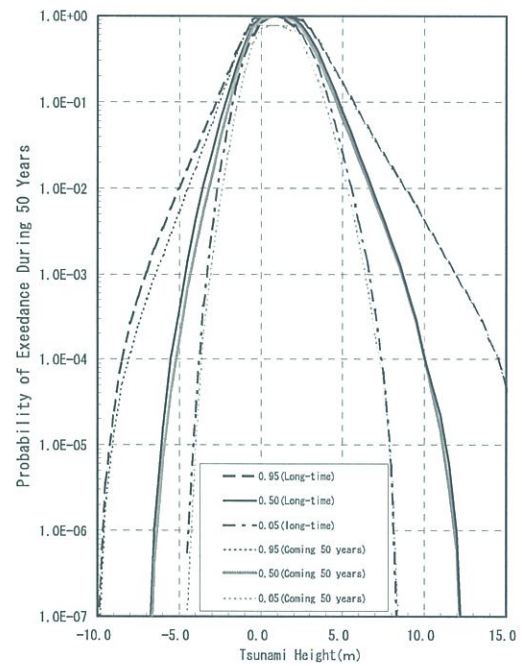
(a) Long-term: Near-field + Far-field



(b) Long-term; Near-field



(c) Long-term; Far-field



(d) Comparison of fractile hazard curves between the long-term and coming 50 years

FIGURE\_9. Example of probabilistic Tsunami Hazard Analysis



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