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CONCEPT FOR DEVELOPING SEISMIC-TSUNAMI PSA METHODOLOGY CONSIDERING COMBINATION OF SEISMIC AND TSUNAMI EVENTS AT MULTI-UNITS

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ABSTRACT: The Tohoku Earthquake occurred and caused a huge tsunami. The Fukushima Dai-ichi NPP were attacked by the tsunami and core damage occurred. In risk evaluation practice for seismic and tsunami events, no consideration have been taken on dependency of ground motion effects and tsunami effects. The concept and important issues for developing seismic-tsunami PSA methodology considering the combination of seismic and tsunami events at multi-units are described.

Key Words: Fukushima Dai-ich NPP accident, Multi-units, Seismic and Tsunami Events, Seismic-Tsunami PSA, Common cause failure, Correlation

1. INTRODUCTION

The Tohoku earthquake (Mw9.0) occurred at 14:46 on March 11, 2011, and caused a huge tsunami. strong seismic motion was observed at the Fukushima Dai-ichi NPP (F1-NPP) and reactors were shut down after control rods had inserted. While the reactors were shut down normally, they were attacked by tsunami about 46 minutes after the earthquake occurred. Various equipment of the water intake system and emergency diesel generators were flooded. External power supply was also lost due to damage by strong ground motions and tsunami. In this situation, station blackout took place. As a consequence, functions of reactor cooling system was lost, core damage (CD) occurred and radioactive materials were released to the off-site area (Japanese government 2011).

In risk evaluation practice for seismic and tsunami events, no consideration have been taken on dependency of seismic ground motion effects and/or tsunami effects, and seismic PSA and tsunami PSA have been developed independently for efficiency. Both of each evaluation methods are composed of the four items (Hirano 2008), (Sugino 2008):

(1) setting of accident scenarios,
(2) hazard evaluation,
(3) fragility evaluation and
(4) accident sequence evaluation.

Based on the lessons learned from the accident of F1-NPPs, development of "seismic-tsunami PSA (S-T PSA)" considering combination of seismic motion and tsunami effects is urgently required.

This paper describes the overview of F1-NPP accident and the outlines of seismic PSA and tsunami PSA. Further the paper represents the concept and important issues for developing S-TPSA methodology considering the combination of seismic and tsunami events at multi-units.

2. OVERVIEW OF FUKUSHIMA NPP ACCIDENT AND LESSONS LEARNED

2.1 Overview of F1-NPP accident at Tohoku earthquake/tsunami

The F1-NPP station is a multi-units site with 6 BWRs. The NPPs detected strong seismic motions of the 3.11 Tohoku Earthquake and control rods were inserted automatically. However seawater supply system (seawater pump, switchboard (switchgear) / signal-processing board (motor control)) for seawater pump and also emergency power supply system (diesel generator (DG), DG switchboard (switchgear) / signal-processing board (motor control)) in the support line were flooded due to the tsunami as shown in **Fig.1**, and as a result all of seawater supply systems / emergency power supply systems were lost in function simultaneously. Function of interconnected power supply between neighboring Units (Units 1 and 2, Units 3 and 4, and Units 5 and 6) was lost. Breakers and emergency transformer in the switchyard were damaged, and a transmission line tower out of the site was collapsed, and offsite power supply was lost. These results led to loss of all AC power (station blackout) (Japanese government 2011).

On the other hand rector core isolation cooling system (RCIC), which is steam-driven cooling system, in the front line (FL) was operated during a certain time but it stopped after a short time operation. Cooling systems in FL other than RCIC (and high pressure coolant injection system (HPCI) or isolation condenser (IC)) were not operated due to loss of AC power. Failure of reactor core cooling resulted in core damage (core melt) in about 5 or 6 hours. Temperature and pressure in the primary containment vessel rose up, and radioactive materials were released through seals to the on-site and the off-site. The land in wide area was contaminated by the radioactive materials (Japanese government 2011). Information relevant to the accidents has not always been provided to the public in a proper manner.

Fig.1 Situation of tsunami and disaster at Fukushima Daiichi nuclear power plant

2.2 Lessons learned from accident

The issues of seismic engineering based on lessons learned from F1-NPP accident are as follows:

① Occurrence of gigantic earthquake and tsunami, and combination of seismic hazard and tsunami hazard
② Risk evaluation of multi-units

③ Combined emergency of both natural disaster and nuclear accident
④ Core damage during short time based on functional failure of support systems(seawater supply, power supply and signal systems)
⑤ Common cause failure of multi structures and components
⑥ Dependency among neighboring units

3. OUTLINE OF SEISMIC PSA AND ITS USABILITY

3.1 Procedure of the Seismic PSA

The procedure of seismic PSA consists of 5 steps as shown in **Fig. 2** (Hirano 2008).

- Step 1: Collection of information related to earthquake and setting of accident scenario
- Step 2: seismic hazard evaluation
- Step 3: Fragility evaluation
- Step 4: Accident sequence evaluation
- Step 5: Documentation

3.2 Collection of information related to earthquake and setting of accident scenario

The collection of information related to earthquake and setting of accident scenario is shown in **Fig. 2**. At first, relevant information should be gathered. Then, conduct "plant walk-down" based on the gathered information. Finally, set various accident scenario based on gathering relevant information and the result of "plant walk-down".

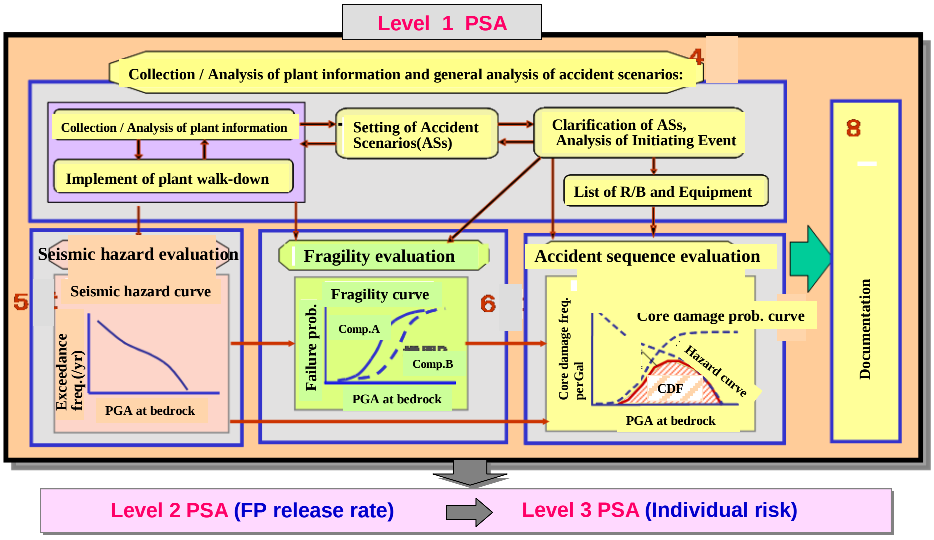

Fig.2 Procedure of seismic PSA

3.3 Seismic hazard evaluation

The seismic hazard evaluation is shown in **Fig.3.** In the evaluation of seismic hazard, set "specified source model" for active faults and set "zone source model" for diffuse seismicity. Strong motions are evaluated for these source models by using propagation model (fault model method and attenuation model). Then, like this seismic hazard curve should be derived with the uncertainty.

The uncertainties do exist in the source models and propagation models of seismic motion described above. The uncertainties are consisted of "aleatory uncertainty" that is accompanied with phenomenology and "epistemic uncertainty" that is accompanied with lacks of recognition and information. Evaluation of uncertainty is conducted by using logic tree (LT) with this epistemic uncertainty as a target as shown in **Fig. 4**.

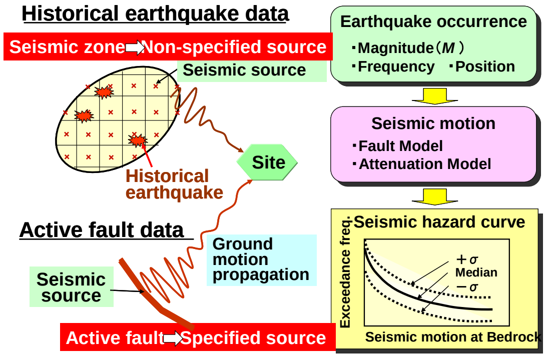

Fig.3 Procedure of seismic hazard evaluation

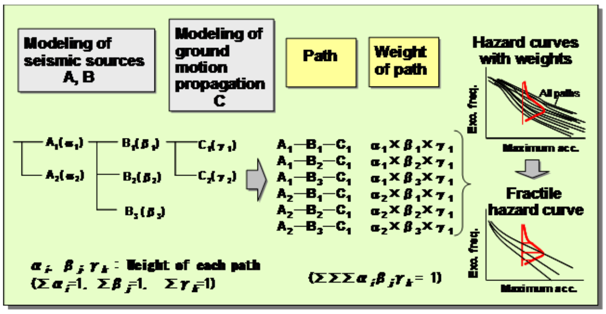

Fig.4 Outline of logic trees

3.4 Fragility evaluation

3.4.1 Targeted Structures and components

In the evaluation method of fragility, targeted buildings, structures and components are those classified as "class S" which is the most important class on seismic safety as shown in **Fig. 5**. Those classified as "class B" and "class C" which would affect safety are targeted as well. These buildings, structures and components include reactor building, outside structures and inside components. Inside components are categorized as static and dynamic components. Each category are consisted of components of mechanical system and those of electrical system.

On the Seismic PSA, structures and components targeted to evaluate are about 200 and categorized as about 50 areas on fault Trees.

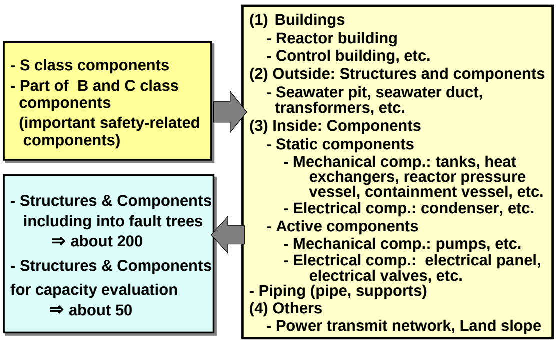

Fig.5 Structures and components to be evaluated

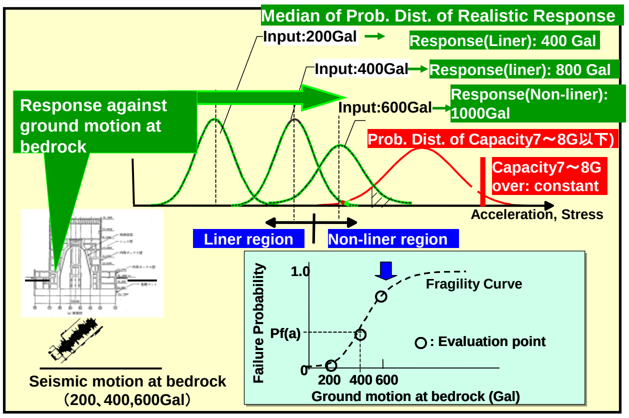

Fig.6 Procedure of fragility evaluation

3.4.2 Fragility evaluation method

The fragility evaluation method by using components installed in a reactor building is shown in **Fig. 6**. In the response evaluation of this component, the seismic motion at the bedrock is set up. Then, the response analysis of soil, buildings and components against this seismic motion is conducted and evaluation would be made with including dispersion. On the fragility evaluation, seismic motion level at the bedrock would be increased like 200 Gal, 400 Gal, 600 Gal, and derive distribution of each responses. Fragility curves are obtained as the conditional probability that the realistic response of component exceeded its capacity as shown in figure. The capacity of targeted components is evaluated by including dispersion.

On the fragility evaluation, the evaluation of functional failure limit of structures and components on the capacity evaluation is extremely important.

3.5 Accident sequences evaluation

In case of evaluating accident sequences, the accident sequences are represented by using event tree based on various accident scenario considered in chapter 4. Then develop fault trees that consists each event trees as shown in **Fig. 7.**

Core damage probabilities (CDPs) are evaluated by using event trees, fault trees and fragilities of components as shown in the **Fig. 8**. The CDF is estimated by multiplying the seismic hazard curve per Gal by CDP curve, and it is corresponded to the area of this semicircular shape that is calculated by integration for seismic motion acceleration (Gal).

In general, the range of seismic motion that might contribute to CDF is from 1 to 2.5 times of design basis seismic motion S2 in Japan. The range of Exceedance frequency on seismic hazard is from 10^{-3} to 10^{-5} (1/year).

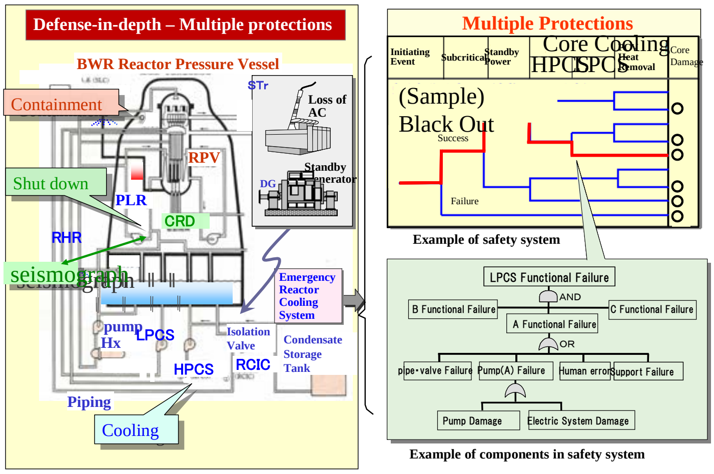

Fig.7 Accident sequence evaluation

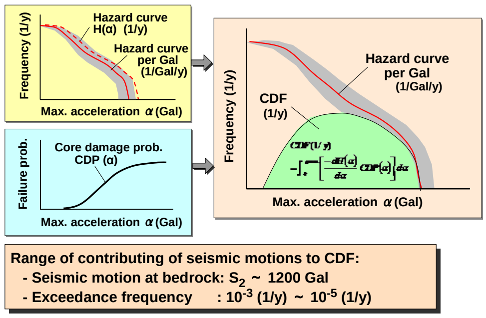

Fig.8 Procedure of core damage frequency (CDF) and dominantly contributing ranges of seismic motion

Table 1 Comparisn table of accident scenario of seismic PSA and Kashiwazaki NPP

Examples for wide range of Accidental Scenario described in the Standard for Procedure of Seismic PSA 2007 (AESJ)	Damage Status of NPP by NCOE
A. Effect on Core Damage by Main Shock	
A1.Direct Effect — ①SSCs having Safety Function (Damage of As, A Facilities)	① None
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	① (Unit 6) Damage of connection part of wheel axis of Overhead Traveling Center
②Effect on As, A facilities by damaging of B, C facilities	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
③Effect on adjacent Building by Turbine Missile	③ None
･Outdoor Facilities	
④Effect on buildings by falling of Stack	④ Incline of Stack, Shift of Duct
⑤Effect on Buildings and Surrounding Facilities by Possible Collapses of the Surrounding Grounds above the foundation	⑤ Partial land slide of slope in the east side of Switchyard
⑥External Power Source Loss by Damages of Power Line Towers of Power Grids	⑥ None
⑦Function Loss of Cooling by stopping Industrial Water Supply	⑦ None. Floods in the basement of Building by Breakage of Piping for Fire Extinction
A2-2 Effect on Human Error	
⑧Incorrect operation introduced by highly stressed operators and workers during and after earthquakes	⑧(Unit 7) Iodine detected at main exhaust tower in periodic measurement
⑨Trouble of backup operation by blackouts for Damage of Insulator of Transformer	⑨(Unit 3) Fire broke out at Auxiliary Transformer 3B (Unit 3,4,6) Oil leakage of Auxiliary Transformer 3B
⑩Trouble of transportation on site by soil liquefaction and damage of retaining wall	⑩ Caving in yard
⑪Effect to operators by Damage of Secondary members of Sealing	⑪ Dropping of secondary members of Sealing
⑫Mistakes on Plans and Designs, Selecting Materials, Manufacturing and Building to Completion of Facilities	⑫ None
B. Effect on Core Damage by Aftershocks — ⑬Evaluate Increase of CDF by Aftershocks	⑬ None

3.6 Usability of seismic PSA

The Niigata-ken Chuetsu-Oki earthquake (NCO) was occurred in the vicinity of Kashiwazaki-Kariwa NPP (KK-NPP) in July 2007. The KK-NPP is consisted with 7 reactor units. Seismometers had been installed in and outside of buildings and many seismic motions are recorded.

The **table 1** shows the comparison between the accident scenario of seismic PSA and accidental event occurred at the NCO earthquake. The accident scenario of seismic PSA was described in the seismic level -1 PSA Implementation standards that was compiled by Atomic Energy Society of Japan in March 2007 that is one and a half year before the occurrence of the NCO earthquake. The contents described in the seismic PSA implementation standard identified well about the points occurred at the NCO earthquake. It clearly showed further usability of seismic PSA method.

4. OUTLINE OF TSUNAMI PSA AND ITS USABILITY

4.1 Procedure of the Seismic PSA

The procedure of tsunami PSA consists of 4 steps as shown in **Fig.9** (Sugino 2008).

-Step 1: Collection of information related to earthquake and setting of accident scenario
- Step 2: Tsunami hazard evaluation
- Step 3: Fragility evaluation
- Step 4: Accident sequence evaluation

4.2 Collection of information related to earthquake and setting of accident scenario

The collection of information related to earthquake and setting of accident scenario as shown in **Fig.10,** at first, relevant information should be gathered. Then, conduct “plant walk-down” based on the gathered information. Finally, set various accident scenario based on gathering relevant information and the result of “plant walk-down” as shown in **Fig. 10**.

The accident scenario should be identified with dividing cases for tsunami run-up and backwash. Following accident scenario are assumed in case of tsunami run-up as shown in this figure.

-Function loss of sea water pump
- Functional loss of power supply system
- Functional loss of DG oil tank
- Function loss of sea water intake pit
- Function loss of sea water facilities by debris flow attack
- Functional loss of sea water intake function by deposition of sea sand
- Turn over of sea water pump cause by tsunami backwash

4.3 Seismic hazard evaluation

The seismic hazard evaluation is shown in **Fig. 11**. The tsunami hazard evaluation is defined by the tsunami wave height at shoreline and its exceedance frequency.

In case of evaluating tsunami hazard, tsunami source models for both near-field active faults and far-field earthquakes such as Chile earthquake should be set. Then, ocean floor topographic model should be set by dividing it for far-field and near-field. In addition, onshore topographic models are set to evaluate onshore run-ups.

The LTs are developed by considering uncertainties of tsunami source models, ocean floor topographic models and onshore topographic models. Conduct tsunami simulation for paths of each LTs, and obtain tsunami hazard curve.

The tsunami hazard curve is needed to obtain in cases of both tsunami run-ups and tsunami backwash as shown in **Fig.12**.

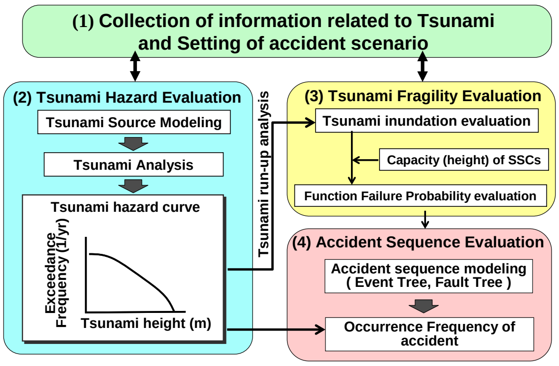

Fig.9 Procedure of tsunami PSA

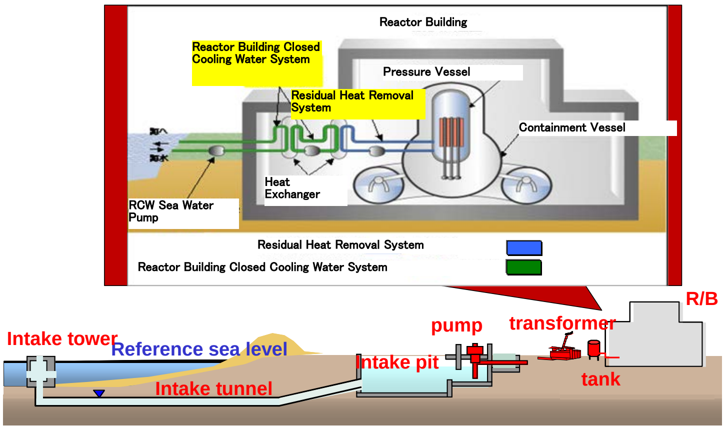

Fig.10 Collection of information related to earthquakes and setting of accident scenario

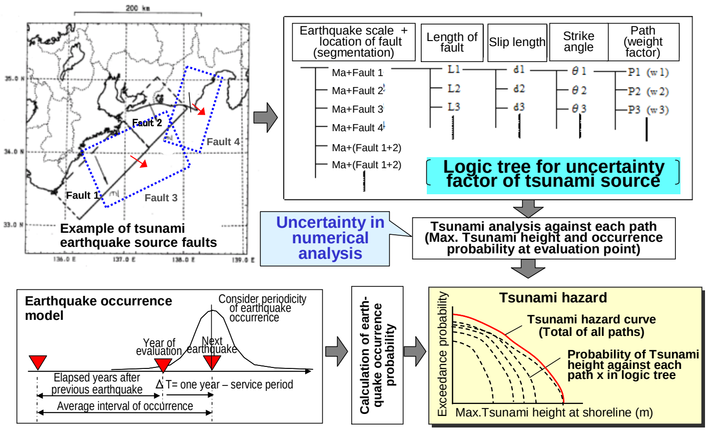

Fig.11 Procedure of tsunami hazard evaluation

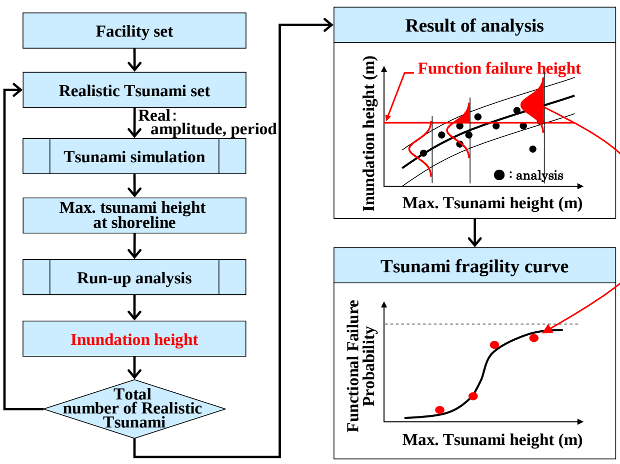

Fig.12 Procedure of tsunami fragility evaluation

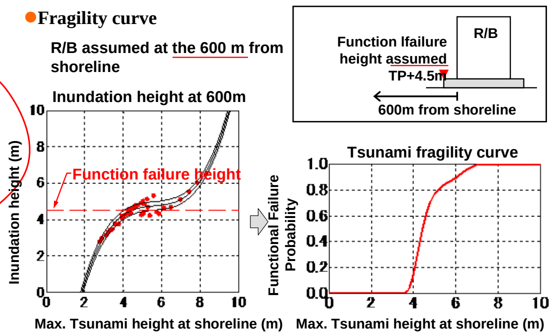

Fig.13 Example of tsunami fragility evaluation

4.4 Tsunami fragility evaluation

4.4.1 Procedure of tsunami fragility evaluation

Fig. 12 shows the evaluation procedure of tsunami fragilities. On the fragility evaluation of tsunami, fragility curves are obtained as the conditional probability that tsunami wave height exceeded the installation height of targeted structures and components as shown in figure.

Tsunami wave heights are evaluated by conducting analysis of onshore run-ups to the area that targeted buildings, structures and components are installed. Evaluate uncertainties and dispersion of the wave heights of tsunami wave run-ups.

4.4.2 Damage part, damage mode and its physical quantities for evaluation of tsunami fragilities

It is important to identify the modes on function failure against tsunami in case of targeting facilities outside and inside of buildings. It is also important to identify their functional failure limits and intensities of tsunami. The intensities of tsunami are consisted of tsunami wave height, tsunami wave force, scour etc.

The failure parts, failure modes and physical quantities representing functional failure limits are different for each targeted structures and components. For quantitative evaluation of tsunami margins, attention should be paid that physical quantities representing margins would differ as the failure parts and failure modes to be evaluated are also different based on targeted structures and components.

4.4.3 Examples of Fragility Evaluation

Fig. 13 shows an example of fragility evaluation. The results on analysis of onshore run-ups of tsunami are shown for targeted point in the **Fig. 13**. This figure shows the result of fragility evaluation in case of assuming the installation point of reactor building is 600 m distant from the shoreline, and function failure is occurred when tsunami run-ups reaches to the building.

4.5 Accident sequence evaluation

In case of evaluating accident sequences, the accident sequences are represented by using event tree based on various accident scenarios considered in chapter 4. The evaluation method as shown in **Fig. 14** is the same as that of Seismic PSA.

The accident scenarios of Tsunami are developed in cases of both tsunami run-ups and tsunami backwash. **Fig. 15** shows the event tree based on an accident scenario for tsunami run-ups. The accident scenario starts from the function failure of facilities outside buildings and spread out to function failure inside buildings, and finally reaching core damage. The ET of tsunami is very simple as shown in the figure. The ET based on an accident scenario for tsunami backwash is also developed. The event tree in case of tsunami backwash is simpler than the case of tsunami run-ups.

4.6 Usability of tsunami PSA

The Tohoku earthquake was occurred off the coast of Tohoku district in March 2011 as shown in **Fig. 1**. The tsunami of the Tohoku earthquake attacked the F1-NPP with the wave height that is about 2 times larger than the design basis tsunami wave height.

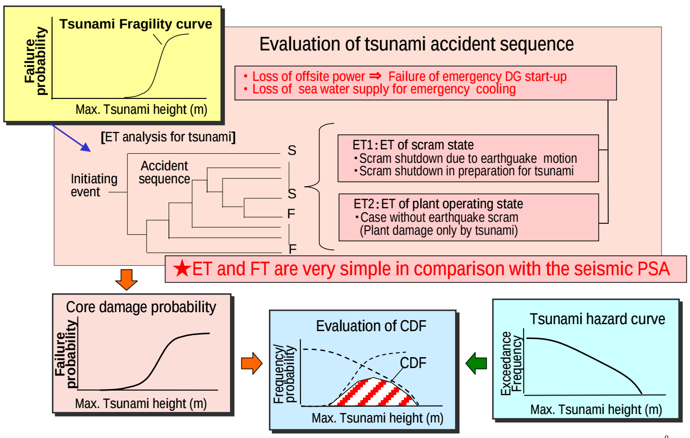

Fig.14 Procedure of tsunami accident sequence evaluation

Table 2 Comparison results between tsunami PSA and Fukushima NPP

Accident Scenarios at Tsunami PSA	Accidents at Fukushima Daiichi NPP
(1) Failure of Sea Water Pump	Occurred
(2) Failure of Power supply	ditto
(3) Failure of emergency DG	ditto
(4) Failure of Transformer at outdoor	ditto
(5) Inundation of reactor building	ditto
(6) Inundation of turbine building	ditto

Table 2 shows the comparison between the assumed accident scenario of tsunami PSA developed by JNES and accidental event occurred at the Tohoku earthquake. The assumed accident scenario of tsunami PSA was identified by JNES from 2006 as a part of developing tsunami PSA method.

The contents of tsunami PSA developed more than a year ago identified well about the points occurred at the F1-NPP. It clearly showed further usability of Tsunami PSA method

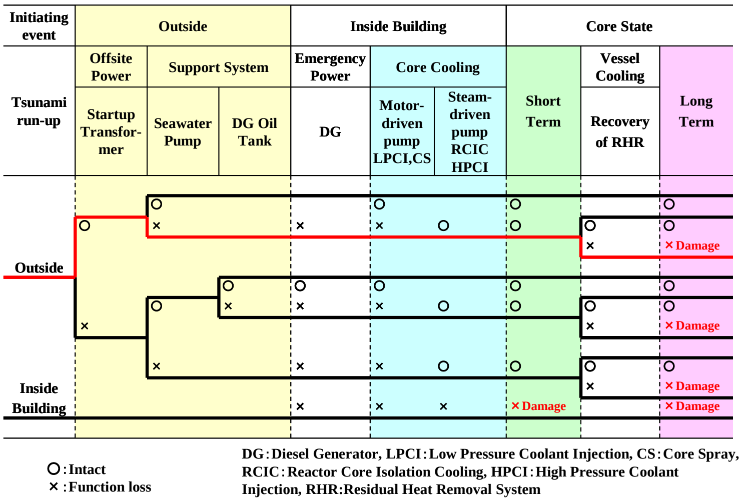

Fig.15 Example of accident sequence by run-up tsunami

5. CONCEPT OF SEISMIC-TSUNAMI PSA METHODOLOGY

5.1 Concept of development

The concept and important issues for developing seismic-tsunami PSA methodology considering the combination of seismic and tsunami events at multi-units are described..

5.2 Setting of accident scenarios

Four cases of seismic and tsunami accident scenario are shown in **Fig.16**;

Case 1: Seismic (no CD) and Tsunami (no CD),
Case 2: Seismic (no CD) and Tsunami (with CD),
Case 3: Seismic (with CD) and Tsunami (no CD) and
Case 4: Seismic (with CD) and Tsunami (with CD).

Of the four cases shown herein, Case 1 is the safe case, while other three are cases with core damage occurrence. 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.

5.3 Seismic-tsunami hazard evaluation

The hazard for the external event at the multi-unit NPPs is evaluated. Seismic and tsunami hazard evaluations are practiced by developing hazard curves for seismic motion and tsunami height, respectively as shown in **Fig.17**. They are plotted against annual frequency of exceedance. Seismic hazard curves and tsunami hazard curves are not independent because they are based on common seismic events. But different nature of strong seismic motion (period range: 0.1~1sec) and tsunami rise time (period range: 10~120sec) requires careful consideration of their source characterization. Because of such difference in period ranges, correlated seismic motions at multi-unit locations should be considered, while tsunami height can be treated as more or less uniform within a single site.

5.4 Seismic-tsunami fragility evaluation

In fragility evaluation, structures and components of multi-unit reactors are covered and correlation of their failures should be considered. The functional failure probability (fragility: $F_i^{S-T}(\alpha, h)$) with conditions that an arbitrary component "i" will secure its function against seismic motion α but fail against tsunami h is represented as equation (1) and shown in **Fig.18**;

$$F_i^{S-T}(\alpha, h) = \overline{F_i^S(\alpha)} \times F_i^T(h) = \left(1 - F_i^S(\alpha)\right) \times F_i^T(h) \tag{1}$$

Where $F_i^S(\alpha)$ and $F_i^T(h)$ are functional failure probability of component "i" against α and h, respectively. $\overline{F_i^S(\alpha)}$ is functional success probability of component "i" against α.

In seismic-tsunami fragility evaluation, it is important to consider the fatigue effect of structure and component under seismic motions by main shock and gigantic aftershock.

5.5 Seismic-tsunami accident sequence evaluation

In accident sequence evaluation involving CD, all of the Cases 2~4 should be incorporated. The total CDF is represented by CDF(S-T) = CDF(Case2)+CDF(Case3)+CDF(Case4). In case of considering combined seismic and tsunami effects, CDF(S-T) will be higher than CDF(S), the cases of seismic actions alone, because of contributions of Case 2.

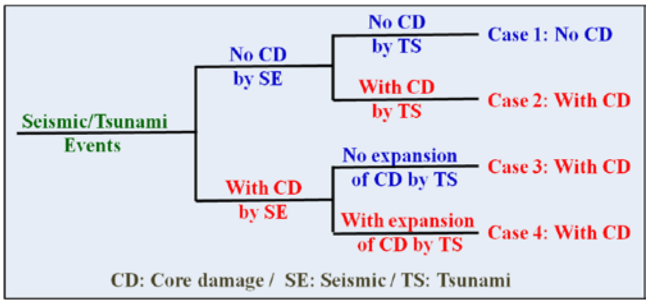

Fig.16 Cases of accident scenarios on seismic-tsunami PSA

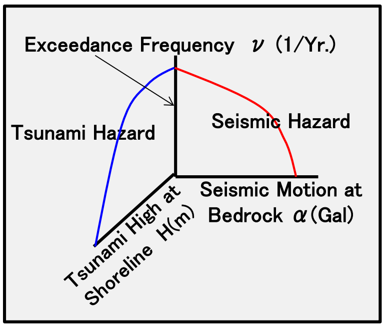

Fig.17 Definition of hazard on seismic-tsunami PSA

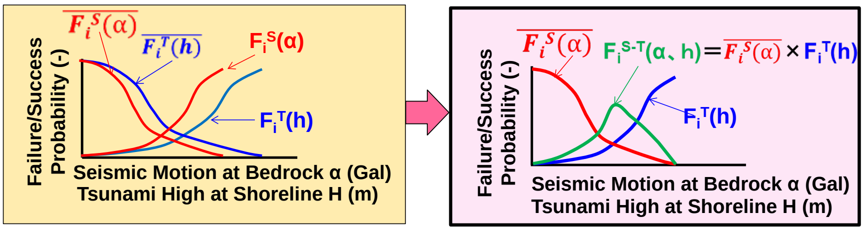

Fig.18 Concept of fragility evaluation on seismic-tsunami PSA

6. CONCLUSIONS

The summarizations of this paper are as follows.

(1) Usability and application of PSA

1) PSA is a usable method to identify important accident sequence, system and components for safety and these results are candidates to take countermeasures as AMs.

2) PSA is an effective measure to evaluate AM's effectiveness.

(2)Improve IAEA/ISSC's guideline on PSA of external events

1) JNES will develop and improve seismic hazard method considering gigantic aftershock.

2) JNES will also develop and improve seismic-tsunami PSA method considering combination of seismic and tsunami events.
3) JNES will contribute improvement of IAEA's guideline on PSA of external events through new EBP of IAEA/ISSC.

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