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ENGINEERING AGENDA ON NUCLEAR SAFETY FROM THE 2011 TOHOKU-PACIFIC EARTHQUAKE

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ABSTRACT: The paper addresses engineering agenda on earthquake and tsunami safety of nuclear power plants (NPP) that were raised by the 2011 Tohoku-Pacific Earthquake (Great East Japan Earthquake Disaster). As an introduction, it is emphasized that a firm technology governance must be established to implement appropriate technology for nuclear safety. On this basis, engineering topics for nuclear safety are discussed. Overall performance of NPPs in the disaster area, characteristics of strong ground motions and tsunamis at the NPP sites are presented. Three critical lessons (risk-based decision, scientific imagination, and speed in action) are proposed. Specific engineering agenda are addressed in terms of establishment of risk-based decision scheme, development of integrated seismic-tsunami PSA, and establishment of tsunami resistant technology.

Key Words: nuclear safety, risk-based decision, "scientific imagination", seismic-tsunami PSA, cliff-edge, smooth fragility, tsunami-resistant technology, water proof-structural resistance-dry siting

1. INTRODUCTION

1.1 Overview as a basis for engineering discussion

The Tohoku-Pacific Earthquake of March 11, 2011 with M=9.0 (moment magnitude) caused a gigantic disaster which was named "Great East Japan Earthquake Disaster (GEJE)".[1] It brought triple major disasters; i.e., damage by strong motions extending over 500km of the eastern Pacific Japan, an overwhelming devastation by gigantic tsunami attacks, and huge impacts of the accident at Fukushima I (Dai-ichi) Nuclear Power Station. The scale of the disaster and its serious societal impacts far exceed any disasters Japan has experienced since the end of the World War II. Among the effects of the Tohoku-Pacific Earthquake, this paper will discuss the performance of nuclear power plants (NPP)

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[1] "Tohoku-Pacific Earthquake" and "Great East Japan Earthquake Disaster" are both commonly used. The former represents geographical location of the source area, while the latter emphasizes its diverse societal impacts. This paper will use the former as source area locations and tsunami source characteristics were key for the performance of nuclear power plants in the disaster area.

in the disaster area, on which basis propose earthquake engineering agenda for nuclear safety.

The nuclear safety is being seriously questioned since the Fukushima I accident. The question has enough reasons to be asked in the presence of the accident that should have never happened. The final judgment is to be made by the people of Japan.

It is critically important to use *appropriate technology* in order for Japan to continue the nuclear power production. But more importantly, *appropriate decision mechanism* should be established to implement appropriate technology. Lessons of the Fukushima I accident raised by prominent bodies (IAEA (2011), NERH (2011), etc.) that extend not only to technical issues but to agenda on regulatory as well as cooperate managements are right judgments. Unless a right decision mechanism be established, the Japanese nuclear energy production will fail to recover supports of the people of Japan and also of the international community. It is the issue of technology governance. We do have technology to realize nuclear safety under the Japanese seismic environments. But the mechanism of implementation needs drastic enhancements. A tough process is going on to realize the target that requires innovation in the Japan's political, bureaucratic, corporate, and academic involvements.

Upon the condition that an appropriate integrated regulatory and operational framework for nuclear safety be established, the author believes that we should positively discuss the option to rely on nuclear energy which is free from greenhouse gas emission as a major social and industrial infrastructure. This includes an urgent issue to devise and implement a proper technical framework to assure safety of existing nuclear power plants. With this recognition, this paper will discuss engineering frameworks of earthquake and tsunami protection for nuclear power plants.

1.2 Background of this paper

The purpose of this paper is to present earthquake engineering agenda for nuclear safety raised by the experiences in the Tohoku-Pacific Earthquake. Discussion will be developed primarily from the view point of earthquake engineering and risk-based decision theory.

On March 30, 2011, Nuclear and Industrial Safety Agency (NISA) proposed for NPPs throughout Japan to implement emergency safety measures as backups in case of nuclear accident emergency (NISA, 2011), which was practiced by all electric utilities. This action is in a right track in order to be prepared for accident management (AM) to stop steps of severe accident sequences in the event of station blackout and malfunction of cooling systems.

It should, however, be recognized that the key requirement is to achieve a total system reliability that will keep the plant from facing such emergency situations under severe earthquake and tsunami actions, which is the main subject of this paper.

The context of this paper is based on the author's article written half a year ago in the Japanese language (Kameda, 2011). This paper is its updated version.

This paper has a background of extensive discussion with relevant researchers and engineers on which basis, four companion papers are presented in an organized session of the Symposium (Ebisawa, Kameda and Hirano, 2012; Miyano and Nakamura, 2012; Takada, 2012; Takamatsu, Kameda and Ebisawa, 2012). The readers are referred to these companion papers.

2. IMPACTS OF THE TOHOKU-PACIFIC EARTHQUAKE
ON NPPs AND FUKUSHIMA I ACCIDENT

2.1 Overall performance of nuclear power plants in the disaster area

There are four NPP sites in the heavily damaged disaster area; i.e., Onagawa NPS[2] (Tohoku EPCO: Tohoku Electric Power Company), Fukushima I and Fukushima II NPSs (TEPCO: Tokyo Electric Power Copany), and Tokai II PS (JAPC: Japan Atomic Power Company). Table 1 shows overall performances of these plants under the strong ground motions that were followed by tsunami attacks

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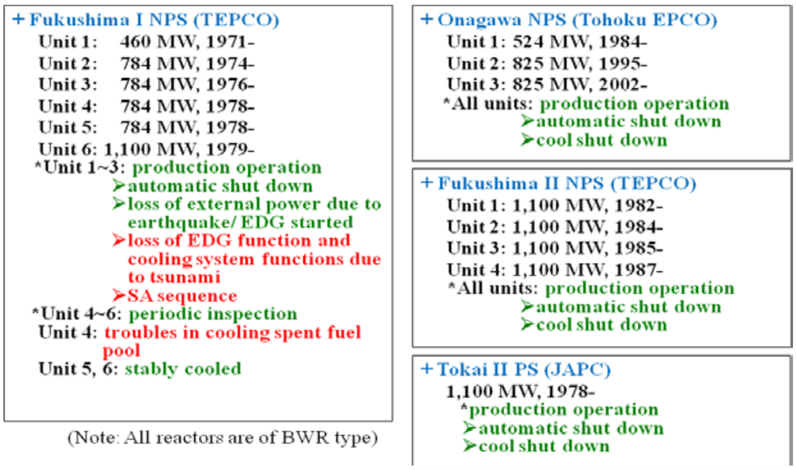
[2] NPS = nuclear power station / PS = power station

about forty minutes later.

The Fukushima I NPS was subject to a serious nuclear accident. It was triggered by loss of all AC powers (SBO: station black-out) and functional failure of residual heat removal systems (RHR). Then followed severe accident sequence that led to core melt down. While loss of external power was caused by strong ground motions, other major functional losses including malfunction of EDG (emergency diesel generator) and RHR were caused by inundation and hydrodynamic effects of tsunami. The other three plants, Onagawa, Fukushima II, and Tokai II were cool shut down despite partial inundation by tsunami. Not only the failure case, the success cases should be carefully observed in order to draw useful lessons for nuclear safety to the future. For further details of the NPP performances, see e.g. NERH (2011). What led to stability and accident on the site is a crucial issue. Regarding this, see Miyano and Nakamura (2012), one of our companion papers for the Symposium.

Table 1 Performance of NPPs in the disaster area of the Tohoku-Pacific Earthquake



+Fukushima I NPS (TEPCO)
Unit 1: 460 MW, 1971-
Unit 2: 784 MW, 1974-
Unit 3: 784 MW, 1976-
Unit 4: 784 MW, 1978-
Unit 5: 784 MW, 1978-
Unit 6: 1,100 MW, 1979-
*Unit 1~3: production operation
➢automatic shut down
➢loss of external power due to earthquake/ EDG started
➢loss of EDG function and cooling system functions due to tsunami
➢SA sequence
*Unit 4~6: periodic inspection
Unit 4: troubles in cooling spent fuel pool
Unit 5, 6: stably cooled

(Note: All reactors are of BWR type)

+Onagawa NPS (Tohoku EPCO)
Unit 1: 524 MW, 1984-
Unit 2: 825 MW, 1995-
Unit 3: 825 MW, 2002-
*All units: production operation
➢automatic shut down
➢cool shut down

+Fukushima II NPS (TEPCO)
Unit 1: 1,100 MW, 1982-
Unit 2: 1,100 MW, 1984-
Unit 3: 1,100 MW, 1985-
Unit 4: 1,100 MW, 1987-
*All units: production operation
➢automatic shut down
➢cool shut down

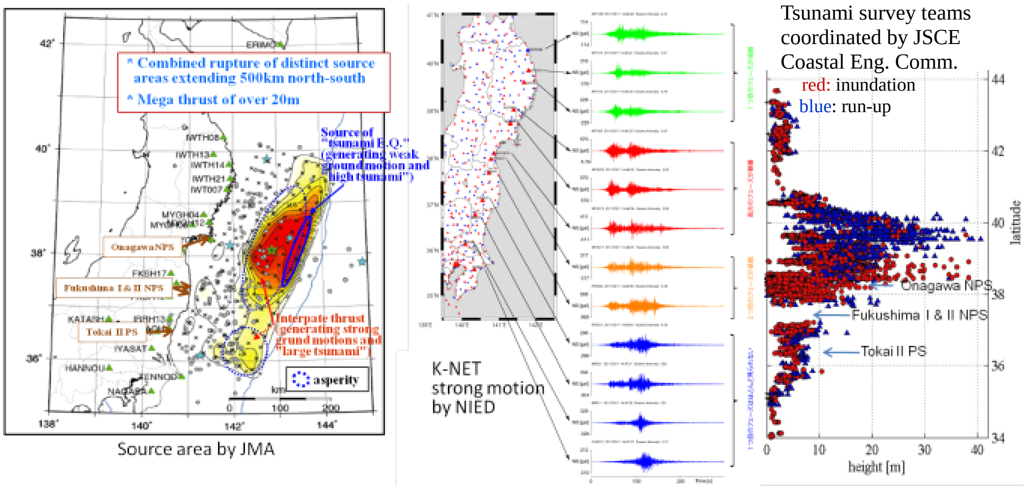
+Tokai II PS (JAPC)
1,100 MW, 1978-
*production operation
➢automatic shut down
➢cool shut down

The overall performance of the four NPPs may be stated that Fukushima I ***"failed catastrophically"*** but Onagawa, Fukushima II and Tokai II ***"failed gracefully"***. We should learn from the facts: both in failure and success stories. We need to learn critical lessons and put them in action to the future.

2.2 Ground motions at NPP sites

The source of Tohoku-Pacific Earthquake was truly a giant event. It was a combined ruptures involving five distinctly defined inter-plate thrust zone source areas and a rupture in the "tsunami earthquake" zone along the Japan Trench. The entire rupture zone extends over the length of 500km north-south and the width of 200km east-west. Fig.1(a) shows a typical source model. Fig.1(b) shows variation of strong motion records. Observe that strong motion time histories vary depending on locations of observation sites relative to the asperities. Fig.1(c) shows tsunami height survey results along the pacific coast. Locations of the four the NPPs in the disaster area are shown in Fig.1(a) and (c). Tsunami survey is missing for a section around Fukushima NPPs because of the nuclear accident. From Fig.1, we get a general picture of the experienced ground motions and tsunami heights.

Strong motions at NPP sites are shown in Table 2 where PGA values (in cm/s^2) at the base mat of reactor buildings (RB) are compared between observed records and response analysis results from design basis ground motions (DBGM: Ss). Site specific DBGMs had been defined on the basis of the revised Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities (NSC, 2006 / hereafter, NSC Seismic Design Guide). The numbers in red indicate that the observed PGA exceeds the corresponding DBGM-based PGA (in blue).



(a) source model (JMA) (b) strong motion records (NIED) (c) tsunami height (JSCE)

Fig.1 Source model, and strong motion and tsunami height records of the Tohoku-Pacific Earthquake

Table 2 Strong ground motions at NPP sites (source: NERH, 2011)

Strong motion (PGA in cm/s²) at base mats of RB						
unit	Recorded			Response to backcheck Ss		
	NS	EW	UD	NS	EW	UD
Fukushima I						
1	460	447	258	487	489	412
2	348	**550**	302	441	**438**	420
3	322	**507**	231	449	**441**	429
4	281	319	200	447	445	422
5	311	**548**	256	452	**452**	427
6	298	444	244	445	448	415
Fukushima II						
1	254	230	305	434	434	512
2	243	196	232	428	429	504
3	277	216	208	428	430	304
4	210	205	288	415	415	504

Strong motion (PGA in cm/s²) at base mats of RB						
unit	Recorded			Response to backcheck Ss		
	NS	EW	UD	NS	EW	UD
Onagawa						
1	**540**	**587**	439	**532**	**529**	451
2	**607**	461	389	**594**	572	490
3	**573**	458	321	**512**	497	476
Tokai II						
1	214	225	189	393	400	456

* backcheck Ss = ground motions defined according to the revised seismic design review guide (NSC, 2006) : to be used as DBGM for new plant design and used for back-check of existing plants

Observe in Table 2 that the three units at Onagawa and three of the six units at Fukushima I experienced PGAs exceeding DBGM-based response values by 2% ~ 26%. Nevertheless, we may say that the observed PGA are generally in the range of DBGM from an engineering stand point where substantial seismic margin is anticipated at carefully designed plant SSCs. This observation implies that our general understanding of multiple-shock earthquakes that strong ground motions in short period ranges are primarily controlled by the nearest asperities applies to the gigantic event like Tohoku-Pacific Earthquake.

2.3 Tsunamis at NPP sites

The gigantic source area of the Tohoku-Pacific Earthquake affected more drastically on tsunami generation than on ground motions. It is important to recognize that we experienced superimposed effects of two distinct types of tsunamis: "large tsunami" and "high tsunami".

The "large tsunami" was generated by the slip of inter-plate thrust zones (see Fig.1(a)). This component of tsunami had a long wave length and therefore momentum of a huge volume of seawater that caused inundation as far as 5km from the coast line in the flat plane of Miyagi Prefecture. This is said to be a recurrence of the type of Jogan tsunami of AD 869 (Satake, Namegaya, and Yamaki, 2008; Namegaya, Satake and Yamaki, 2010). These inter-plate thrust slips were the sources of major strong ground motions.

The "high tsunami" was generated by the slip at a belt zone adjacent to the axis of Japan Trench (see

Fig.1(a)). The belt zone produces so-called "tsunami earthquake" which is characterized as generating weak ground motions but very high tsunamis. The major reason for the very high tsunami comes from extremely large slips occurring there. The largest slips in the zone are estimated to be over 40 m far exceeding the slips in the inter-plate thrust zones (Fujii, Satake, Sakai, Shinohara and Kanazawa, 2011). This type of earthquake is regarded as recurrence of Meiji Sanriku Tsunami of 1896.

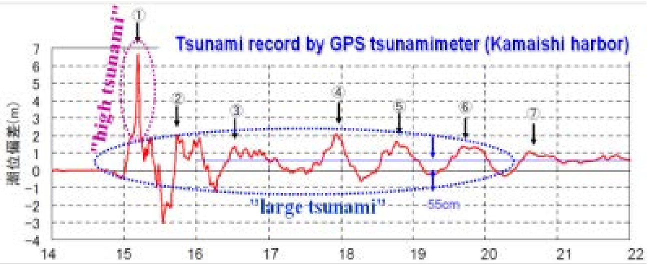
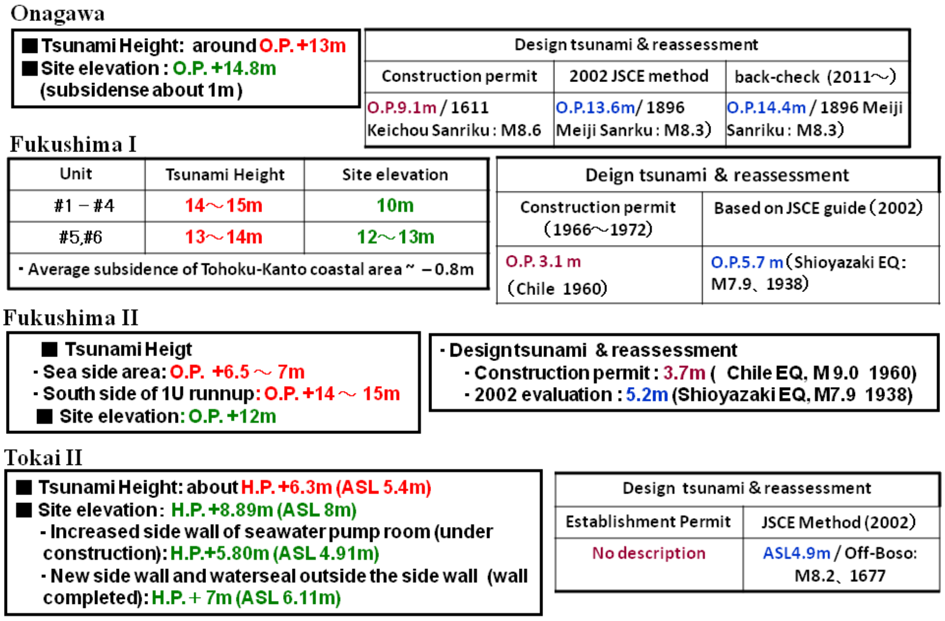


Fig.2 Superposition of "large tsunami" and "high tsunami"
in the Tohoku-Pacific Earthquake (PARI)

Fig.2 shows the tsunami record at Kamaishi harbor where we observe distinct components of "large tsunami" with a long period (large wave length) and "high tsunami" with a short period (small wave length). Thus, simultaneous occurrence of the two types of tsunamis that made it "large and high tsunami" is found to be specific characteristics of the Tohoku-Pacific Earthquake.

Table 3 Tsunami height at NPPs (red: observed in Tohoku-Pacific Earthquake; green: site elevation; violet: assessment in construction permit; blue: re-assessments)



Onagawa

■ Tsunami Height: around O.P.+13m
■ Site elevation : O.P. +14.8m
(subsidense about 1m)

Design tsunami & reassessment		
Construction permit	2002 JSCE method	back-check (2011～)
O.P.9.1m / 1611 Keichou Sanriku : M8.6	O.P.13.6m/ 1896 Meiji Sanrku : M8.3)	O.P.14.4m / 1896 Meiji Sanriku : M8.3)

Fukushima I

Unit	Tsunami Height	Site elevation
#1 – #4	14～15m	10m
#5,#6	13～14m	12～13m
・Average subsidence of Tohoku-Kanto coastal area ~ –0.8m		

Deign tsunami & reassessment	
Construction permit (1966～1972)	Based on JSCE guide (2002)
O.P. 3.1 m (Chile 1960)	O.P.5.7 m (Shioyazaki EQ: M7.9、1938)

Fukushima II

■ Tsunami Heigt
・Sea side area: O.P. +6.5～7m
・South side of 1U runnup: O.P. +14～15m
■ Site elevation: O.P. +12m

・Designtsunami & reassessment
・Construction permit : 3.7m (Chile EQ, M9.0 1960)
・2002 evaluation : 5.2m (Shioyazaki EQ, M7.9 1938)

Tokai II

■ Tsunami Height: about H.P. +6.3m (ASL 5.4m)
■ Site elevation: H.P. +8.89m (ASL 8m)
- Increased side wall of seawater pump room (under construction): H.P.+5.80m (ASL 4.91m)
・New side wall and waterseal outside the side wall (wall completed): H.P. + 7m (ASL 6.11m)

Design tsunami & reassessment	
Establishment Permit	JSCE Method (2002)
No description	ASL4.9m / Off-Boso: M8.2、1677

Table 3 shows tsunami height at the four NPP sites. The observed tsunami heights (inundation heights: some run-up height) in the Tohoku-Pacific Earthquake are shown in red, site elevations in green, official assessments in construction permit in violet, and re-assessments practiced later based on scientific progress and increase in technical information in blue colors. Observe that Fukushima I NPS was subject to tsunami height remarkably larger than the site elevation which caused severe inundation and led to severe accident sequences. Onagawa NPS was also subject to a high tsunami but fortunately slightly lower than the site elevation. For further details of the NPPs under tsunami action, see the companion papers presented in this Symposium (Kameda, Takamatsu and Ebisawa, 2012;

Miyano and Nakamura, 2012).

It is important to note that major tsunami sources that affected the four NPPs are the segments near the trench axis; i.e., "tsunami earthquake" zone. This aspect is typically seen in the fact that the tsunami height at Onagawa NPS observed in the Tohoku-Pacific Earthquake is nearly equal to the simulation results from the Meiji Sanriku Tsunami (1896). Meiji Sanriku is case of typical "high tsunami". It was an isolated tsunami earthquake, not combined with other inter-plate thrust rupture. This implies that key for the tsunami hazard assessment for NPPs should be proper incorporation of "tsunami earthquakes". This aspect has been demonstrated in JNES's detailed tsunami analysis (Sugino, 2011). It was shown that major contributors to the tsunami heights at the four NPP sites are the sub-zones near the trench axis that generated "high tsunami".

2.4 A note on the giant event and NPP performance information

There were arguments that such a mega thrust as Tohoku-Pacific Earthquake was beyond expectation of seismology and beyond the capability of science. However, within the gigantic scale of the entire event, individual sub segments are accounted for using the context of existing seismological and tsunami science (e.g., Fujii, Satake, Sakai, Shinohara and Kanazawa, 2011). The question was in the unexpected mega scale combined rupture of multiple source areas. This aspect is also being discussed with a concept of super-cycle of plate boundary activities. In this way, scientific reasoning of the entire event is progressing.

Engineering hazard assessments should carefully incorporate all these real world information. Yet, engineering decision is always subject to various sources of uncertainties as decision is to be made against the future events. Risk-based decision is extremely important where physically sound models and systematic uncertainty models are appropriately integrated.

It should be emphasized that details of structural and functional damage at the NPPs should be clarified and made open. It is particularly important to identify the mode of load effects; i.e., if they are due to ground motion effects, tsunami effects, or ground motion and tsunami combined effects.

No such survey activities have been performed in a systematic manner. A preliminary table of component failure have been disclosed (Tohoku EPCO, 2011) which is valuable information, but not enough for engineering discussion. Information that enables to perform final assessment through structural and hydraulic analysis should be compiled. It will be a precious real-world input to the component vulnerability evaluation that takes essential roles in risk assessments.

3. CRITICAL LESSONS FOR NUCLEAR SAFETY

The following three lessons are proposed as a basis of discussion on earthquake engineering agenda in the following part of this paper. They address fundamental issues that must be implemented in practice absolutely in order never to have a recurrence of the Fukushima I accident.

(1) ***Risk-based decision*** should be the basis of nuclear safety measures.
(2) ***“Scientific imagination”*** should be a key for establishing risk models.
(3) ***Speed in action*** is critical.

These items point out serious gaps between theory and practice that were direct causes of the nuclear accident. It is a critical task to close the gaps. These lessons are elaborated below.

3.1 Risk-based decision should be the basis of nuclear safety measures (Critical lesson 1)

Lack of beyond-design tsunami protection was a major cause of the accident at Fukushima-I. In engineering context, this is an issue of risk-based decision for safety assurance covering beyond-design hazard levels.

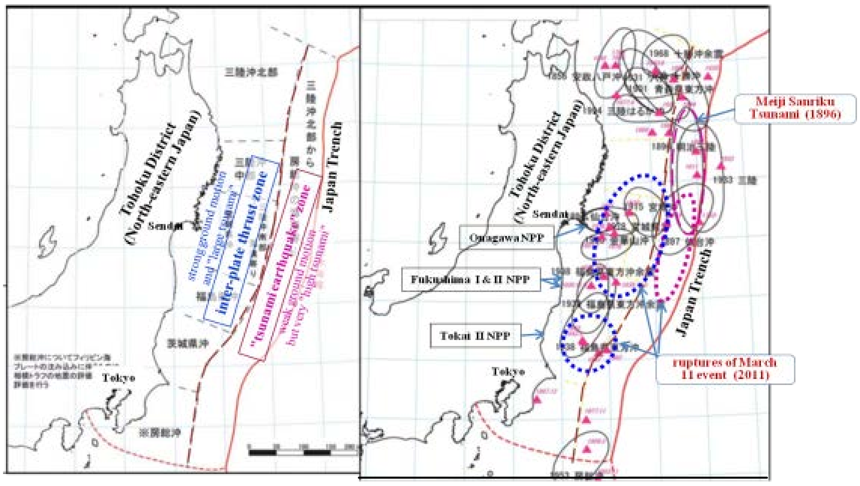
In the Japanese regulatory framework, the NSC Seismic Design Guide revised in 2006 (NSC, 2006) made explicit statements of the risk concept in terms of "residual risk" which stands for seismic risk of the plant in the beyond-design hazard levels. PSA (probabilistic safety assessment) application was promoted (not enforced) for assessment of residual risk. While its implementation has been in limited activities, it has important roles for discussion of nuclear safety.

The same context should have been applied to tsunami effects. But despite some important achievements (Sugino, Iwabuchi, et. al, 2008; JSCE, 2009), the process of implementation was much slower than PSA application to ground motion effects. Then the 3.11 giant tsunami. The engineering community should take the situation seriously, and speed up implementation of the risk concept for tsunami protection of NPP.

The risk concept is an indispensable roadway in decisions to avoid NPP plant systems being unguarded in beyond-design hazard levels. We should establish implementation of risk-based decision for nuclear safety against mega earthquakes and mega tsunamis that will continue to recur in Japan and other seismic regions of the world.

3.2 “Scientific imagination” should be a key for establishing risk models (Critical lesson 2)

Using historical high record was a major reason for underestimation of the tsunami height at Fukushima NPS. Tsunami simulation activity was confined to source models identified for the events within the recent 1.5 century, a time span where geophysical verification is available. But 1.5 century is only a small time window in the entire process of the nature.



(a) distinction of "tsunami earthquake" and inter-plate thrust zones

(b) past events and sources of Tohoku-Pacific Earthquake

Fig.3 Seismicity of Tohoku-Pacific Japan
(added to Earthquake Research Committee, 2002)

As discussed in **2.3**, the most dangerous tsunami sources for NPPs in eastern Pacific Japan is the "tsunami earthquake" zone extending 800km north-south adjacent to the trench axis (see Fig.3(a)) where "high tsunami" is generated. The only scientifically verified "tsunami earthquake" is Meiji Sanriku Tsunami of 1896 (see Fig.3(b)). But the Earthquake Research Committee, government of Japan issued a long-term forecast for the eastern Pacific Japan (Earthquake Research Committee, 2002), where it was proposed on the basis of information in the past 400 years that "tsunami earthquakes" can take place anywhere of the belt zone. It was reported at the expert meeting of the Central Disaster Management Council (CDMC) but this concept was not adopted for general disaster management. Using historical high was the decision. Tsunami hazard assessments for Fukushima NPS stayed in the same context. The reality of Tohoku-Pacific Earthquake is that "tsunami earthquake" took place in the south side of the Meiji Sanriku source with the NPPs directly faceing in the front (Fig.3(b)).

Paleo-tsunami studies (e.g.: Abe, Sugano and Chigama, 1990; Imaizumi, et. al, 2008,) provide important information for tsunami hazard assessment for nuclear safety, as they contribute to looking at the tsunami histories in a timeframe much longer than geophysical observations. On this basis warning by scientists had been appealed. But it is after Tohoku-Pacific Earthquake that paleo-tsunami studies have established its firm position.

From these two examples, we should be aware that the judgmental fault was not in the fact that we could not expect the mega thrusts of Tohoku-Pacific Earthquake but in the fact that we could not incorporate scientific warnings in engineering modeling. There was a general atmosphere immediately after the Tohoku-Pacific Earthquake that seismologists were shocked, but not very much among earthquake engineers. Engineers are responsible for building risk models. Engineers should seriously look at the event.

From these considerations, we should establish a view that extreme events with very long return periods should be incorporated in risk modeling if no observed data but sound scientific bases. This is a departure from being confined to historical highs. We may call this attitude "*scientific imagination*". We need to mobilize "scientific imagination" in the process of decision. In an engineering terminology, it may be called a "sound logic of extrapolation".

3.3 Speed in action is critical (Critical lesson 3)

Tohoku-Pacific Earthquake has taught us in an extreme manner that "the nature does not wait for us". It was only one year after publication of the paper demonstrating that AD 869 Jogan Tsunami extended extensively from Miyagi to Fukushima and its inundation heights were quantitatively estimated through numerical simulation (Namegaya, Satake and Yamaki, 2010). But it was seven years after long-term forecast of "tsunami earthquakes" (Shimazaki, 2011), enough to get prepared.

There is no excuse "the nature acted before we acted" with nuclear accidents. It is urged to establish new criteria to put promptly new scientific knowledge into action. Efficiency and transparency of discussion is important. There should be lively brain storming, integration, and leadership for decision. As an example, the case of Tokai II PS should be highlighted where construction of new side walls with increased height (7m) to enclose sea water pump areas, nearly completion at the time of the great tsunami, protected the ultimate heatsink function (NERH, 2011).

4. ENGINEERING AGENDA (1): ESTABLISHMENT OF RISK-BASED DECISION SCHEME FOR NUCLEAR SAFETY

4.1 Nuclear safety against earthquakes and tsunamis by integration of deterministic benchmark assurance by design and beyond-design assurance by residual risk

Fig.4 proposes a risk-based decision scheme of nuclear safety against earthquakes and tsunamis. It has been developed to conform with the NSC Seismic Design Guide (NSC, 2006). It constitutes a framework of safety assurance of the entire plant system by combined effects of deterministic design and probabilistic assessment in beyond-design hazard levelsbu residual risk. Key safety parameters in this context are 1) ***design point*** to define benchmark assurance, 2) ***seismic margin*** of SSC to clarify their beyond-design capacity, and 3) ***residual risk*** to define seismic margin of the entire plant system. It is emphasized that these parameters are connected consistently through fragility concepts. On this basis, we can discuss them on the same arena of physical phenomena.

As explained in the caption for Fig.4, the same framework is applicable to tsunami risk problems. Major differences between seismic PSA and tsunami PSA come from the nature of load effects; i.e., ground motion effects and water inundation-hydrodynamic effects. The difference affects characterization of fragility and accident scenarios. Despite these differences, basic structure of risk-based decision is commonly applicable.

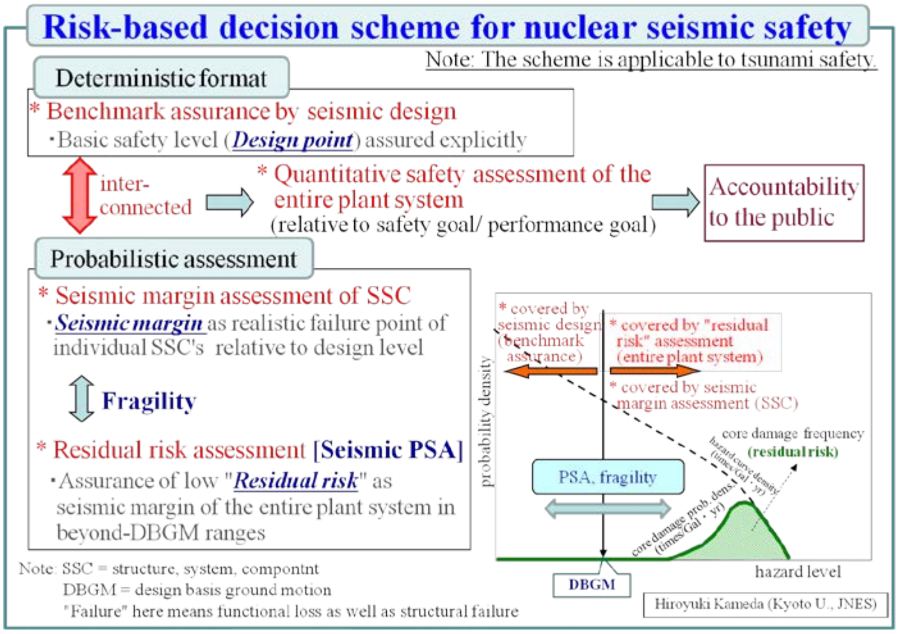


Fig.4 Scheme of seismic safety assurance of NPP that should be realized under the 2006 NSC Seismic Design Guide

(While the figure illustrates the framework of design for strong ground motions, the same context should be applied to tsunami safety: the terminologies seismic design, seismic margin, seismic PSA, and DBGM are to be replaced by tsunami design, tsunami margin, tsunami PSA, and DBT (design basis tsunami), respectively.)

4.2 Significance of implementing PSA in risk assessment

PSA (probabilistic safety assessment) is the only methodology currently available for risk assessment of complex systems like nuclear power plants. Herein, significance of implementing PSA is discussed.

4.2.1 Framework of PSA procedure

The procedure of seismic PSA consists of the following five steps.

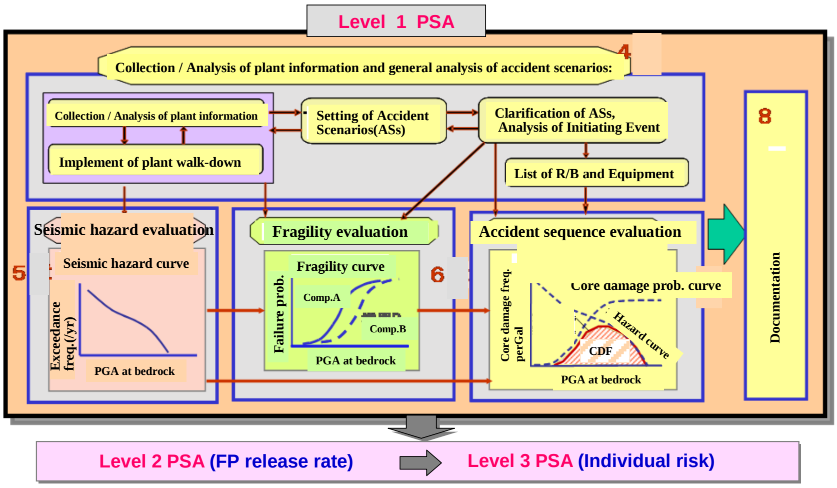


Fig.5 Procedure of level 1 seismic PSA (Hirano, Nakamura and Ebisawa, 2008)

- Step 1: Collection of information related to earthquake and identification of accident scenario
- Step 2: Seismic hazard evaluation

- Step 3: Fragility evaluation
- Step 4: Accident sequence evaluation
- Step 5: Documentation

The role of each step is illustrated in Fig.5.

The algorithm of seismic PSA is analogous to constituting a convolution integral of i) hazard (ground motion / tsunami) - occurrence rate for each hazard level, ii) fragility (probability of functional failure of SSC) - function of hazard level, and iii) accident scenario - event tree and fault tree with branch probabilities. As discussed in **4.1**, the same context is applicable to tsunami PSA.

For further details of the procedure, see the AESJ Standard (AESJ, 2007).

4.2.2 Benefit of using PSA

Major benefits of using PSA for seismic-tsunami safety of NPPs may be addressed as follows:

+ **Integrated system reliability:** We have solid technology to be used in deterministic design. We can expect that neatly designed and constructed plant components will have substantial level of seismic margin. But no matter how well we know about high reliability of individual components, the reliability of the entire plant as an integrated system is still in a "black box". We need to integrate component reliabilities into the integrated system reliability of the entire plant. This is the only way to make the plant safety transparent and accountable to the public (see Fig.4). In this way, we can discuss the plant reliability relative to safety goals and/or performance goals. PSA is the only applicable methodology developed so far.

+ **Identification of critical accident scenarios and critical plant components:** By conducting a de-convolution analysis of the integrated results of PSA, we can identify critical accident scenarios and relevant SSCs. In this manner, PSA results can be used for importance evaluation of individual plant components. Through this process, we can establish consistent relations between actual component design or enhancement plans and the reliability of the entire system. The key point is avoiding unrecognized critical missing links. This will help making consistent and appropriate cost-effective choice of earthquake and tsunami countermeasures.

+ **Rigorous application to common-cause failures caused by earthquake and/or tsunami:** NPPs are designed to protect its safety in the event of accidents by defense-in-depth mechanism. The effectiveness of defense-in-depth has been well established for accidents caused by internal events. But when the plants are subjected to strong earthquake ground motions and tsunami attacks, we face possibilities of simultaneous failure of several important safety components. That is, we must deal with the plant safety with common-cause events. In this case, logics of sequential safety scenario of defense-in-depth no longer holds. Seismic PSA provides methods for quantitative risk assessment for these common-cause events with correlated component failures (Ebisawa, Ogura and Hirano, 2010).

+ **Synthetic treatment of inherent uncertainties:** Throughout this paper, it has been repeatedly emphasized that we need risk concepts in safety assessment for NPPs. Major reason is that our future events are subject to uncertainties. Seismic events including ground motions and tsunamis have very high level of uncertainty. Even in Japan where ample geophysical and seismological observation data as well as paleo-seismological and paleo-tsunami information are available, we need to treat various types of uncertainties (aleatory and episteic) to establish engineering models for safety assessment. PSA incorporates methods of synthetic treatment of uncertainties, which is a key factor to make PSA useful (AESJ, 2007).

4.3 Implementation of risk concepts in Japan for nuclear safety - a slow process

Development of seismic PSA methodologies for Japanese seismic environments began at Japan Atomic Energy Research Institute (JAERI) (1985-2001) which was aimed at establishing a comprehensive framework of the theory. A seismic PSA project targeting its implementation was conducted at Nuclear Power Engineering Corporation (NUPEC) (1994-2003), then succeeded by Japan Nuclear Energy Safety Organization (JNES) (2003~).

The pioneering works on PRA[3] through the SSMRP project by US Nuclear Regulatory Commission (USNRC) was available in 1981 (USNRC, 1981). The developments in the U.S. were conducted for application in the central and eastern U.S. where seismicity is low or moderate, and not for high seismicity areas like California. It is the author's understanding that the primary purpose of SSMRP was to provide quantitative answers to seismic margins of NPPs in the central and eastern U.S. whose design seismic loads are considerably lower than those in California, but once a severe earthquake takes place actual ground motion will far exceed design values, yet the plant must withstand them so that severe accident like core melt down will not occur.

In the Japanese environment where seismicity is very high and with ample geophysical and seismological data are available, nuclear safety assessment practice has been done under deterministic frameworks. There was an atmosphere to hesitate discussing "risks" which looks inevitably at possibilities of earthquake ground motions exceeding design levels. However, particularly after the 1995 Great Hansin-Awaji (Kobe) Earthquake Disaster and various major earthquakes occurring at unidentified active faults, treatment of inherent uncertainties in seismic hazard assessment attained wider recognition. Meanwhile, the NUPEC/JNES PSA project made substantial progress in systematic treatment of uncertainties under the Japanese high seismicity environments.

With these backgrounds and after heated controversy at the code development committee, the risk concept was adopted in the Japanese regulatory guide with a terminology "residual risk" in the NSC Seismic Design Guide (NSC, 2006). This terminology was employed to represent the plant risk in the beyond-design hazard levels.

Seismic PSA plays a central role in residual risk assessment. Along with revision works for the seismic design guide at NSC, Atomic Energy Society of Japan (AESJ) worked on compiling Implementation Standard for Probabilistic Safety Assessment of of Nuclear Power Plants, and it was published in September 2007 (AESJ, 2007). It provides technical bases for implementation of seismic PSA (Hirano, Nakamura and Ebisawa, 2008).

One year after the revision of the NSC Seismic Design Guide, Niigata-ken Chuetsu-oki Earthquake (NCOE) of 16 July 2007 took place and heavily affected TEPCO's Kashiwazaki-Kariwa Nuclear Power Station (K-K NPS). The plant was subjected to very strong ground motions some exceeding three times the DBGM (under old design guide), but cool shut down was achieved at all of the reactor units. This experience explicitly demonstrated that assessment of residual risk is a practical demand, which led to a certain progress in the consensus development on the significance of seismic PSA.

Fundamental principle of implementing risk-based decision is for 1) treatment of external loads in excess of design values, and 2) quantitative incorporation of inherent uncertainties involved in future events. The principle is indispensable to achieve high reliability of complex systems. Nuclear safety is a typical case. In this regard, the current NSC Seismic Design Guide needs improvements, as it does not enforce application of seismic PSA, just stipulating reference to the annual excess probability of DBGM (NSC, 2006-2). Because of this situation, implementation of seismic PSA in nuclear regulatory activities was a slow process. As mentioned earlier, implementation of tsunami PSA was even slower. The reality of nature repeatedly pose questions through NCOE, Tohoku-Pacific Earthquake, etc. seismic risk management of NPPs based on PSA is an urgent agenda.

5. ENGINEERING AGENDA (2): ESTABLISHMENT OF SEISMIC-TSUNAMI PSA

5.1 Seismic PSA and Tsunami PSA - a usability check

Usability of seismic PSA depends on how realistically the hazard, fragility and scenario models are defined. This point can never be overly emphasized in each of the aforementioned five Steps of PSA. Two such examples are shown in Fig.6

Fig.6 (a) shows a comparison between the accident scenario of level 1 seismic PSA based on the AESJ Standard (AESJ, 2007) and events that actually occurred at K-K NPS in the NCO earthquake of

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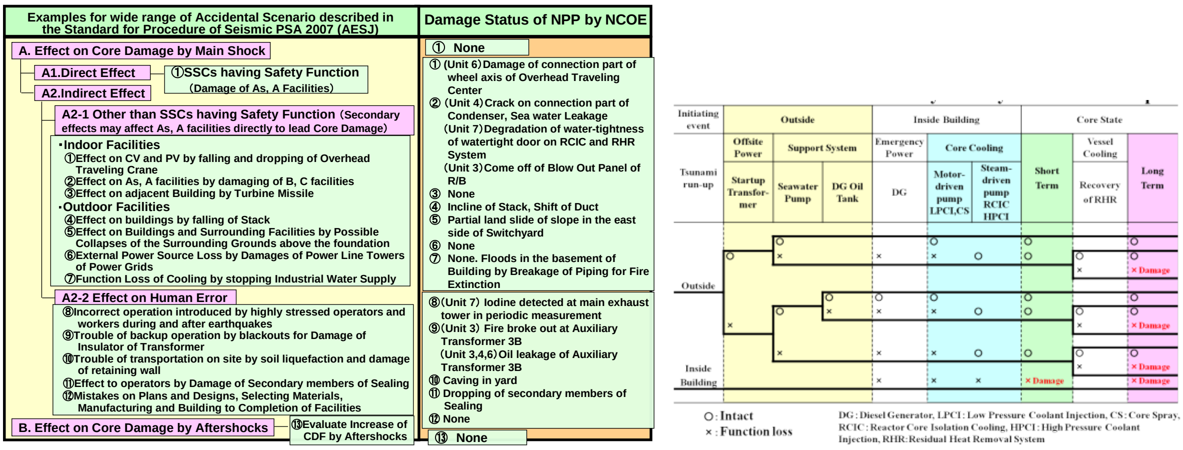
[3] PRA: Probabilistic risk assessment. It is a common terminology in the U.S. instead of PSA.

July 2007. The final draft of the AESJ Standard were completed half a year before the NCOE. Fig.6(a) shows that the AESJ Standard identified well about the events before they actually occurred.

Fig. 6(b) shows accident scenarios identified in the tsunami PSA project that started at JNES in 2006 (Sugino, Iwabuchi et. al, 2008). It is shown that functional loss of seawater pumps and diesel generators would be major causes of scenarios leading to core damage, which is exactly what happened in the Fukushima I accident as shown in the attached table.



Examples for wide range of Accidental Scenario described in the Standard for Procedure of Seismic PSA 2007 (AESJ)

A. Effect on Core Damage by Main Shock

A1.Direct Effect

①SSCs having Safety Function (Damage of As, A Facilities)

A2.Indirect Effect

A2-1 Other than SSCs having Safety Function (Secondary effects may affect As, A facilities directly to lead Core Damage)

- Indoor Facilities
  - ①Effect on CV and PV by falling and dropping of Overhead Traveling Crane
  - ②Effect on As, A facilities by damaging of B, C facilities
  - ③Effect on adjacent Building by Turbine Missile
- Outdoor Facilities
  - ④Effect on buildings by falling of Stack
  - ⑤Effect on Buildings and Surrounding Facilities by Possible Collapses of the Surrounding Grounds above the foundation
  - ⑥External Power Source Loss by Damages of Power Line Towers of Power Grids
  - ⑦Function Loss of Cooling by stopping Industrial Water Supply

A2-2 Effect on Human Error

⑧Incorrect operation introduced by highly stressed operators and workers during and after earthquakes
⑨Trouble of backup operation by blackouts for Damage of Insulator of Transformer
⑩Trouble of transportation on site by soil liquefaction and damage of retaining wall
⑪Effect to operators by Damage of Secondary members of Sealing
⑫Mistakes on Plans and Designs, Selecting Materials, Manufacturing and Building to Completion of Facilities

B. Effect on Core Damage by Aftershocks

⑬Evaluate Increase of CDF by Aftershocks

Damage Status of NPP by NCOE

① None

① (Unit 6) Damage of connection part of wheel axis of Overhead Traveling Center
② (Unit 4) Crack on connection part of Condenser, Sea water Leakage
(Unit 7) Degradation of water-tightness of watertight door on RCIC and RHR System
(Unit 3) Come off of Blow Out Panel of R/B
③ None
④ Incline of Stack, Shift of Duct
⑤ Partial land slide of slope in the east side of Switchyard
⑥ None
⑦ None. Floods in the basement of Building by Breakage of Piping for Fire Extinction

⑧(Unit 7) Iodine detected at main exhaust tower in periodic measurement
⑨(Unit 3) Fire broke out at Auxiliary Transformer 3B
(Unit 3,4,6) Oil leakage of Auxiliary Transformer 3B
⑩ Caving in yard
⑪ Dropping of secondary members of Sealing
⑫ None

⑬ None

(a) Scenarios by AESJ Standard as compared with reality at K-K NPS in NCOE (Ebisawa et. al, 2012)

(b) Accident sequences by run-up tsunami (Sugino, et.al, 2008)

Fig.6 Usability of seismic PSA and tsunami PSA in terms of accident scenario identification

So far, seismic PSA and tsunami PSA have been developed independently. Seismic PSA is now implementable (AESJ, 2007). Tsunami PSA development came later, but catching up. AESJ implementation standard for tsunami PSA is being compiled by its committee and task force. As ground motion effects and tsunami effects are inter related, next step should be integration into "seismic-tsunami PSA".

5.2 Seismic-Tsunami PSA

Most of severe tsunamis we experience in Japan are near-source tsunamis. We meet strong ground motions first, and tsunami attacks with delays of several minutes~1 hour. The Tohoku-Pacific Earthquake was a typical case. We need to establish PSA methodology to deal with correlated ground motion and tsunami effects, i.e., integrated "***seismic-tsunami PSA***".

A companion paper for the Symposium (Ebisawa, Kameda and Hirano, 2012) discuses challenges to seismic-tsunami PSA. Herein its basic framework will be presented.

Following lessons must be learned from the Fukushima I accident as engineering agenda under strong ground motion and tsunami combined actions.

① Occurrence of gigantic earthquake and tsunami requiring combined consideration of seismic hazard and tsunami hazard
② Risk evaluation of multi-units
③ Combined emergency management of both natural disaster and nuclear accident
④ Protection of support systems (seawater supply, power supply and signal systems) whose functional failure caused core damage in a short period of time.
⑤ Common cause failure of multi structures and components
⑥ Dependency among neighboring units

All of these items require development of an integrated seismic-tsunami PSA, particularly items ①. ③, ④ and⑤ directly involve seismic-tsunami hazard, seismic-tsunami fragility, and seismic-tsunami accident scenarios.

Items ② and ⑥, treatment of multi-unit issues, are not necessarily the agenda for seismic-tsunami combined effects. Multi-unit correlation is a vital issue in seismic PSA as well (Ogura, et. al, 2011). But modes of correlations are different between ground motion effects and tsunami effects. Highly correlated tsunami fragilities of electric devices, very vulnerable to water, is a typical tsunami specific example. They often constitute step-function type fragility; i.e., cliff-edge effects.

Seismic-tsunami PSA will be performed according to the steps:

+ Setting accident scenarios
+ Seismic-tsunami hazard evaluation
+ Seismic-tsunami fragility evaluation
+ Seismic-tsunami accident sequence identification in detail

Fig.7 is a schematic illustration of seismic-tsunami accident scenarios. Of the four cases shown herein, Case 1 is the safe case, while other three are cases with core damage occurrence.

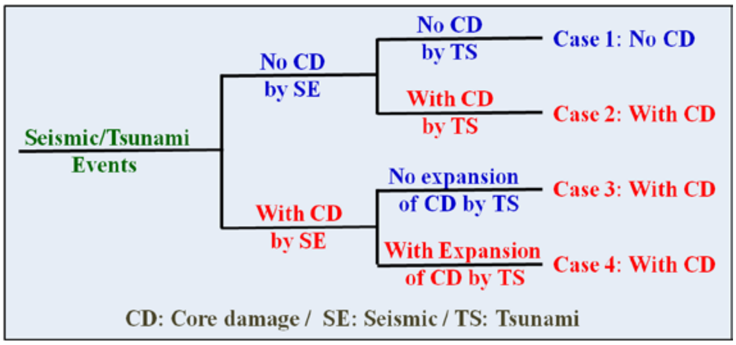


Fig.7 Seismic-tsunami accident scenarios (Ebisawa, Kameda and Hirano, 2012)

While it is clear that the nuclear accident at Fukushima I NPS corresponds to Case 2, general framework of seismic-tsunami PSA should incorporate all the four cases in Fig.7. We need to establish site specific seismic-tsunami hazard models with careful scientific surveys, "scientific imagination", and a sound risk concept.

6. ENGINEERING AGENDA (3): FRAGILITY ENHANCEMENT THROUGH ESTABLISHMENT OF TSUNAMI RESISTANT TECHNOLOGY

6.1 Motivation

Improving seismic and tsunami resistance of plant SSCs is the most straightforward way of seismic-tsunami risk reduction of nuclear power plants. In the context of safety assurance in Fig.4, it corresponds to the enhancement of seismic-tsunami fragility. It will contribute to reduction of residual risks through seismic-tsunami PSA. It also feeds back to seismic-tsunami margin of SSCs relative to design point. In this way, fragility enhancement is a key action in the seismic-tsunami risk reduction.

While we already have tremendous information on seismic fragility technology and data, tsunami fragility assessment needs much more efforts. Tsunami science and tsunami engineering have made remarkable contributions to tsunami hazard assessment and tsunami simulation. Engineering aspects including PTHA (probabilistic tsunami hazard assessment) and tsunami forces applied to objects have been significantly contributed (JSCE, 2002, 2009; Shuto et. al, 2007). On the other hand, tsunami vulnerability issues have not drawn adequate attention. In this context, a proposal is addressed herein from a standpoint of structural engineering. The proposal is to establish ***"tsunami resistant technology"*** like we have earthquake resistant technology. Detailed discussion of this issue is presented in a companion paper of the Symposium (Takamatsu, Kameda and Ebisawa, 2012).

6.2 Key issue = Elimination of Cliff-edge Effects

The most overwhelming effects of tsunami in the Fukushima I accident was that the critical safety support systems including emergency diesel generators and seawater pumps for residual heat removal systems were inundated and immediately lost their functions. In these cases, their fragility functions are nearly step functions as shown in Fig.8(a). This situation is called ***cliff-edge effects***. The residual tsunami risk in the beyond-design hazard levels becomes discontinuously too large.

Cliff edge effects in seismic fragility are observed in brittle failure of piping, etc. In the tsunami case, most dangerous cliff edge effects are typically found in the vulnerability of electric devices against water. They include motors for seawater pumps, cables, switch boards, instrumental sensors, data transmission devices, etc.

To eliminate cliff-edge effects, we need to improve the fragility to "***smooth fragility***" (Fig.8(b)) or "***safe relocation***" (Fig.8(c)).

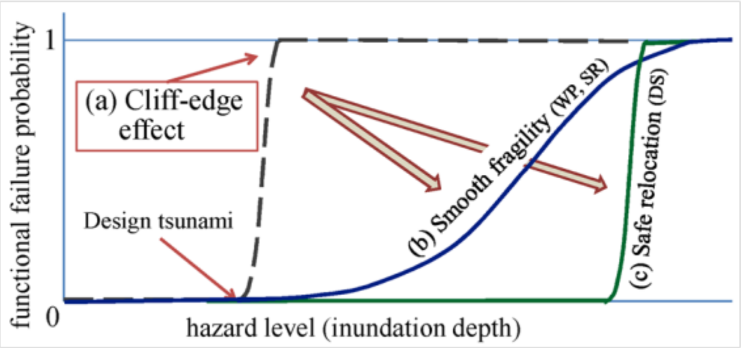


Fig.8 Scheme of fragility enhancement for eliminating cliff-edge effects (Kameda, 2011)

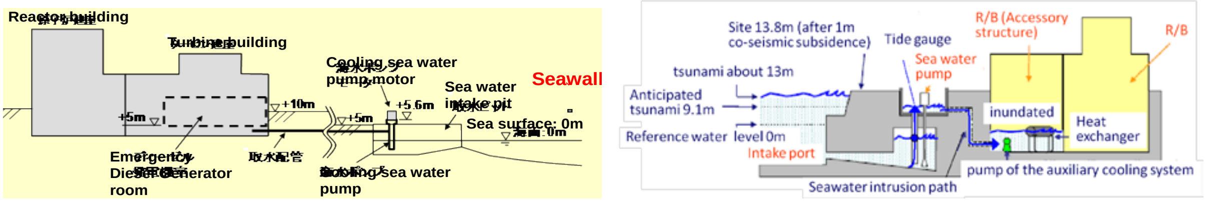
6.3 Load effects of tsunami

Tsunami hazard is represented typically by the tsunami heights. We should, however, be aware that there are various types of load effects of tsunami that should be considered for nuclear safety depending on how the plant components face tsunami attacks with various conditions of location, elevation, angles relative to tsunami flow direction, etc. They will affect the feasible technologies to be implemented for tsunami protection.

6.3.1 Inundation height

Photo 1 Inundation at Fukushima I NPS (by TEPCO)

Photo 1 shows scenes of inundation at Fukushima I NPS. It was the primary cause of triggering the sever accident sequence. These scenes cover the sea front to the turbine buildings in Fig.9(a). Fig.9(b) shows the case of Onagawa NPS. One major difference in inundation states at the two plants is seen in the layout of sea water pumps for emergency cooling systems that need to be located lower than site elevations for efficient performance. At Fukushima I, the pumps were installed at 5m elevation and bare to the sea front. At Onagawa, elevation of the pumps was low at 3m, but the entire pump pit was located behind the front bank facing the sea with the full site elevation of 14.9m (13.9m at the time of tsunami because of co-seismic tectonic subsidence) and was protected from direct inundation (Fig.9(b)). Many lessons should be drawn from the experiences in the great tsunami.



(a) Fukushima I NPS (Unit 1) (b) Onagawa NPS (Unit 2)

Fig.9 Illustration of sea water supply systems (source: NERH, 2011)

6.3.2 Hydrodynamic forces

Hydrodynamic forces should be a key factor for nuclear facilities that directly face tsunami front. The tsunami forces have different phases such as dynamic pressure (impulsive tsunami front pressure), followed by sustained pressure (run-up, and backwash) (Shuto et. al, 2007; JSCE, 2007).

Photo 2 shows some examples. Photo 2(a) is deemed as a case of failure due to impulsive tsunami front pressure, and Photo 2(b) due to sustained run-up pressure.

Photo 3 shows a positive example, tsunami wall across Fudai River (TP+15.5m). The tsunami flew over the wall, and destroyed the maintenance decks. But the main structure and the foundation were intact. The tsunami flow was wakened: it did not reach an elementary school 300m upstream.

(a) Destroyed sea wall gate (Miyako) (b) Bent steel pillars (Onagawa)

Photo 2 Structural failure due to hydrodynamic tsunami forces

Photo 3 Tsunami wall across Fudai River
(Fudai, Iwate Prefecture)

Photo 4 Seawalls toppled due to scouring
(Ryou-ishi, Miyako)

6.3.3 Scouring

Many coastal seawalls along the Pacific coast of Tohoku District were destroyed due to scouring by huge sustained flows once tsunami overflows them. Photo 4 shows such example.

New sea wall constructions are planned or underway at many Japanese NPP sites. A risk-based decision in the wall design to incorporate the case of overflow is critically important. They should be devised with strong wall structures and strong foundations to withstand impulsive and sustained tsunami pressure and sea bed consolidation to prohibit excessive scouring. The case of Photo 3 is recognized as a promising example of this premise.

6.3.4 Buoyancy and uplift

In the Tohoku-Pacific Tsunami, everything that can float floated and drifted, cars, trucks, railway vehicles, storage tanks without tight foundations, ships moving on to the land. Photo 5 shows a fuel tank at Onagawa NPS just sitting on the ground that floated and dislocated. In photo 1, we see a surge tank not dislocated by the tsunami although structurally damaged.

Another mechanism to raise structures is uplift. Bridge decks with T-shaped cross section in Rikuzen Takada is believed to have been pulled up from the piers due to uplift.

Photo 5 Fuel tank floated and dislocated (by Tohoku EPCO)

Photo 6 Heat exchanger room at Onagawa NPS RB basement (by Tohoku EPCO)

6.3.5 Seawater intrusion through unanticipated paths

We must be aware that water creeps in anywhere if it has pressure head and find accessible intrusion paths. While Onagawa NPS was able to avoid direct tsunami inundation, the basement of the RB accessory structure was partially inundated by seawater that intruded by an inverted siphon effect through seawater intake tunnel - tide gage pipe - pump pit - trenches (pipe ducts) (see Fig.9(b)). Photo 6 shows the heat exchanger room that got wet. The water level reached 2.5m above the floor: center of the heat exchanger drum.

Sealing of possible water intrusion path is very important. Cases are reported that cable trays crossing partition walls with urethane resin seals stopped tsunami pressure, but those with plaster board could not. This arouses us about the importance of sealing materials.

6.3.6 Sea sand immixed in seawater

Tsunami is a mixture of seawater and sea sand that is produced when it reaches shallow sea. Fine sands mixed in the seawater can harm active plant devices such as motors, generators, turbines, etc, particularly their shaft bearings.

6.4 Elements of tsunami-resistant technology: A framework of Water proof (WP), Structural resistance (SR) and Dry siting (DS)

From the arguments in **6.1**~**6.3**, it is pointed out that tsunami protection of NPPs should be a set of proper technologies to withstand various forms of tsunami hazard including inundation, hydrodynamic forces, scouring, etc. This requires establishment of tsunami - resistant technology that will help tsunami fragility enhancement.

It is believed that ample technological resources are available in the fields of machinery, architectural and civil engineering that can be mobilized effectively for tsunami protection of NPPs. R&D should be conducted for new developments and verification.

On this basis, a framework of the following three technological elements is proposed; i.e., Water proof (WP), Structural resistance (SR), and Dry siting (DS).

6.4.1 WaterProof (WP)（防水）: Isolate from direct contact with water

Isolation of electric devices from direct contact with water is critical. Especially safety-related electric devices are important such as control panels for water injection, switch boards, monitoring systems, seawater pumps, emergency diesel generators, etc. Technical elements for protection include waterproof casings, watertight partitions, enforced isolation seals, waterproof cables/connectors, sealing of seawater intrusion paths.

6.4.2 Structural Resistance (SR)（耐水）: Withstand hydrodynamic tsunami effects

Plant components that directly face approaching tsunamis must withstand their hydrodynamic effects such as impulsive and sustained tsunami pressures, scouring, buoyancy, and uplift. Protection of seawater pumps that are inevitably installed at relatively low elevation is critical. Technical options would be to make the pumps and motors completely water tight, constructing isolation walls tall enough, or both combined. Tsunami walls to enclose the plant site should have strong structure and foundation design and sea bed consolidation. Water and fuel tanks important in emergency operation should be connected to tight foundations.

6.4.3 Dry Siting (DS)（避水）: Locate at high elevation

This is to install plant facilities and equipments at high enough elevations so that none of the future tsunamis will ever reach. They may include part of emergency diesel generators, storage of equipment stocks to be used under emergency, control systems critical for safety management, etc. As relocation sites, high elevation point adjacent to the plant will be the first choice. Equipments with light weight can be relocated to upper floor of the plant buildings.

In case of a new plant construction, decision on site elevation is by itself an important dry siting judgment.

6.5 Practical perspective

Table 4 shows a listing compiled from practical observations on SSC design and enhancement. Major SSCs critical for tsunami issues have been identified. They include sea wall, residual heat removal function following reactor shut down, core cooling system, emergency power supply system, electric devices, equipments for emergency management, building components, and possible paths of intrusion. Locations of these SSCs were assumed to be standard cases of existing plants.

Table 4 SSC design and enhancement for tsunami protection of NPP (typical examples) (Takamatsu, Kameda and Ebisawa, 2012)

Structures, Systems, Components (SSC)		Location	Actions (e.g.)	WP	SR	DS
***Seawall**		*outdoor *facing the open sea	***strong walls** ***strong foundation** ***sea bed consolidation**		○	
***Residual heat removal function following reactor shut down (scram)**	*Pumps for the residual heat removal system , etc.	*building basement	***watertight chamber**	○		
***Core cooling system**	*High pressure-low pressure core pumps, etc.	*bldg. basement	***watertight chamber**	○		
***Emergency power supply system**	*Emergency diesel generator	*bldg. basement & vicinity	***watertight chamber, or** ***relocate in high elevation**	○		○
	*Fuel oil tanks	*outdoor	***strong foundation**		○	
***Emergency component cooling system**	*Sea water pumps, etc.	*outdoor & seawater level	***watertight protection for driving motors, etc.**	○	○	
*** Electric devices**	*power cable & signal cable *monitoring instruments *electrical panels, etc.	*outdoor *indoor	***water-sealed cable** ***strong cable supports** ***watertight chambers** ***upper floor of bldg**	○	○	○
***Equipments for emergency management**	*Portable emergency power supply systems	*(optional)	***install at high elevation**			○
	*Portable pumps	*(optional)	***install at high elevation**			○
***Building components**	*Carry-in entrance to bldg. *Ventilation louvers, etc.	*Outer wall of bldg.	***watertight & strong doors to resist tsunami loads**	○	○	
	*Hatches and openings within buildings	*Inside bldg.	***waterproof hatches & doors**	○		
*** Possible paths of intrusion** (seepage, siphon effects, etc.)	* Openings at intake tunnels * Trenches, etc.	* Outdoor & underground	*** Watertight lids, etc.**	○		

Then options of engineering actions for enhancements and their categorization in Water proof (WP), Structural resistance (SR), and Dry siting (DS) have been identified. This type of clarification will help consistent implementation of SSC design and enhancement.

6.6 Roles of tsunami-resistant technology

Tsunami-resistant technology is expected to enable flexible adoption of tsunami protection alternatives through WP, SR, and DS. In this way, it will contribute to realizing comprehensive and appropriate tsunami protection measures depending on site specific conditions as well as to risk reduction by redundant protection measures. This aspect is particularly important for existing plants where the site elevations are pre-fixed.

It will also be a basis for tsunami fragility assessment for tsunami PSA and/or seismic-tsunami PSA, which will help establishing a risk-based safety assurance scheme, discussed in **4.1.**

7. CONCLUSIONS

This paper addressed engineering agenda for nuclear safety based on the experiences of the 2011 Tohoku-Pacific Earthquake. Discussion was focused on how technological developments and implementation should be conducted for the nuclear safety in the future. Major points of discussion in this paper may be summarized as follows.

1. Based on the performance of nuclear power plants in the disaster area, three critical lessons were proposed: i) Risk-based decision, ii) "Scientific imagination", and iii) Speed in action.
2. Risk-based decision scheme for nuclear safety was proposed. It constitutes an integrated safety assurance of the entire plant system by combined effects of deterministic design and risk-based assessment by residual risk. It urges improvements of Japan's NSC Seismic Design Guide.
3. Significance of implementing PSA methodology was discussed, where benefits of using PSA were addressed as i) Integrated system reliability ii) Identification of critical accident scenarios and critical plant components, iii) Rigorous application to common-cause failures caused by earthquake and/or tsunami, and iv) Synthetic treatment of inherent uncertainties:
4. Establishment of seismic-tsunami PSA was proposed. Scheme of integrating seismic PSA and tsunami PSA was presented.
5. Establishment of "tsunami-resistant technology" was proposed. For eliminating "cliff-edge effects", "smooth fragility" and "safe relocation" were proposed. Based on observation of various types of tsunami load effects, a framework of technical categories i) Water proof (WP), ii) Structural resistance (SR), and iii) Dry siting (DS) were proposed.

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