Upgrading Tsunami PRA for Onagawa Nuclear Power Plant Unit 2

Atsushi Nishikimi[a*] , Hiroyuki Takahasih[a], Tsunehito Ootomo[a], Daisuke Sato[a] ,
Chikako Ogura[b], Yukihiro Kirimoto[c], Naoto Kihara[c]
[a]Tohoku Electric Power Co, Sendai, Miyagi, Japan
[b]Toshiba Energy Systems & Solutions Corporation, Yokohama, Kanagawa, Japan
[c] Central Research Institute of Electric Power Industry, Tokyo, Japan

Abstract: In order to take effective safety measures based on the vulnerability to tsunamis and the effectiveness of protection during the safety improvement phase after the restart of Onagawa Nuclear Power Station Unit 2, a method for upgrading the tsunami PRA model was studied. This paper presents the items and concepts examined for upgrade of the current tsunami PRA model.

Keywords: Probabilistic Risk Analysis **(**PRA), Tsunami flooding profiles, HRA

1. INTRODUCTION

In order to prevent core damage from tsunamis, Nuclear Regulation Authority requires the sea level rises due to tsunamis do not reach or enter the Nuclear Power Station (NPS) site as a design criterion. The Onagawa NPS has determined the design-basis tsunami of 23.1 m height and has taken tsunami countermeasures for prevention inflow through an opening connected to the sea. As one of the countermeasures, a seawall whose top level is 29 m above sea level was installed.

The current tsunami PRA model for Onagawa NPS Unit 2 adopts a conservative approach and evaluates the relationship between the tsunami height and the site inundation depth under which the water surface level reaches the lower end of the outer door of the reactor building, and the core is directly damaged by the unrestricted inflow of water into the reactor building. Based on the results of this conservative evaluation, the storage locations of mobile equipment were determined so that the water surface level does not reach the bottom of the outer door of the reactor building until the tsunami height of 33.9 m, which has an annual exceedance probability in the order of 10^{-7}(/year). In Onagawa NPP Unit 2, it has been confirmed that the frequency of core damage by tsunami has been reduced to about 10^{-7}(/rcy) by tsunami countermeasures even under such conservative evaluation conditions . In addition, the contribution ratio of tsunami to the total core damage frequency including internal and seismic events is kept low at less than 1%.

In the safety improvement phase after the restart of Onagawa NPS Unit 2, it is important to identify realistic risk triplet due to tsunami and to obtain risk information to discuss further safety measures by updating conservative assumptions of the current tsunami PRA model to realistic conditions.

This paper shows the items examined for upgrading the current tsunami PRA model of Onagawa NPS Unit 2. This examination referred to researches on tsunami fragility assessment by the Central Research Institute of Electric Power Industry (CRIEPI) and on human reliability analysis (HRA) for earthquake by the Electric Power Research Institute (EPRI), and practical tsunami PRA that have been carried out for PWR plants in Japan in the safety improvement evaluations. The outline of this paper is as follows. First, the models of severe accident countermeasures applied in the internal Level 1 PRA model will be incorporated into the tsunami PRA model. Next, the assessment of accident sequence is refined by evaluating the fragilities of watertight doors and through-hole seals and by considering the opening/ closing states of doors on the exterior walls of the reactor building. Furthermore, for the upgrade of the fragility assessment, probability distribution of the site inundation height is obtained by using numerical results of tsunami inundation simulations were used, so that the uncertainty of the site inundation height can be taken into account.

2. CURRENT TSUNAMI PRA MODEL

The tsunami PRA model of Onagawa NPS Unit 2 was built, based on the internal event L1PRA model.

For development of the tsunami PRA, tsunami-specific facilities were added to the internal event model. The equipment associated with the tsunami accident scenarios is shown in Figure 1. The main equipment that was added in the tsunami PRA is as follows.

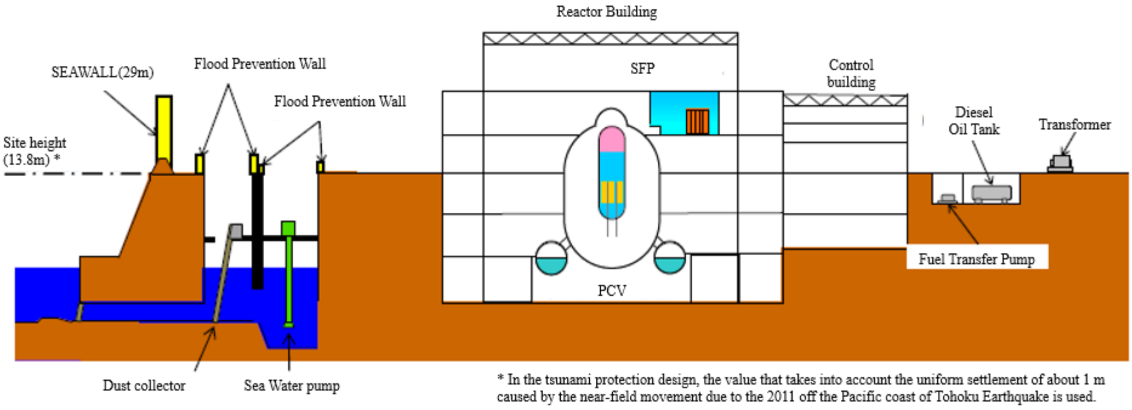
The SEAWALL (O.P.+29 m) was installed to prevent the approach of the design-basis tsunami to the facilities subject to the design criteria.

The Flood Preventing Wall was installed to prevent the inflow of water into the building from the intake channel connected to the sea.

Watertight doors and watertight seals of penetrations were installed at the routes and openings (doors, openings, penetrations, etc.) where flooding into the building may be possible.

Accident scenarios leading to core damage due to tsunami were analysed and the following assumptions were made in the evaluation.

- The reactor is operated at power output before the earthquake occurrence.
- The earthquake causes no damage to safety-critical buildings, systems, or equipment that could lead to loss of function, i.e., no direct impact on the plant by the earthquake.
- The tsunami is assumed to hit the plant after the earthquake.
- The watertight sealing measures in the underground openings of each building work, and there are no flooding from these openings.
- The doors on the exterior walls of the reactor buildings are opened, and functions of watertight sealing measures inside the buildings do not work. Therefore, if a tsunami flows into the building beyond the height of the bottom of the outer door of the building (hereinafter referred to as the "curve height"), the same floor of the building and the entire lower floor will be flooded at the same time. (Of course, this assumption is very conservative.)
- The Flood Preventing Wall around the auxiliary pump area is expected to work function to prevent the loss of all AC power.



* In the tsunami protection design, the value that takes into account the uniform settlement of about 1 m caused by the near-field movement due to the 2011 off the Pacific coast of Tohoku Earthquake is used.

Figure 1 The equipment associated with the tsunami PRA

For damage to equipment due to either submersion or tsunami wave force loading, the fragility curves of the equipment are assumed to be stepwise. The assumption for the fragility assessment of main equipment are as follows.

(1) The start-up transformer loses its function when the depth of flooding on the site exceeds its foundation height.

(2) The reactor auxiliary equipment cooling seawater pump and the high-pressure core spray auxiliary equipment cooling seawater pump will lose their function if the inundation depth on the site exceeds the height of the flood prevention wall around the auxiliary equipment pump area.

(3) The EDG fuel transfer pump is located underground and has a water-tight structure, but it loses its function when the inundation depth exceeds the height of the water-tight wall.

(4) The SSCs for mitigating the event in the building will lose its function due to submersion caused by flooding in the building.

The results of the current tsunami PRA are shown in Table1, and the main results are summarized as follows.

(a) Tsunami Category A (tsunami height O.P.+29 m to O.P.+33.9 m)

Inundation of the site starts when the tsunami height exceeds O.P.+29m. The start-up transformer, reactor auxiliaries cooling seawater pumps, high-pressure core spray auxiliaries cooling seawater pumps, and fuel transfer pumps are not affected by inundation of the site, but various transient events occur due to inundation of the turbine buildings, and "loss of external power supply", an event representing a transient event that results in the loss of functions of a wide range of mitigation systems, shall occur. The "loss of external power supply," which represents a transient event that results in the loss of a wide range of mitigation system functions, shall occur. Since there is no inundation into the reactor and control buildings, the mitigation system is sound.

- This classification is equivalent to a core damage sequence due to a combination of external power loss due to an earthquake and random failure of the mitigation equipment, and is included in the earthquake PRA, because all mitigation equipment is sound, although external power loss occurs.

(b) Tsunami Category B (tsunami height O.P. +33.9m~)

The depth of inundation on the site exceeds the curve height of the reactor and control buildings, causing massive inundation into the buildings, resulting in loss of function of multiple mitigation facilities and core damage. This leads to loss of function of multiple mitigation facilities and core damage.

- The CDF of this classification is 7.3×10^{-7} (/reactor year), which accounts for 100% of the total core damage frequency. This classification results in the loss of multiple safety functions and core damage due to massive flooding of the site and reactor building or control building.

Table 1 The results of the tsunami PRA

Tsunami classification	Tsunami height	Tsunami frequency (/year)	CDF (/rcy)
A	O.P.+29m ~O.P.+33.9m	3.8×10^{-6}	-
B	O.P.+33.9m~	7.3×10^{-7}	7.3×10^{-7}

3. METHODOLOGY FOR UPGRADING TSUNAMI PRA

3.1. Summary

In the current tsunami PRA, as shown in table 1, a tsunami exceeding 33.9m is considered a direct core damage event. However, this is a conservative setting because it assumes that the outer doors of the reactor and control buildings are open. In this upgraded tsunami PRA model, non-stepwise fragility curves will be implemented for relevant SSCs such as outdoor equipment and the impact of tsunami height on equipment will be detailed.

3.2. Fragility Assessment

3.2.1 Uncertainties On Tsunami Flooding Profile

Information on tsunami flooding profiles is required for the evaluation of realistic tsunami responses in fragility assessments of outdoor equipment and buildings. Tsunami flooding profiles are information on degree and impact of tsunami flooding in the site and include elevation of water surface or inundation depth. Tsunami flooding profiles depend on the type of tsunami, or tsunami source, and vary significantly from place to place even within a site. And furthermore, tsunami flooding profiles are predicted either numerically, analytically, or empirically. Thus, uncertainties on tsunami flooding profiles that should be considered are divided into tsunami variety, spatial variations, and numerical modeling. Uncertainty on numerical modeling is already considered in PTHA, and there is no need to consider this uncertainty in fragility assessment in order to avoid double counting of uncertainty. However, uncertainty on tsunami variety and spatial variations must be considered in the assessment of realistic tsunami responses.

The method proposed by Haraguchi et al.[1] has been applied to tsunami PRAs for PWR plants in Japan, and in the method, a simple approach is adopted for the consideration of uncertainties of tsunami flooding profiles. In the approach, the probability distribution of flooding elevation in a site is assumed to be expressed as the log-normal distribution. The median and the log-normal standard deviation is assumed to be the tsunami height just in front of the site and 0.3, respectively. This assumption means that the 99% value of the flooding elevation can be expressed as the twice of the design tsunami height, which is the permitted tsunami height in the safety assessment, taking into account for both the uncertainties on tsunami variety and spatial variations. Indeed, application of this model is reasonable to the sites which have no seawalls or seawalls with low top elevations because flooding elevations should be close to tsunami heights in front of the sites. However, for the site which have seawalls with high top elevations, flooding elevation should be much lower than a tsunami height when the tsunami height is lower or slightly higher than the seawalls. Thus, this model predicts much higher flooding elevations than a realistic situation, for such situations.

In order to solve this issue, using numerical results of tsunami inundation simulations is an effective approach. Some previous studies have proposed methods for evaluations of tsunami flooding profiles by considering uncertainties on tsunami variety[2][3][4]. Some of the proposed methods, tsunami hazard deaggregation is conducted, and dominant tsunami sources for each tsunami height are identified, by considering consistence with result of PTHA[2][4]. For the dominant tsunami sources, tsunami inundation simulations are carried out. However, in some cases, the number of tsunami sources which have non-negligible contribution to the hazard curve becomes enormous. In such cases, the number of tsunami source for inundation simulation has to be limited. However, the selection of tsunami source and usage of a limited number of inundation simulations involves uncertain operations. Kihara et al.[4] applies a graded approach concept for the selection of tsunami source and present the model of Takahashi et al.[5] for the consideration of uncertainty on the usage of tsunami inundation simulation for a limited number of tsunami sources.

In the model of Takahashi et al.[5], two kinds of uncertainty are separately modeled; the uncertainties of tsunami flooding profiles dependent on the tsunami source and representativeness of the selected tsunami source. Here, realistic tsunami flooding profiles are modeled as the lognormal distribution. The log-normal standard deviation for the uncertainties of dependence on the tsunami source is set as $\beta_{c1}^{r} = 1.0$ for inundation depths less than 5 m and $\beta_{c1}^{r} = 0.5$ for those greater than 5 m. This model also assumes that widths of the epistemic and aleatory uncertainties, β_{u1}^{r} and β_{r1}^{r}, are equivalent and thus given as $\beta_{u1}^{r} = 0.71$ and $\beta_{r1}^{r} = 0.71$ for inundation depths less than 5 m and $\beta_{u1}^{r} = 0.35$ and $\beta_{r1}^{r} = 0.35$ for inundation depths greater than 5 m. The model also assumes that the standard deviation for the uncertainty of the representativeness of the selected tsunami source is assumed as $\beta_{u2}^{r} = 0.9$ for inundation depths less than 5 m and $\beta_{u2}^{r} = 0.4$ for those greater than 5 m. This uncertainty is regarded as the epistemic uncertainty. Applying this model, uncertainty on tsunami variety for the evaluations of tsunami flooding profiles can be considered.

Uncertainty on spatial variation for tsunami flooding profiles can be explicitly considered in the approach with tsunami inundation simulations because the tsunami inundation depth and velocity at every grid point in a site can be numerically solved. On the other hand, because there are many watertight openings on important buildings, it is difficult to evaluate the fragility for each watertight opening in the evaluations of flooding occurrence from the openings into the buildings. Thus, it is reasonable to divide the site spatially into several partitions and evaluate the fragilities of watertight openings together in each spatial partition. For the fragility assessment, spatial variation of tsunami flooding profiles in each partition must be modeled. It would be a good approach to model the spatial variation by fitting a cumulative log-normal distribution to a histogram of inundation depths and obtaining the median and log-normal standard deviation.

3.2.2. Fragility Assessment of Buildings and Components

As described above, the probability density function of the inundation depth at the evaluation point is calculated by inundation simulation. An example of a tsunami inundation simulation is shown in Figure 2.

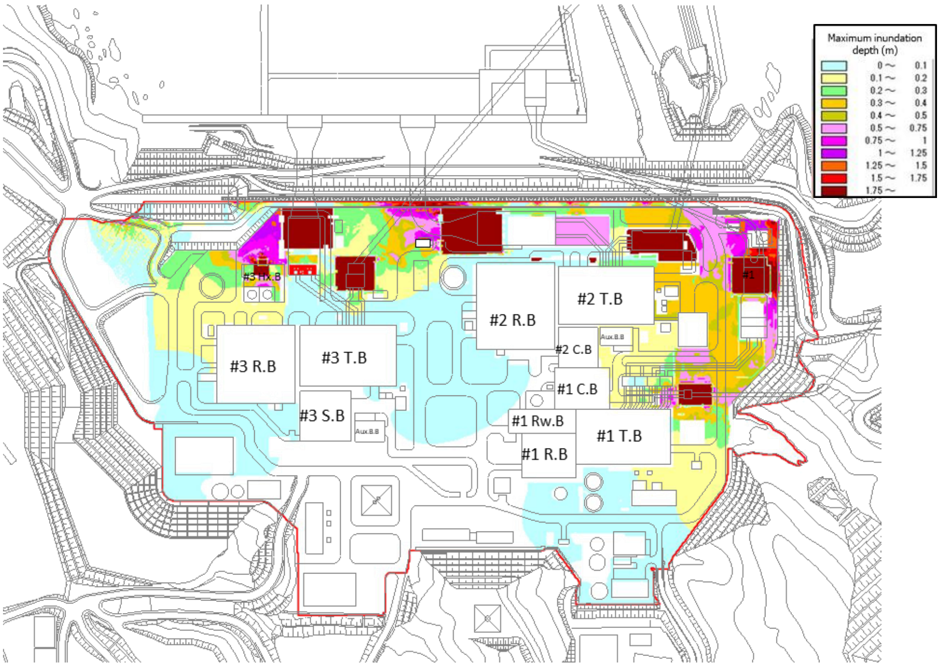


Figure 2 Example of maximum inundation depth on site (O.P.+33.9m Tsunami)

The fragility of the equipment is evaluated from the inundation depth distribution. For example, in the case of outdoor equipment, assuming that the equipment is damaged when the inundation depth reaches the equipment installation height, the damage probability is calculated from the log-normal distribution of the inundation depth at each tsunami height and approximated by a fragility curve (Figure 3).

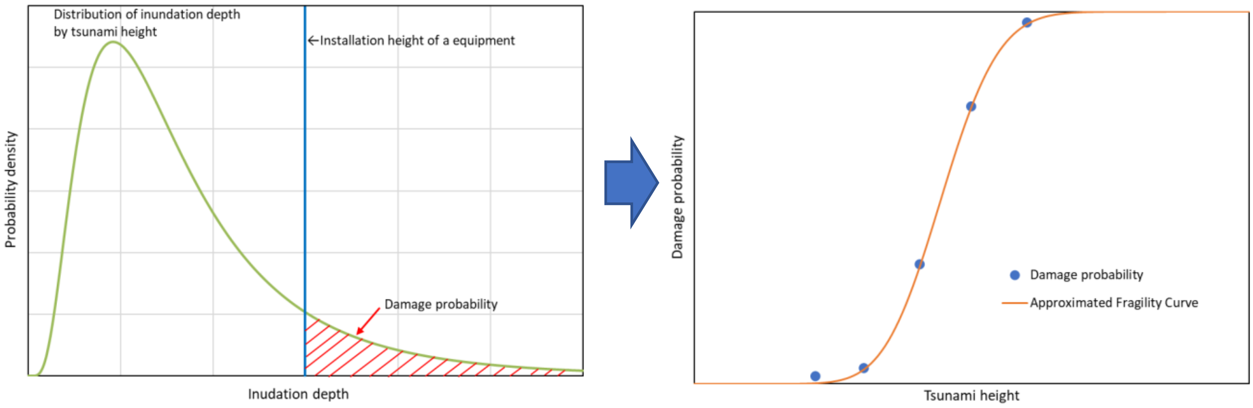


Figure 3 Schematic of fragility evaluation of outdoor installed equipment

3.4. ACCIDENT SEQUENCE ANALYSIS

3.4.1. Human Reliability Analysis

3.4.1.1 Damage State Consideration and Quantification

The impact of a tsunami event on the performance of operators is one important element in the development of a modern tsunami PRA in light of the Fukushima Daiichi accident. The effects of the tsunami on components and structures may adversely affect the performance of plant operator during the resulting severe plant conditions. These effects must therefore be considered when evaluating failure probability of operator actions in response to tsunami events.

In the tsunami PRA, tsunami hazards are split into bins so SSC failure probabilities can be calculated across the spectrum of the hazard (“hazard bins”). Damage state bins are distinct from hazard bins in that they define the break points at which the underlying context of the action changes substantially enough to impact the reliability of the action. The definition of hazard bins and their number and size (i.e., hazard span) is normally driven by quantification optimization. HRA damage states, on the other hand, are defined by grouping the plant SSCs by their level of expected impact on human performance if they fail (e.g., increased general workload, more difficult cognition, more challenging working environment, etc.). For quantification purposes, the HRA damage bins need to align with the tsunami hazard bins. Thus, the damage state bins provide the map between the human performance drivers or PSFs and the hazard bins, which represent levels of damage to the plant SSCs. In developing a tsunami HRA methodology applicable to Japan, it is necessary to define damage state bins based on the results of tsunami impact and fragility evaluation for individual plants in Japan.

Using the above plant-defined damage state bin and other factors including action location, time margin, cue, etc., screening quantification is performed. These factors are used to determine the screening Human Error Probabilities (HEPs) or multiplier to be applied to the HEPs evaluated in the internal event PRA. In this screening quantification, for example, if the time margin is not sufficient, the screening HEP is set to 1.0 because the operator action is always assumed to fail.. Detailed quantification of HEPs for the tsunami PRA is done for HFEs that are shown to be risk significant to the model following initial quantification with the screening quantification. For these HFEs, detailed analysis is performed for each plant-defined damage state bin. Finally, the impact of tsunami events on operator performance is evaluated by incorporating the HEPs calculated by screening quantification or detailed quantification into the tsunami PRA model.

3.4.1.2 The Watertight Doors Being Left Open When Workers Were Evacuating Before The Tsunami Strikes

In the Tsunami HRA, reference is made to significant human error events (HFEs) from the results of internal event level 1 PRA, as well as to the results of studies of external PRAs at other plants [6]. The HRA will also be improved by referring to the analysis methods and assessment examples in the NRRC HRA Guide [7], which emphasizes qualitative analysis. An HRA case specific to a tsunami event, the event of a watertight door being left open when workers were evacuating before the tsunami strikes is shown in bellow.

When analyzing flooding inside buildings during a tsunami, it is important to determine the building openings that serve as entry points. These are primarily considered in terms of the resistance to wave force of watertight doors and large item access points through fragility assessments. However, if a watertight door is manually opened due to human operation factors during an emergency response, it can become an inlet for seawater and have a major impact.

This HFE consist of "workers manually opening the watertight door during evacuation and not closing it" and "the operator becomes aware that the watertight door is open due to an alarm in the control room, and the operator moves to the watertight door and fails to close it".

Initially, based on the emergency manual, it was assumed that evacuation would take place through emergency doors No.1 to 5. However, interviews at the plant revealed that the doors in question had signs posted saying "Do not open in the event of a tsunami," and that evacuation routes No.6 to 9 would be used (Table 2). An outline of this route is shown in figure 2.

a) Failure to close watertight doors by workers during evacuation
There was no place in the reactor building where the evacuation paging could not be heard, and since it was repeated about twice and multiple people could hear it, evacuation behavior was certain to occur. For failure of the closing operation, "Omission error: Forgot to close" and "Commission error: Closing failure" were set, and the stress level was selected as High.

b) Failure to close watertight doors by operators

The dependency of the error recovery changes depending on the margin of time from the operator's recognition to the completion of the closing operation, and has a large impact on the HEP . Here, the margin of time (T_{Margin}) was evaluated in five stages from over 60 minutes (ZD: Zero Dependency) to 0 minutes (CD: Complete Dependency). Table 2 shows the results of total HEP for 30 minutes < $T_{Margin} \leqq$ 60 minutes , which is assumed in the base scenario. If a tsunami exceeding 10 m will arrive within 35 minutes of the earthquake, or if the shift supervisor determines that it is not possible to send an operator to the plant in order to ensure the safety of the operators, the HEP will be evaluated as 1.

Table 2 Qualitative analysis and interview results

Qualitative analysis steps	Main results
Assuming evacuation watertight doors and actions based on emergency manuals and blueprints	It is assumed that the watertight doors for evacuation in an emergency will be opened and closed in the emergency opening operation as shown in the diagrams No.1 to 5 below.
Confirm the validity of assumptions and actual equipment through interviews and plant walkdowns	Identified the actual evacuation route and the watertight doors (No.6 to 9) that were opened and closed, which were different from what was expected. No emergency opening operation was required.

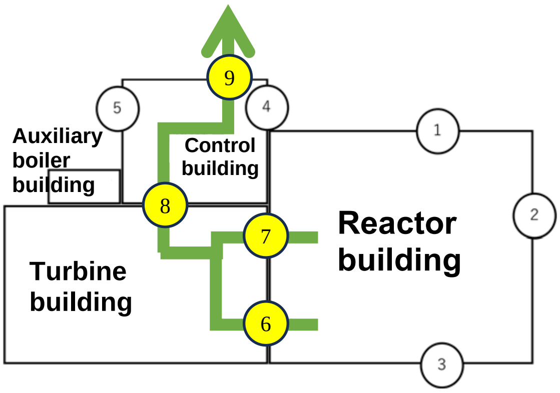


Figure 4 Evacuation rotation

Table 3 HEP estimate results

Conditions for "leaving the watertight door open"	Probability※
(1) Probability of workers staying in the building	0.1 (Tentative value)
(2) Failure of closing the watertight door by workers during evacuation	2.55×10^{-2}
(3) (2) At the time of occurrence, the operator fails to close the watertight door (recovery operation)	7.15×10^{-5}
Final HEP (accumulation above)	1.82×10^{-6}

※These values are the results of the current evaluation and will be reviewed in the future.

4. Conclusion

In this paper, upgrading methods to the tsunami PRA model are discussed in order to obtain more detailed information on the vulnerability to tsunamis and the effectiveness of protection during the post-restart safety improvement phase of Onagawa Unit 2. By applying these methods, the tsunami height classification is expected to be refined as shown in table 4. The core damage frequency will be calculated based on this tsunami height classification.

Through these efforts, realistic risks of Onagawa NPS will be evaluated and effective safety measures will be implemented.

Table 4 Assumption of tsunami classification obtained from tsunami PRA after upgrading

Tsunami Classification	**Initiate Event**	**CDF(ry)**	
		Reactor building Flooded	**Reactor building without Flooding**
A	Loss of Offsite Power	－*	－*
B	Loss of Offsite Power and Loss of Component Cooling Sea water	－*	－*
C	Loss of multiple mitigating Systems	－*	－*

*under estimate

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