Tsunami PRA for Onagawa Nuclear Power Plant Unit 2 (1) Probabilistic Tsunami Hazard Assessment (PTHA)

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Abstract: The Tohoku Pacific Coast Earthquake that occurred on March 11, 2011 was the largest earthquake (Mw9.0) observed in Japan. The tsunami that it brought about was enormous inflicting damage across a broad swath of the country. In particular, at the Fukushima Daiichi Nuclear Power Plant, the tsunami entered the site and was the main factor causing a station blackout and the loss of safety system functions. The Government of Japan report (2011) [1] stated that measures should be taken to ensure that facilities maintain critical safety functions even in the event of tsunamis exceeding the design tsunami water level. Lessons learned included the implementation of risk management using Probabilistic Risk Assessment (PRA). Tsunami assessments and countermeasures for Onagawa NPP reflect the latest findings from time to time. At the time of Unit 1 construction (1960s-1970s), the expected tsunami height was estimated to be about 3 m based on a literature survey and interview survey. The site height was then set at 14.8 m based on discussions at an internal committee meeting that included experts. At the time of Unit 2 construction (1980s), the assumed tsunami height was revised to 9.1 m using numerical simulation technology, and protective measures for the slope of the site were implemented. Based on the lessons learned from 2011 off the Pacific coast of Tohoku earthquake and Tsunami, the assumed tsunami height was revised to 23.1 m and the 29 m high seawall was installed. In addition, to prepare for tsunamis that exceed the design basis, The tsunami PRA was evaluated and countermeasures against flooding of the site, such as the installation of watertight doors on the buildings. This section describes an overview of the Probabilistic Tsunami Hazard Assessment (PTHA), which shows the relationship between tsunami height and exceedance probability used in the PRA. PTHA is based on historical earthquake data. Uncertainty in the Earthquake area, Earthquake scale, Occurrence interval, and location are considered in a logic tree. In particular, the Earthquake area with a large impact on PTHA is assumed to be a giant earthquake with no previous record of occurrence. To cope with unpredictable cases based on the current knowledge, the variation of tsunami heights obtained from numerical simulations is considered as aleatory uncertainty.

Keywords: PTHA, Tsunami measures, Epistemic uncertainty, Tsunami earthquake

1. INTRODUCTION

The 11 March 2011 off the Pacific coast of Tohoku earthquake was the largest earthquake (Mw9.0) ever recorded in Japan, and the Pacific coast was severely damaged by the tsunami. In particular, the TEPCO's Fukushima Daiichi NPP was the main cause of the loss of all power and safety system functions due to the inundation of the site by a tsunami that exceeded expectations. The Government of Japan report (2011) [1] stated that measures should be taken to ensure that facilities maintain critical safety functions even in the event of tsunamis exceeding the design tsunami water level. Lessons learned included the implementation of risk management using Probabilistic Risk Assessment (PRA). The Sanriku coast, where the Onagawa NPP is located, has long been a region that has suffered major tsunami damage, including the 869 Jogan tsunami, the 1611 Keicho tsunami, the 1896 Meiji Sanriku tsunami, the 1933 Showa Sanriku tsunami and the 1960 Chile tsunami. Our first priority is to ensure the safety of nuclear power plants against natural phenomena, and we carry out tsunami assessments and tsunami measures, reflecting the latest knowledge from time to time. Onagawa NPP is located near the epicentre of the 2011 off the Pacific coast of Tohoku earthquake, and was hit by severe shaking and a tsunami approximately 13 m high, but was safely brought to a cold shutdown. The tsunami assessment and tsunami measures implemented so far at Onagawa NPP are presented (Chapter 2). Next, the tsunami countermeasures for tsunamis exceeding the design basis are presented using the PRA. his paper presents the details of the Probabilistic Tsunami Hazard Assessment (PTHA), which is the premise of the PTHA (Chapter 3).

2. TSUNAMI ASSESSMENT AND TSUNAMI MEASURES AT ONAGAWA NPP

2.1. During construction of Unit 1 (1960s-1970s)

For Unit 1 (BWR, 524 MW, 1984.6 Commercial operation started), a literature survey was conducted to identify tsunamis of large magnitude along the Sanriku coast in the vicinity of the power station and the tsunami heights were investigated. Interviews were also conducted in the Koyadori area near the site. Based on these results, the tsunami height was assessed to be around 3 m. An in-house committee including experts in civil engineering, geophysics and other fields was set up to incorporate professional perspectives in determining the site height, which is the basis for tsunami protection. The tsunami height was assessed to be around 3 m based on a literature survey, but 'Earthquakes with epicentres further south than the 1897 Meiji Sanriku tsunami and the 1933 Showa Sanriku tsunami. Tsunami heights from earthquakes such as the 869 Jogan and 1611 Keicho may be much larger.' The discussion was as follows. Empirical formulae and research papers on tsunami heights at the time were also discussed, and it was consolidated that 'tsunami protection should be based on the height of the site' and that 'the height of the site should be around 15 m'. Based on these results, the site height was set at 14.8 m and the height above ground level of the first floor of the main building and the important outdoor civil engineering structures was set at 15.0 m.

2.2. During the construction of Unit 2 (1980s)

In the 1980s, when Unit 2 (BWR, 825 MW, 1995.7 Commercial operation started) was planned, numerical tsunami simulation techniques were established by Aida (1977) [2] and others. Wave source models were also proposed for the 1611 Keicho tsunami, the 1896 Meiji Sanriku tsunami and the 1933 Showa Sanriku tsunami, for which trace heights were obtained at several locations along the Pacific coast of the Tohoku region. Tsunami deposit surveys were also carried out in the Sendai Plain (for details, see Abe et al. (1990) [3]) and a numerical simulation of the 1611 Keicho tsunami was carried out, revising the tsunami height from around 3 m to 9.1 m. Regarding tsunami countermeasures, the site height (14.8 m) was set to provide a margin against the rise in water level caused by tsunamis, but based on a review of the tsunami height, concrete blocks were constructed to a height of 9.7 m to prevent the slope of the site from being scoured by the tsunami (Figure 1). Furthermore, as a countermeasure against the risk of not being able to take in seawater to cool the reactor due to the drop in water level caused by the tsunami, a storage weir was installed in the channel to ensure a continuous supply of seawater (Figure 2).

Figure 1. Construction status of concrete blocks.

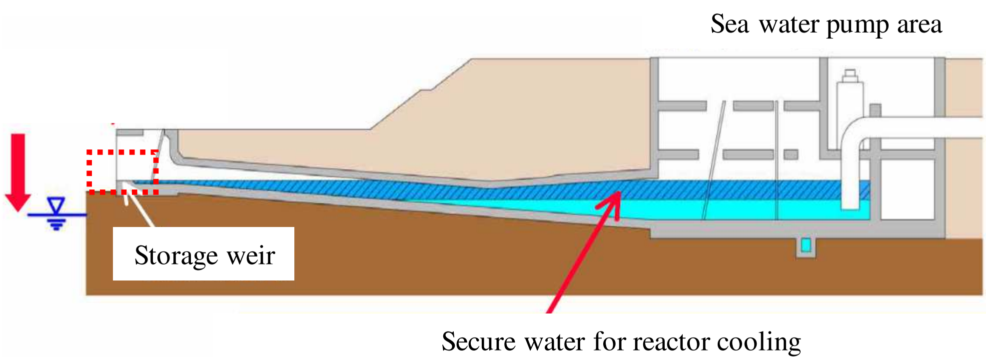

Figure 2. Measures against water level lowering due to tsunami

2.3. Reflecting the knowledge from the 2011 off the Pacific coast of Tohoku earthquake

The 2011 off the Pacific coast of Tohoku Earthquake (Mw9.0) caused up to 50 m of slip in the sea area in front of the Onagawa NPP due to the accumulation of slip remnants from the Miyagi-Oki Earthquake (Mw8 -class), which occurs repeatedly at intervals of about 37 years, as sticking (Satake and Fujii (2014) [4]). The 2011 off the Pacific coast of Tohoku earthquake provided a large amount of accurate observational data and many reports on the mechanism of the earthquake. The main new knowledge on tsunami assessment are: (1) Slip remnants from Mw8-class earthquakes accumulated as sticking and caused large slips, (2) Earthquakes with multiple interlocking segments, and (3) Contribution of slip near the trench axis to coastal tsunami heights. Based on these knowledges, a new tsunami assessment was carried out, the assumed tsunami height was revised to 23.1 m and the tsunami wall height of 29 m wall was installed. The tsunami wall height of 29 m was set in terms of maximum margin and structural feasibility of the tsunami wall to ensure further safety. The tsunami wall was a hybrid structure, combining the steel-pipe vertical wall (length approx. 620 m) and the cement-improved soil embankment (length approx. 180 m), taking into account the location characteristics surrounded by mountains on three sides and the access from the power station to the sea side (Figure 3). Seawalls can maintain their integrity against impacts by Superposition of tsunami and aftershocks and Tsunami debris (small vessels and vehicles) in addition to Seismic motion and Tsunami (Tsunami Wave Force).

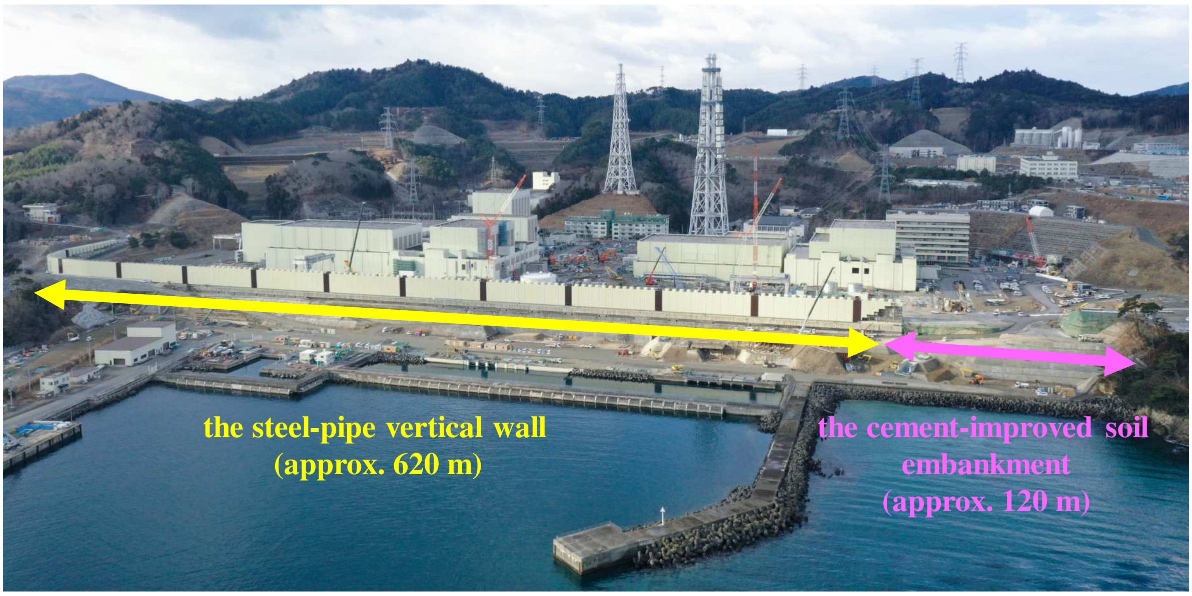

Figure 3. Panoramic view of the tsunami wall (taken in February 2023)

3. PROBABILISTIC TSUNAMI HAZARD ASSESSMENT

3.1. Summary

Probabilistic Tsunami Hazard Assessment (PTHA) assumes uncertainty and is divided into Epistemic uncertainty and Aleatory uncertainty. JSCE (2016) [5] and AESJ (2017) [6] present a method that assumes a logic tree approach to systematically handle these two uncertainties. This evaluation also used this approach. Epistemic uncertainty is uncertainty that is attributable to insufficient knowledge or awareness, such as the problem of whether or not there is an active faults or the range of magnitude that might occur, a solution to the problem may be finalized if research is advanced, but, currently, the issue is unpredictable, and it is taken into consideration as branches of logic tree and expressed by multiple tsunami hazard curves. Illustration of the logic tree is shown in Figure 4.
Aleatory uncertainty is uncertainty that is attributable to randomness inherent in a physical phenomenon and is regarded as unpredictable. In the present assessment, the probability density function was prepared by considering logarithmic standard deviation of estimation error in the tsunami height obtained from the tsunami simulation, and aleatory uncertainty was considered in the curve of one tsunami hazard. The logarithmic standard deviation of estimation error was set from the variation between the calculated tsunami

height from simulations of the reproduction of existing tsunamis and the historical tsunami height, with reference to JSCE (2016) [5].

Illustration of the tsunami hazard curve is shown in Figure 5. First, numerical simulations were performed for all branches of the logic tree to calculate the maximum water level ascent (median value) in front of the tsunami wall. Next, a probability density function was calculated to account for errors, and the probability of exceeding a certain tsunami height was calculated sequentially.

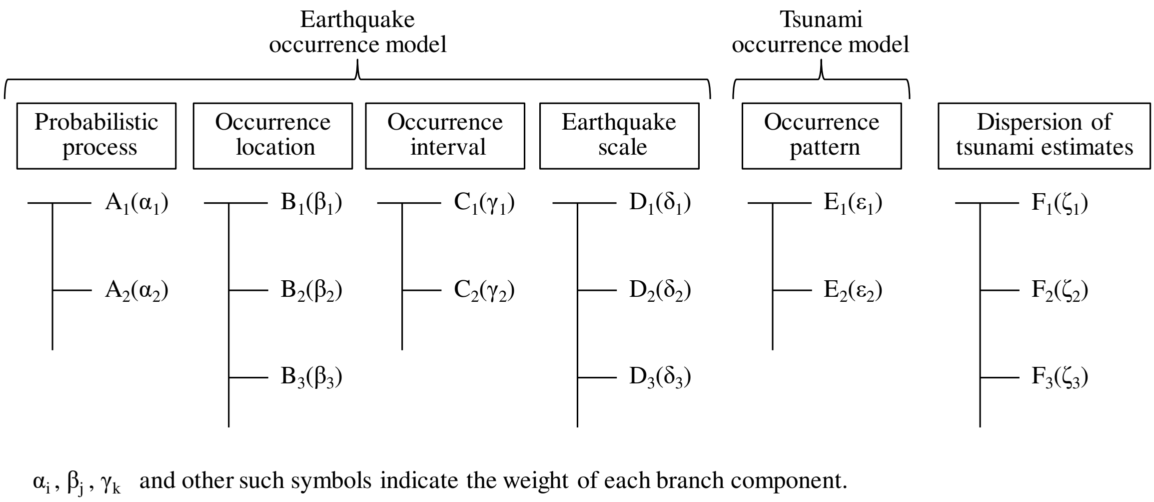

Figure 4. Illustration of the logic tree

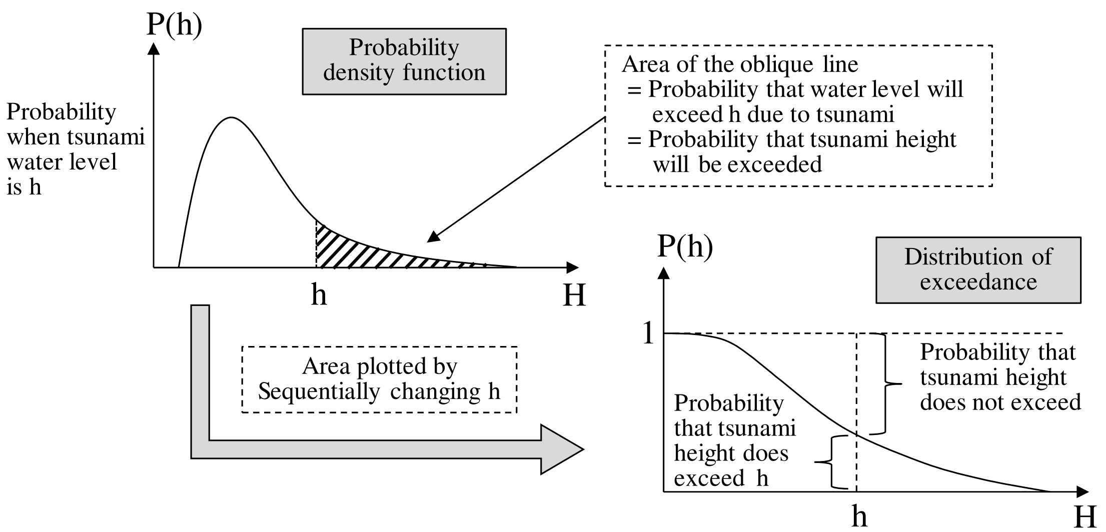

Figure 5. Illustration of the tsunami hazard curve

3.2. Tsunami considered

The assessment covered the area along the Japan Trench and the Kuril Trench affecting Onagawa NPP. Tsunami earthquake (code: JTT) and Normal fault earthquake (code: JTNR) with significant impact on the Sanriku coast were considered among the tsunamis that have occurred in the past along the Japan Trench and Kuril Trench. As the 2011 off the Pacific coast of Tohoku earthquake was a multi-segment interlinked earthquake, the earthquake was also included as a huge earthquake with no previous record of occurrence, such as the interlinked earthquake from off Nemuro-Oki to Iwate-Oki (codes : single (1), single (2), interlocking (1)+(2)).

The 2011 off the Pacific coast of Tohoku earthquake (codes : single (3)) was excluded because it has an almost 0% probability of occurring within the next 50 years (Headquarters for Earthquake Research Promotion (2019) [7]). The tsunami occurrence region is shown in Figure 6. The considered tsunamis are shown in Table 1.

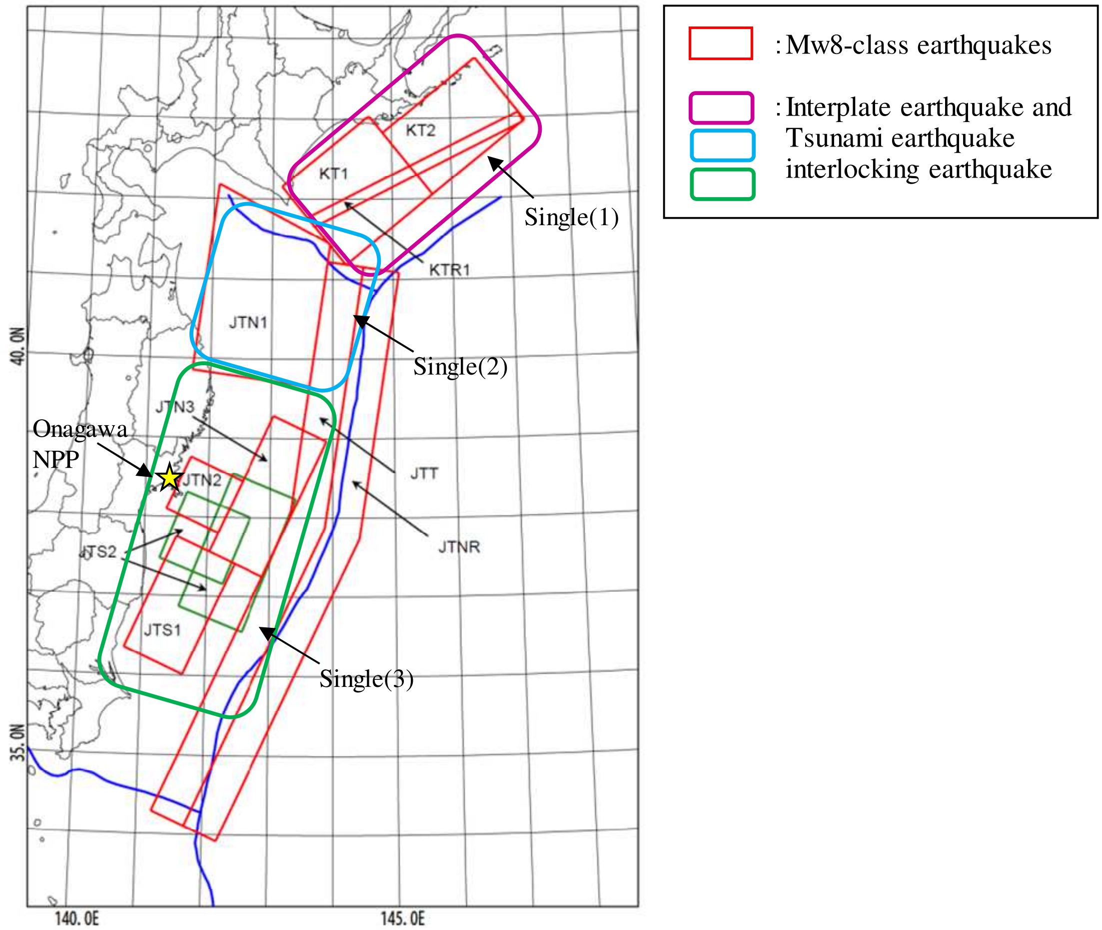

Figure 6. The tsunami occurrence region

Table 1. The considered tsunamis (code is as shown in Figure 6)

Code	Name of the tsunami	Examples of earthquakes	Notes
KT1	Tokachi-Oki	2003., 1952.	
KT2	Nemro-Oki	1973., 1894.	
KTR1	Intraplate earthquake within a subducting plate	1994., 1958.	
JTT	Tsunami earthquake	1896., 1677.	considered
JTNR	Normal fault earthquake	1933.	considered
JTN1	Northern part of Sanriku-oki	1968., 1856.	
JTN2	Miyagi-Oki	1978., 1936.	
JTN3	Southern part of Sanriku-oki	1897.	
JTS1	Fukushima-Oki	1938.	
JTS2	Jougan type	869.	
Single (1)	Nemuro-Oki to Tokachi-Oki	17th century.	considered
Single (2)	Northern part of Sanriku-oki	no occurrence	considered
Single (3)	Iwate-Oki to Fukushima-Oki	2011.	
interlocking (1)+(2)	Nemuro-Oki to Iwate-Oki	no occurrence	considered

3.3. Logic tree of Tsunami earthquake

Examples of tsunami earthquakes with significant impact on Onagawa NPP among the tsunamis considered are described. Tsunami earthquake is an earthquake in which the fault shifts more slowly than normal, resulting in a smaller tremor felt by humans but a larger tsunami. An example of a past earthquake is the 1896 Meiji Sanriku tsunami. In order to take into account the uncertainties intervening in Tsunami earthquake, information on the magnitude distribution of past tsunamis, the occurrence patten of earthquakes and the occurrence interval was collected and a logic tree was developed, as shown in Figure 7. A feature of the logic tree is that the occurrence pattern of the 1611 Keicho tsunami was taken into account as a branch. As the 1611 Keicho tsunami occurred approximately 400 years ago, there is a lack of data on tsunami heights and archival records to examine the mode of occurrence. Therefore, different researchers have different views on the mode of occurrence of tsunamis. Specifically, Tsunami earthquake and Normal fault earthquake were set as branch, as the Earthquake Research Promotion Unit (2019) [7] estimates Tsunami earthquake, while Aida (1977) [1] and Imai et al. (2012) [8] estimate Normal fault earthquake. Note that this bifurcation affects the average occurrence interval. Specifically, tsunami earthquakes occurred in 1896 and 1677, and only a normal fault earthquake occurred in 1933. If the 1611 Keicho tsunami was a tsunami earthquake, this means that tsunami earthquakes have occurred three times in the past. Conversely, for normal-fault earthquakes, the number of earthquakes is two, in 1896 and 1677. A weight (probability) needs to be set for the branch. The weights for “branches based mainly on differences in judgment,” such as the branch related to the occurrence pattern of the 1611 Keicho tsunami, were set based on the results of the expert questionnaire conducted by JSCE (2009) [9] and the weight distribution shown in Fig. 8, after hearing the opinions of experts individually. For “bifurcations based primarily on errors in the data-based estimates,” such as the average occurrence interval, the JSCE (2016) [5] was used as a reference for setting the bifurcations.

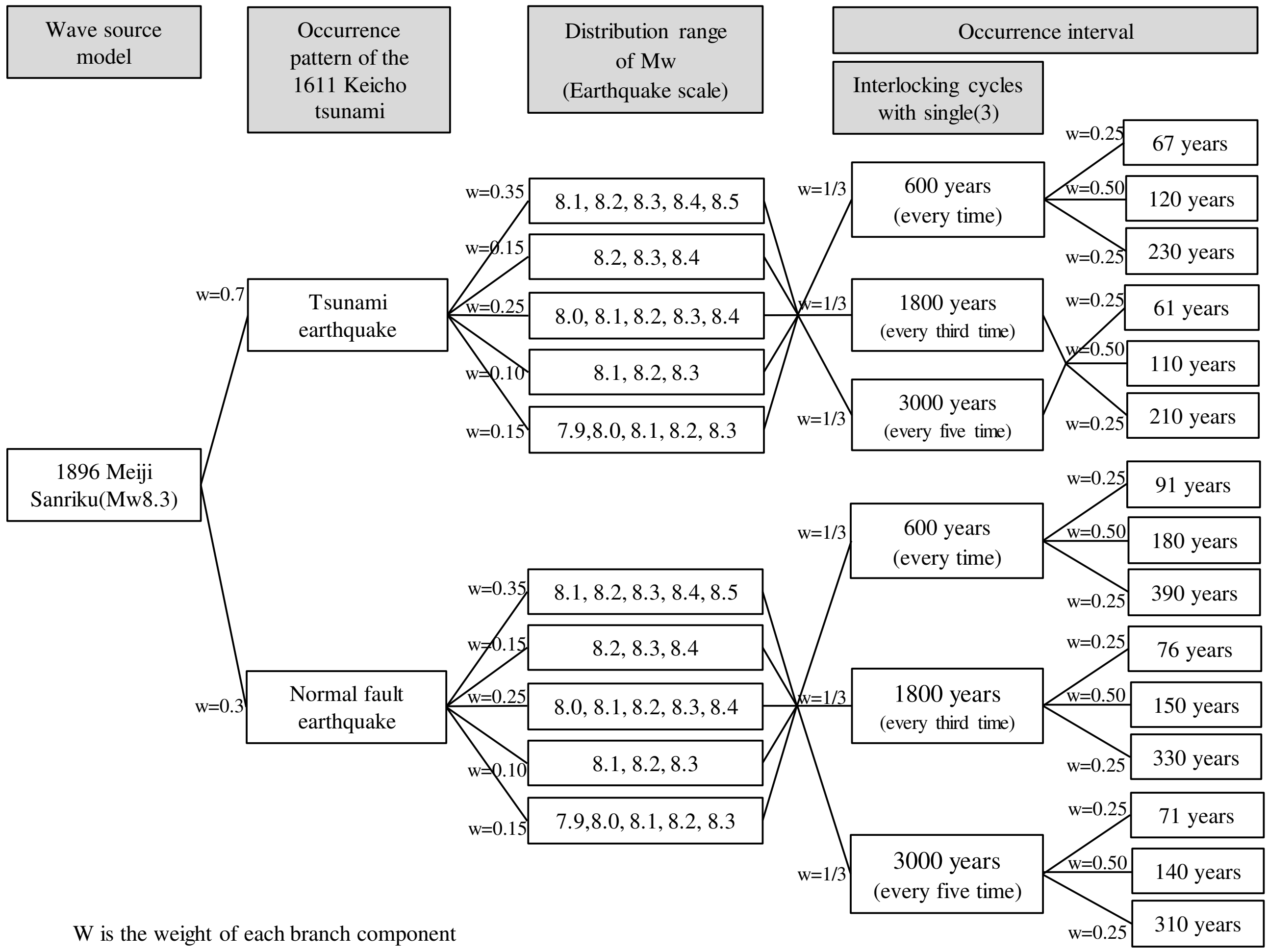

Figure 7. Logic tree of Tsunami earthquake (Consideration of epistemic uncertainty)

Weighting allocation (case of two branches)	Prerequisites
0.5 : 0.5	Case where a determination on weighting is difficult using currently available knowledge
0.3 : 0.7	Case where weight of one side is regarded as high if based on relevant data
0.1 : 0.9	Case where although the creation of branches is not regarded as necessary if based on relevant data, consideration is given to the feasibility of forming this into a branch

Figure 8. Allocation of weighting in cases not based on questionnaire surveys

3.4. Results

Tsunami hazard curves in front of the tsunami wall are shown in Figure 9. The tsunami hazard curve for all branches calculated for each tsunami occurrence region (The logic tree for tsunami earthquake is shown in Fig.7) was calculated by extracting 5000 samples using the Monte Carlo method. In addition to the overall hazard (arithmetic mean hazard), tsunami hazard curves are shown for each tsunami under consideration. For tsunamis contributing to the overall hazard (arithmetic mean hazard), in the range of 10^{-4} to 10^{-5} annual exceedance probability, they are normal fault earthquakes. On the other hand, in the range of annual exceedance probabilities lower than 10^{-5}, the contribution of tsunami earthquakes is higher, confirming that the contributing tsunami wave sources vary with the exceedance probability. Probabilistic risk assessments are carried out using tsunami earthquakes with large contributions in the range 10^{-6}~10^{-7}.

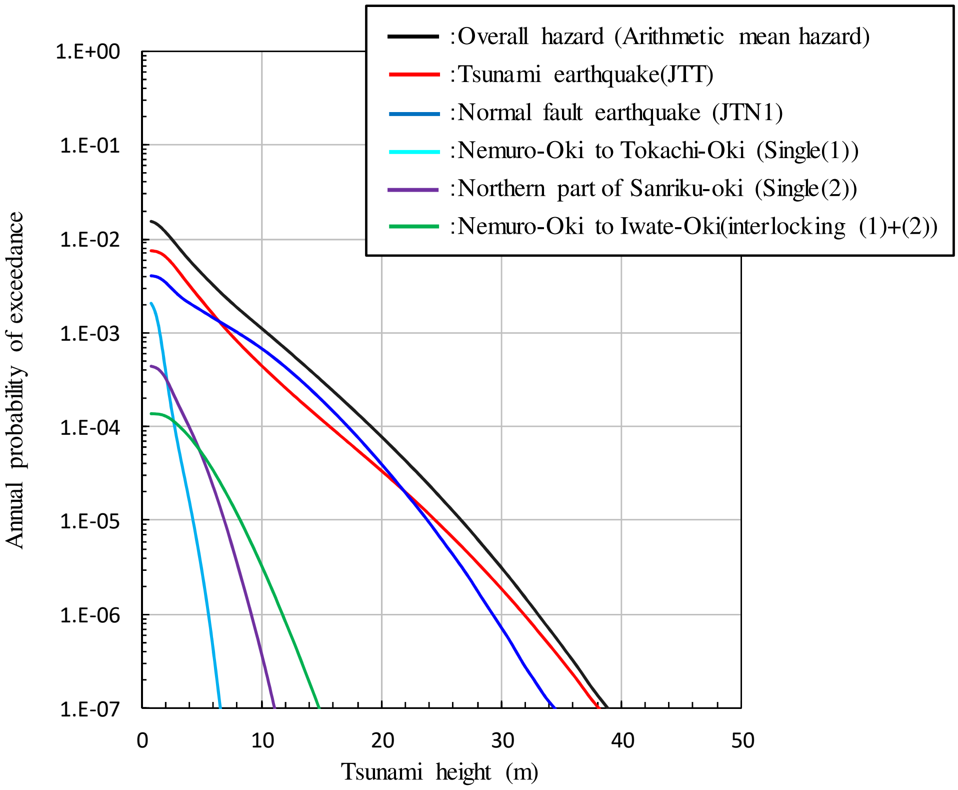

Figure 9. Tsunami hazard curves in front of the tsunami wall

4. CONCLUSION

Onagawa NPP was safely cold shutdown following the 2011 off the Pacific coast of Tohoku earthquake (Mw9.0), the largest in Japan's recorded history. This is because tsunami assessments and countermeasures in nuclear power plants have been carried out since the construction of the plants, reflecting the latest knowledge from time to time. To further improve safety measures, the assumed tsunami height was revised to 23.1 m based on the knowledge from the 2011 off the Pacific coast of Tohoku earthquake, and a 29 m high tsunami wall was installed. Tsunami countermeasures have also been implemented using PRA, and this paper presents an overview of the PTHA which it is based. PTHA considered epistemic uncertainty and aleatory uncertainty for tsunamis that have a significant impact on the tsunami water level of power plants, using a logic tree approach with reference to JSCE (2016) [5] and AESJ (2017) [6]. The results of the study show that the contribution of tsunami earthquake is highest in the range of probabilities lower than the annual exceedance probability of 10^{-5}.

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