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Standardized Procedure for Tsunami PRA by AESJ

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ABSTRACT

After Fukushima Accident (March 11, 2011), the Atomic Energy Society of Japan (AESJ) started to develop the standard of Tsunami Probabilistic Risk Assessment (PRA) for nuclear power plants in May 2011.
As Japan is one of the countries with frequent earthquakes, a great deal of efforts has been made in the field of seismic research since the early stage. To our regret, the PRA procedures guide for tsunami has not yet been developed although the importance is held in mind of the PRA community. Accordingly, AESJ established a standard to specify the standardized procedure for tsunami PRA considering the results of investigation into the concept, the requirements that should have and the concrete methods regarding tsunami PRA referring the opinions of experts in the associated fields in December 2011 (AESJ-SC-RK004:2011).

KEYWORDS

Probabilistic Risk Analysis (PRA), Tsunami, Hazard,

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1. Introduction

The Standards Committee (SC) and the Risk Technical Committee (RTC) of the AESJ has understood that the tsunami risk should be emphasized and developed with the highest priority, has established the Tsunami PRA Subcommittee to develop a standard for Tsunami PRA procedures. Japanese nuclear facilities are subject to the external hazard risk such as an earthquake and associated incidents with the earthquake. It is noticed that a comprehensive risk assessment related to both the internal and external events.

The accumulation of seismic research results has been incorporated in the seismic design of nuclear power plants and analytical methods have been improved accordingly and the seismic PSA (PRA) standard has been published in March 2007 [1]. The Japan Society of Civil Engineers (JSCE) issued a report that sets up the reevaluation of design tsunami height of the nuclear power plants [2]. JSCE considers the Tsunami appraisal method based on the probability theory from 2003. That result is issued “Methods for Probabilistic Tsunami Hazard Analysis,” in March 2009 [3]. Because this tsunami hazard evaluation technique should be reflected on the Tsunami PRA standard, the commissioner of JSCE joined a Tsunami PRA subcommittee.

AESJ will develop the external event PRA in four steps. The first step is Tsunami influence in consideration of “loss of off-site power (LOOP)”. The second step is interaction with seismic and tsunami. The third step is other external events (such as fire, flood and volcano). In the last step, evaluate the synthetic risk of the whole external events. This paper describes about the first step, Tsunami PRA standard.

2. Scope of Application of the Tsunami PRA Standard

The Tsunami PRA Standard defines the scope of application in one of the opening chapters. It covers the core damage scenarios in the commercial light water reactors in operation. The initiator of the accident is a tsunami that is caused by earthquakes. The nuclear power plant is in power operation condition when an earthquake occurs.

According to the earthquake and/or tsunami alarms, it is considered that the reactor is in a safe shutdown. The first important assumption is that the earthquake itself does not influence the safety

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function of the nuclear power plant (NPP). In other words, the safety-related structures, systems and components (SSCs) for the reactivity control, core cooling, and containment of the fission products are all intact. It is the premise, “no direct effect by earthquakes.” There is a certain time allowance between the occurrence of an earthquake and tsunami triggered by the earthquake reaches a plant. As the insertion of control rods after an earthquake requires only a short period of time, it may be thought that a sufficient time margin is left for the reactor to be shut down.

However, we consider one exception. The seismic capacity of the off-site power grid system is not so high as most of us expect in comparison to the safety-related SSCs. In the 2011 earthquake off the Pacific coast of Tohoku, the off-site power of the Fukushima Dai-ichi nuclear power plants were lost by the earthquake although the safety-related SSCs had successfully operated and the safety functions were intact. The fact tells us that some earthquakes that may cause a significant tsunami possibly deteriorate the off-site power supply system. Therefore, the standard requires a additional assessment of the tsunami risk on condition that the availability of the off-site power is lost before the tsunami attacks the NPP site.

3. Assesment Procedure of Tsunami PRA

Tsunami PRA is carried out in accordance with the assessment procedure shown in **Fig. 1**.

For **Surveys of the Configuration and Characteristics of the Plant and the Status of the Site,** the collection and analysis of plant-related information and a walk-down of the site and plant will be carried out.

For **Identification of Accident Scenarios**, an extended analysis of accident scenarios will be carried out using the information available, and then the accident scenarios will be screened to clarify the accident scenario to be assessed. In addition, the lists of buildings and components required for an Initiating Event Analysis and an Accident Sequence Assessment will be created.

For **Tsunami Hazard Assessment**, the method for handling uncertain factors in Tsunami Hazard Assessment will be examined. Subsequently, a Tsunami Generating Area Model and a Numerical Model of Tsunami Generation and Propagation will be defined to obtain a tsunami hazard curve that shows the relationship between tsunami height and probabilities (or frequencies) at which that height is exceeded. In addition, a Tsunami Running-up Analysis will be carried out.

For **Fragility Assessment of Buildings and Components**, buildings and components to be assessed and the damage modes will be determined. Subsequently, the evaluation methods to be used for capacity evaluation and response evaluation will be selected to evaluate realistic capacity and response. Thereby obtain fragility curves that show damage probabilities at which the response exceeds the capacity.

For **Accident Sequence Assessment**, an initiating event, an Accident Sequence Model, and a System Model will be defined, and subsequently, the accident sequence will be quantified based on those definitions.

The evaluation result of each step are fed back to the process required. In addition, the details of each of these assessments will be documented.

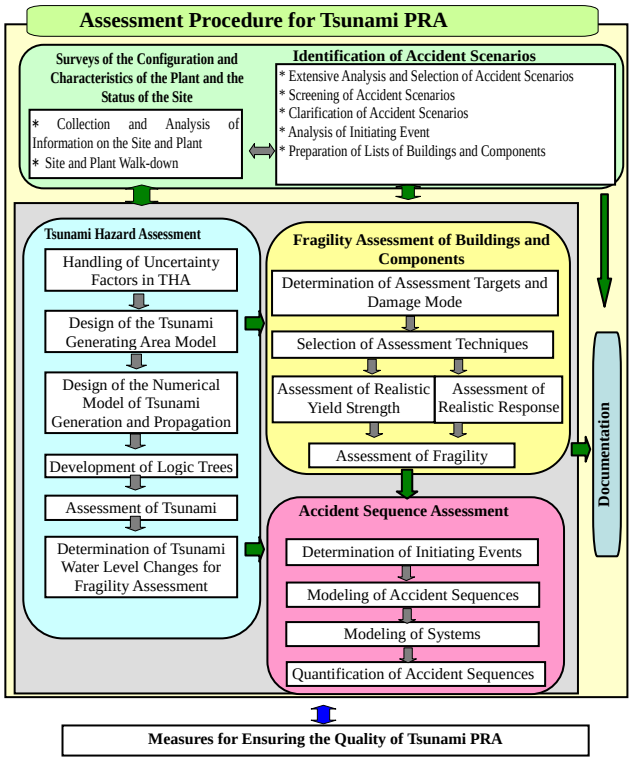

Fig.1 Assessment Procedure for Tsunami PRA

4. Surveys of the Configuration and Characteristics of the Plant and the Status of the Site

4.1. Collection and Analysis of Information on the Site and Plant

Required information on the plant and site will be collected, such as the latest status of the site, the design, the operation and the management. In addition, if multiple reactors share the same facilities flexibly (as seen in use of power supply), information on those facilities will also be collected. In addition, information on existing tsunami PRA, information on domestic and overseas tsunami disaster cases, and related literature, etc., will be also collected. When up-to-date knowledge, etc., that may have a significant influence has been published, various surveys will be carried out to collect such information as part of the recollection of information. The example of the information necessary for assessment and main information sources are shown in **Table.1**.

Table.1 Ex. The Information Necessary for Assessment and Main Information Sources

	Assessment work in PRA		Necessary information	Main information sources
1	Understanding of plant design and plant operation		Information on design and operation management that is thought to be necessary for carrying out PRA ・Basic specifications ・Structural characteristics of systems and facilities ・Characteristics of facility design ・Characteristics of plant configuration	1) Application for the reactor establishment license 2) Piping and instrument wiring diagrams 3) Electric system diagrams (lists of transmission systems, in-plant skeleton diagram, etc.) 4) Plant unit plot plans 5) Application for permission for construction work plan 6) System design specifications 7) Component design specifications 8) Safety preservation rules 9) Plant visiting 10) Discussions with design engineers and plant personnel 11) Structural drawings 12) Materials on emergency safety measures*
2	Tsunami Hazard Assessment		Information on the occurrence patterns of earthquakes causing tsunami events that may have an impact on the target site	1) Application for the reactor establishment license 2) Catalogs of active faults and historical earthquakes 3) Parameter handbooks of earthquake faults in Japan 4) Maps of earthquakes and regional geological structure 5) Results of long-term assessment by the Headquarters for Earthquake Research Promotion 6) Tsunami trace height catalogs and sediment databases 7) Marigrams 8) Water level fluctuation records 9) *Comprehensive List of Past Damaging Tsunami Events in Japan* (second edition) 10) Topographic data, such as submarine topographic maps and land elevation maps
3	Fragility Assessment of Buildings and Components		Information on the yield strength assessment and response assessment of buildings and components inherent in the plant	1) Application for the reactor establishment license 2) Application for permission for construction work plan 3) Standards for design and construction 4) Specifications for component design 5) Structural drawings 6) Component piping diagrams
4	Accident Sequence Assessment	a) Analysis of accident scenarios and classification of initiating events	Expected plant condition during tsunami events	1) The same information sources as those mentioned in Item 1 above 2) Previous PRA reports and their related reports
		b) Analysis of accident sequences ・Setting of success criteria ・Development of event trees	・Service conditions of systems, such as safety systems ・Realistic performance of systems ・Mitigation operation by operators	1) The same information sources as those mentioned in Item 1 above 2) Reports on realistic system performance assessment based on success criteria 3) Operation procedures manuals (manipulation procedures manuals for individual facilities, manipulation procedures manuals for accidents,

	Assessment work in PRA		Necessary information	Main information sources
		c) Modeling of systems	・Component failure modes and operation procedures appropriate to target plants	surveillance procedures manuals) 4) Periodic inspection instructions 5) Training programs for operators etc.
		c) Quantification of accident sequences	・Information that makes it possible to confirm the validity of assessment results	6) Previous PRA reports and their related reports 7) Procedures for post-tsunami actions

∗ Materials related to "On Implementation of Emergency Safety Measures at Other Nuclear Power Stations Based on Accident at Fukushima Dai-ichi and Dai-ni NPSs (published by the Nuclear and Industrial Safety Agency on March 30, 2011)"

4.2. Site and Plant Walk-down

An implementation team will be organized, the scope of implementation will be clarified, the points aimed at will be defined, and subsequently, walk-down of the site and plant will be carried out according to the implementation procedure.

5. Identification of Accident Scenarios

5.1. Extensive Analysis, Screening and Clarification of Accident Scenarios

All accident scenarios appropriate to tsunami events will be extracted and selected. Accident scenarios will be selected with consideration given not only to accident scenarios reflecting direct damage caused by a tsunami but also to accident scenarios reflecting its indirect impact. For accident scenarios reflecting direct damage, the following impacts of a tsunami will be taken into consideration in Table.2. The possibility of a tsunami running up along rivers and on land will be also taken into consideration.

Table.2 Influence to take into consideration as accident scenarios by direct damage

Impact of tsunami	Impact on buildings, components, etc.
Immersion and inundation of facilities due to flooding	Damage to dynamic functionality of facilities and damage to power generation and transmission functionality of electric facilities
Wave power and fluid force of tsunami	Structural damage of buildings and structures, components, etc.
Movement of seabed sand	Damage to functionality of seawater intake facilities
Drop in water level due to backrush	Damage to functionality of seawater intake facilities

- Considering Indirect Influence such as Floating Wreckage, Ships, Lumber etc
- Considering Tsunami's Influence to Accident Management Procedures, especially for Multi Reactor Site, e.g. Failure of Restoration from Station black out (SBO) by Tsunami

As something unique to tsunami events, loss of the functionality of components, etc., due to tsunami will have a severe, extensive influence on safety functionality, so this loss of functionality must be particularly clarified. For component damage, etc., that causes severe, extensive influence on safety functionality, the loss of functionality, etc., of instrumentation and control systems, emergency power supply systems, reactor component cooling water systems, and seawater systems must all be taken into consideration.

5.2. Analysis of Initiating Event

The initiating events will be analyzed and classified with the characteristics of the accident scenarios unique to tsunami events taken into consideration, and buildings, components and mitigation system.

5.3. Preparation of Lists of Buildings and Components

The lists of buildings and components that undergo the tsunami PRA are prepared based on initiating events analysis result. Information of fragility assessment and modeling the accident sequence are reflected in the revision of the above lists of buildings and components.

6. Tsunami Hazard Assessment

6.1. Procedure of Probabilistic Tsunami Hazard Assessment

Probabilistic Tsunami Hazard Assessment (PTHA) is necessary for evaluating tsunami hazard in consideration with many uncertainties in a process of estimating tsunami heights at coastal area from tsunami source models. Flow chart in accordance with the assessment procedures of PTHA is shown in **Fig. 2**.

PTHA is carried out from the data of active faults, historical earthquakes and tsunamis, etc., in considering uncertainties in numerical models of tsunami generation and propagation. Two kinds of uncertainty, aleatory and epistemic, are generally distinguished in the PTHA. Aleatory uncertainty is due to the random nature in earthquake or tsunami occurrence and its effects. Its nature can be determined from the variation in the ratios of observed to numerically calculated tsunami heights for historical tsunami sources. Epistemic uncertainty is due to incomplete knowledge and data about the earthquake process. Uncertainties in various model parameters and various alternatives about the PTHA model are treated as epistemic uncertainty. A hazard curve is obtained by integration over the aleatory uncertainties.

A large number of tsunami scenarios will be created by constructing tsunami generation model. Subsequently, the probability of earthquake occurrences will be calculated. In addition, a logic tree will be developed by specifying the branches of the logic tree. For each scenario, the tsunami heights at the site will be calculated by numerical simulation. The distribution of the tsunami heights around the median value is assumed to be log-normal based on the previous research on the distribution of the ratios between observed and numerically calculated tsunami heights.

By combining the tsunami generation model and the numerical model of tsunami generation and propagation, we calculate tsunami hazard curves. Both long-term stationary tsunami hazard and instantaneous tsunami hazard are evaluated. In the logic-tree approach, a tsunami hazard curve is obtained for each path of the logic-tree. Then the total number of tsunami hazard curves that can be calculated is equal to that of all paths in the logic-tree. Uncertainty in the tsunami hazard can be displayed by fractile hazard curves, as shown in **fig.3**.

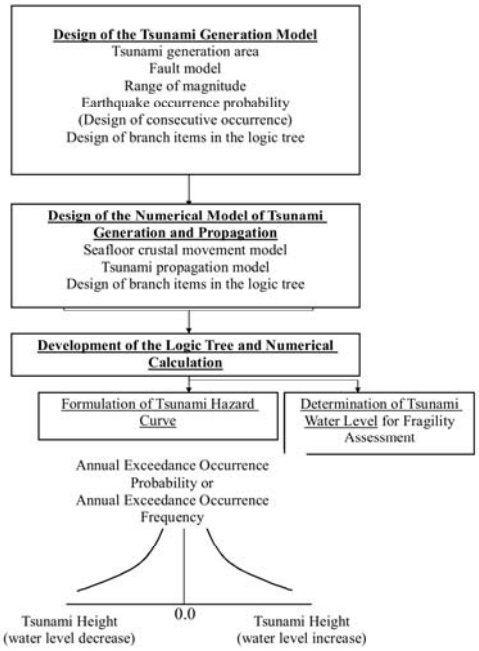

Fig. 2 PTHA Procedures

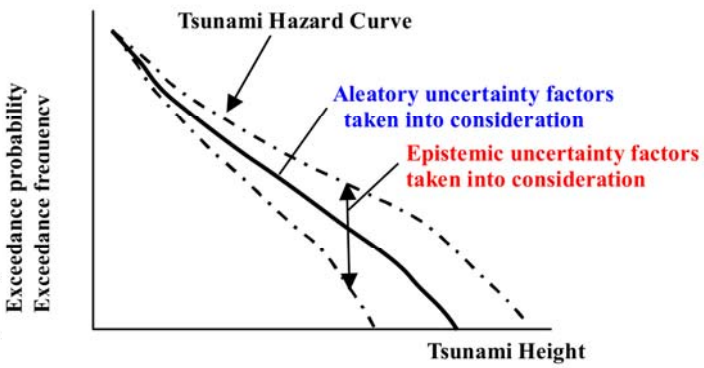

Fig.3 Image of result by PTHA, fractile hazard curve

7. Fragility Assessment of Buildings and Components

7.1. Determination of Assessment Targets and Damage Modes

The targets of fragility assessment will be selected on the basis of the lists of buildings and components. Subsequently, dominant or potential damage modes and damage-expected locations will be extracted for the selected assessment targets. Damage assessment indexes will be also selected for fragility assessment, appropriate to the selected damage modes and damage-expected locations.

Conditions for fragility assessment specified here will be arranged and shared with the evaluators of tsunami hazard assessment and accident sequence assessment.

7.2. Selection of Assessment Techniques

Techniques for assessment of the realistic capacity and realistic response of target buildings and target components will be selected depending on the application and accuracy required for the assessment. For selection of each assessment technique, any one of those techniques may be selected for use in the assessment, or a proper combination of several techniques may be used.

7.3. Assessment of Realistic Capacity

The damage limit of a target location corresponding to a damage mode leading to its structural and functional damage due to inundation and immersion, wave power, scouring, collision of drifting articles, and movement of seabed sand caused by a tsunami will be assessed as realistic capacity. In

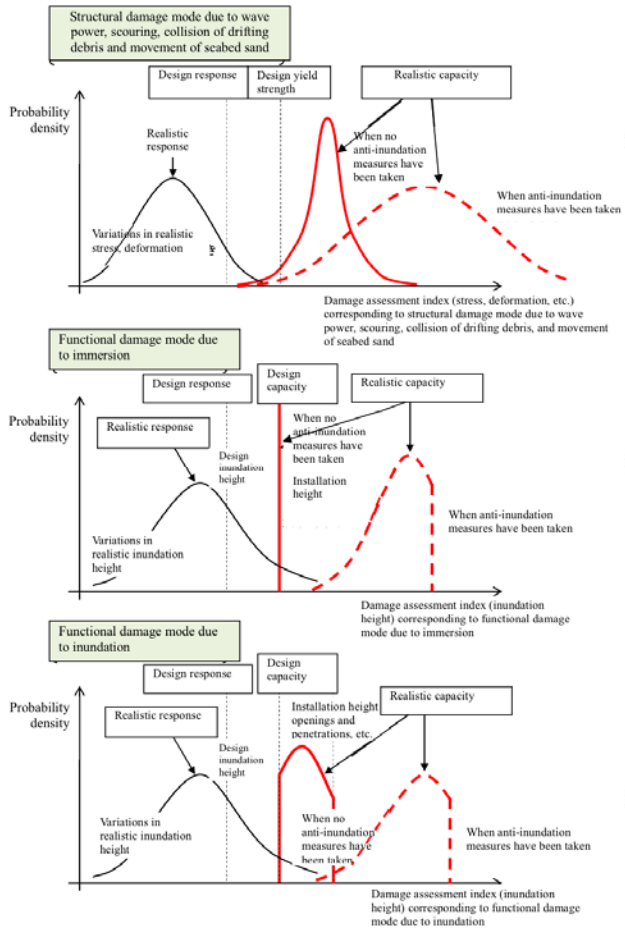

Fig.4 General concept of realistic capacity assessment for each damage mode

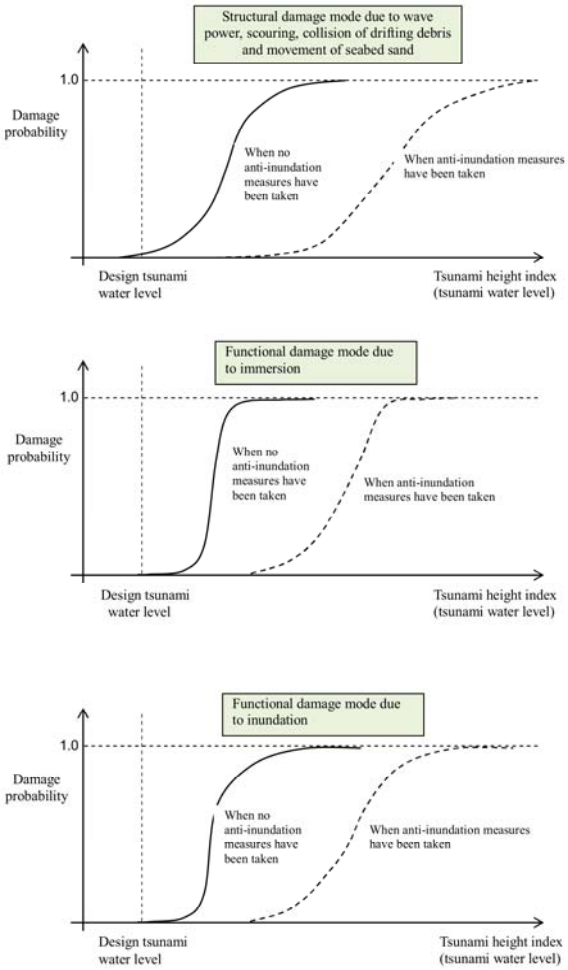

Fig.5 General concept of fragility curves corresponding to each of the damage modes

general, a probability distribution with an upper and a lower limit will be assumed for a functional damage mode due to inundation and immersion caused by a tsunami, whereas a logarithmic normal distribution will be assumed for a structural and functional damage mode due to wave power, scouring, collision of drifting articles, and movement of seabed sand caused by a tsunami.

7.4. Assessment of Realistic Response

Inundation depth, etc., at a damage-expected location corresponding to a damage mode, which leads to structural and functional damage due to inundation and immersion, wave power, scouring, collision of drifting articles, and movement of seabed sand caused by a tsunami, will be assessed as probabilistic quantities. In general, a logarithmic normal distribution will be assumed. The uncertainty factors will be divided into uncertainty related to aleatory factors and those related to epistemic factors, and then specified. Similar to the techniques for assessment of realistic capacity, those for assessment of realistic response include empirical techniques (experiments), theoretical techniques (analysis), and techniques based on engineering judgment, both empirical and theoretical. The tsunami water level defined in assessment of tsunami hazard will be used for reference in the realistic response assessment.

7.5. Fragility Assessment

Damage probability at which the realistic response obtained in "**Assessment of Realistic Response**" exceeds the realistic capacity obtained in "**Assessment of Realistic Capacity**" will be calculated by using the techniques for assessment of realistic capacity and realistic response selected in "**Selection of Assessment Techniques"**. By using this damage probability, the fragility curves of buildings and components will be created. At this point, the epistemic uncertainty of the fragility curves corresponding to the accuracy of the selected assessment techniques, etc., will be specified appropriately based on the judgment of experts. The result of this fragility assessment of buildings and components will be used in accident sequence assessment. **Fig. 4** shows a general concept of realistic capacity and response assessment for each damage mode due to inundation and immersion, wave power, scouring, collision of drifting articles, and movement of seabed sand caused by a tsunami. **Fig. 5** shows the general concept of fragility curves corresponding to each of the damage modes caused by inundation and immersion, wave power, scouring, collision of drifting articles, and movement of seabed sand due to a tsunami. These curves are calculated by focusing on whether the anti-inundation measures to be taken into consideration in realistic capacity assessment have been taken or not.

8. Accident Sequence Assessment

8.1. Determination of Initiating Events

Accident sequences, mitigation systems, buildings, structures, components, etc., that are important to core damage frequency are identified to determine initiating events and model accident sequences and systems. Accident sequences will be quantified using these models to calculate core damage frequency, etc., when the site suffers a tsunami and to analyze major results. In addition, in order to understand the uncertainty of core damage frequency, etc., and the sensitivity of factors that will influence the result of PRA, uncertainty analysis and sensitivity analysis will be carried out.

8.2. Modeling and Quantification of Accident Sequences

In order to assess the development of events that are triggered by a tsunami and lead to core damage, accident sequences are modeled as event trees. In modeling, safety functions required for preventing core damage will be selected for the initiating events. The occurrence frequency of accident sequences and core damage frequency will be assessed with uncertainty taken into consideration by using the typical methods of even trees and fault trees. Important parameters in each

assessment will be obtained by sensitivity analysis. In addition, the proportion of contribution, etc., of each of the systems and components that influence core damage frequency will be assessed as an importance index.

9. Conclusion

The Tsunami PRA standard has been established by the AESJ in December 2011[4]. It is based on the up-to-date knowledge and methodologies for the tsunami characteristics, and the NPP response and fragility to the tsunami. However, new findings are being obtained from the 2011 Great East Japan Earthquake and the Fukushima Dai-Ichi NPP accident. Because of the limited knowledge and less experience in the tsunami PRA, some simplifications are made in the PRA procedure. The AESJ continues the activity of the Tsunami PRA Subcommittee and the update process tunami PRA standard for correlation of the impact of the earthquake and tsunami that. .

Collection of Case studies of Tsunami PRA will be created in a separate volume of the standard, as to be able to reflect the latest findings, make additional / replacement of the contents in the future. It will be summarized for the case to consider a step-by-step method of each evaluation, scheduled to be published the first edition in December 2012.

Tsunami PRA Standard is being translated into English, scheduled to be published in early 2013 from the end of 2012.

Acknowledgement

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