USABILITY OF TSUNAMI PRA BASED ON ACCIDENTS OF FUKUSHIMA DAI-ICHI NPP UNDER 2011 TOHOKU TSUNAMI

Katsumi Ebisawa, Hideharu Sugino, Yoko Iwabuchi and Masahide Nishio
Japan Nuclear Energy Safety Organization, Japan

SUMMARY:
The Tohoku earthquake occurred off the coast of Tohoku district in March 11, 2011 and caused a gigantic tsunami. The tsunami attacked Fukushima Dai-ichi Nuclear Power Plant (F1-NPP) with the wave height that is about 2 times larger than the design basis tsunami wave height. An extreme core damage accident was caused at F1-NPP. On the other hand, as a part of developing Tsunami Probabilistic Risk Assessment (TPRA) method, Japan Nuclear Energy Safety Organization (JNES) has been conducting to identify the accident scenarios of NPP against tsunami event based on TPRA method since 2004. JNES compared and examined the relationship between the above accident scenarios by TPRA and accidents at F1-NPP. The accident scenarios by TPRA more than a year ago identified well about the points occurred at the F1-NPP. It clearly showed further usability of TPRA.

Keywords: Tohoku earthquake and tsunami, Fukushima Dai-ichi NPP accident, Tsunami PRA, Usability

1. INTRODUCTION

The Tohoku earthquake (Mw9.0) occurred at 14:46 on March 11, 2011 and caused a huge tsunami. The strong seismic motion was observed at the Fukushima Dai-ichi Nuclear Power Plant (F1-NPP) of the Tokyo Elec. Power Co. (TEPCO) 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. The various components of the water intake system and emergency diesel generators were flooded. External power supply was also lost due to damage by strong seismic motions and tsunami. In this situation, station blackout occurred 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, Kameda, 2012).

On the other hand, as a part of developing Tsunami Probabilistic Risk Assessment (TPRA) method, Japan Nuclear Energy Safety Organization (JNES) was conducting to identify the accident scenarios of NPPs against tsunami event based on TPRA method from 2004 (Sugino, 2008, Ebisawa, 2012).

JNES compared and examined the relationship between the above accident scenarios by TPRA and accidents at F1-NPP. The accident scenarios by TPRA more than a year ago identified well about the points occurred at the F1-NPP. It clearly showed further usability of TPRA method (Ebisawa, 2012).

This paper describes the overview of F1-NPP accidents and the TPSA. Then the paper represents comparison results the relationship between the accident scenarios by TPRA and accidents at F1-NPP and usability of tsunami PRA. Further the paper describes also the future issues.

2. TSUNAMI DISASTER OF NUCLEAR POWER PLANTS AND VARIOUS TYPES OF LOAD EFFECTS BY TSUNAMI

2.1. Fukushima Dai-ichi NPP

2.1.1. Outline of F1-NPP and Tsunami system observed tsunami

The F1-NPP is a multi-units site with 6 BWRs as shown in Fig. 1 (a)-(c). Fig. 1 (c) shows the location of each unit. Fig. 1 (a) and (b) are the EW and NS sections of reactor and turbine buildings respectively. The turbine buildings are in front on the sea. The emergency diesel generators are installed at the basement on the site of the sea in the turbine buildings.

F1-NPP was attacked by tsunami about 46 minutes after the earthquake as shown in Fig. 2. The tide level observation system consists of the tide gauge and the recording device at building. The arrival time and tsunami height of first big wave were 41 min after the main shock and O.P. about 4 m respectively. The arrival time of second big wave was 8 min after the first big wave and the water level by the second big wave was unknown due to tide gauge failure. The maximum scale of the tide gauge is 7.5 m. The tsunami height was more than 10 m according to the experts' estimation from the picture showing the overflow status of tsunami seawall (10 m).

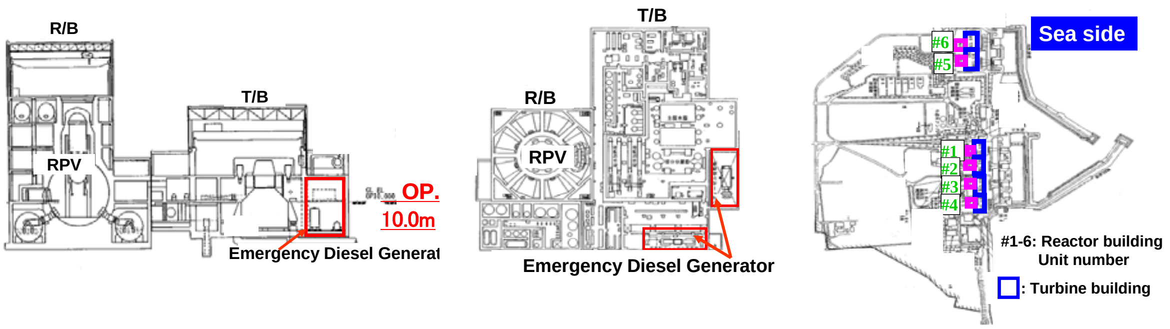
2.1.2. Design tsunami height and site height

TEPCO evaluated the design tsunami height based on Japanese Society Civil Engineering (JSCE) guide (JSCE, 2002), assessing Shioyazaki EQ. (M7.9) as M8.0 voluntary, and the highest water level of each unit was set as 5.4 to 5.7 m. The design tsunami height (5.7m) is lower than the tsunami height (10m). The site height (10 m) is lower than the inundation height (14m).

2.1.3. Damage of NPP

As to the sea water pump facilities for component cooling (height: 5.6 to 6 m), all units were flooded by tsunami as shown in Fig. 3. Whether or not they were damaged by wave power is under investigation. The Emergency Diesel Generators (EDGs) and switchboards installed in the basement floor of the reactor and the turbine buildings (height: 0 to 5.8 m) were flooded except for Unit 6, and the emergency power source supply (EPS) was lost. Regarding Unit 6, two out of three EDGs were installed in the first basement of the RB and were flooded, but one DG installed on the first floor of DG building was not flooded and the EPS supply was possible. A transmission line tower out of the site was collapsed, and offsite power supply was lost.

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. Information relevant to the accidents has not always been provided to the public in a proper manner.



(a) Reactor building (b) Turbine building (c) Location of F1-NPP

Figure 1. (a)-(c) Location of Fukushima Dai-ichi nuclear power plant

Figure 2. Situation of tsunami (by Tokyo Elec. Power Co., 2011)

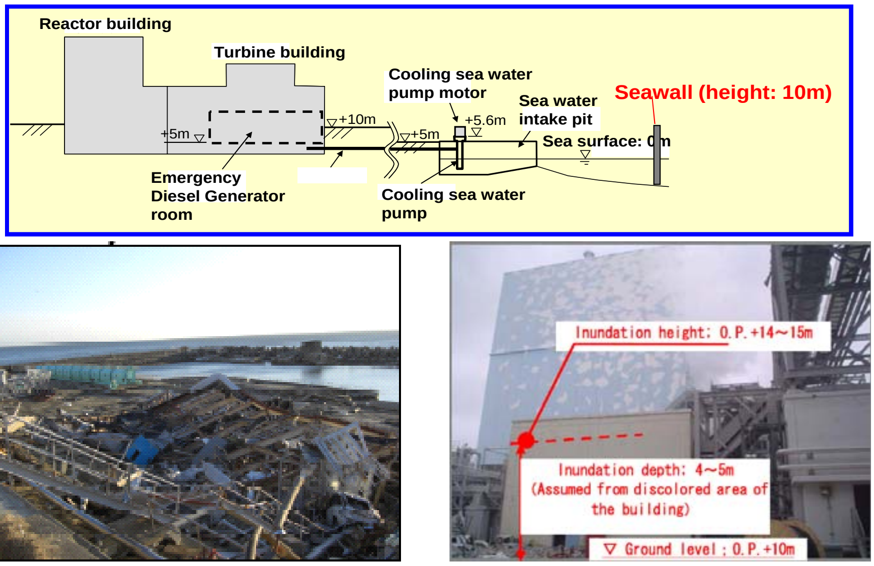


Figure 3. Illustration of sea water supply system and situation of tsunami disaster at Fukushima Dai-ichi nuclear power plant (by Tokyo Elec. Power Co., 2011)

2.2 Others NPPs

2.2.1 Tokai Dai-ni NPP

The Tokai-Daini-NPP of Japanese Nuclear Elec. Power Co. is a single unit site with BWR. The arrival time and tsunami height of first big wave were 30 min after the main shock (14:46) and O.P. about 5.4 m respectively. The record of tide gauge was not recorded because the power supply was disrupted from16:40 and the tsunami height exceeded the tsunami measurement scale.

The design tsunami height was H.P. +5.8 m. The design tsunami height (5.8m) is lower than the inundation height (6.3m). The site height (6.1 m) is lower than the inundation height (6.3m). When the earthquake hit the site, the north emergency seawater pump room was under leveling construction of its sidewall as protection against tsunami. The construction work put in place a new sidewall up to H.P. +7.0 m outside the existing sidewall, but the waterproof sealing of the penetration of the wall had not been completed as shown in Fig. 4. The tsunami flooded the north emergency seawater pump area in the seawater pump room through the small holes. One of three seawater pumps for EDGs was submerged, and one of three EDGs stopped. The other two EDGs were able to operate, successfully ensuring emergency power supply.

Tokai Dai-ni plant where inundation was slight and light enough was able to avoid total loss of the terminal heat sinks.

2.2.2 Onagawa NPP

The Onagawa NPP of Tohoku Elec. Power Co. is a multi-units site with 3 BWRs. The arrival time of first big wave was 43 min after the main shock (14:46). The observed maximum tsunami height was O.P. about 13 m. Height of site was 14.8 m. Subsidence due to crustal deformation was about 1m.

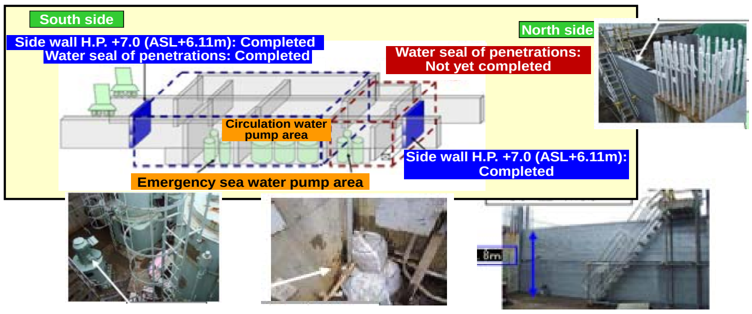
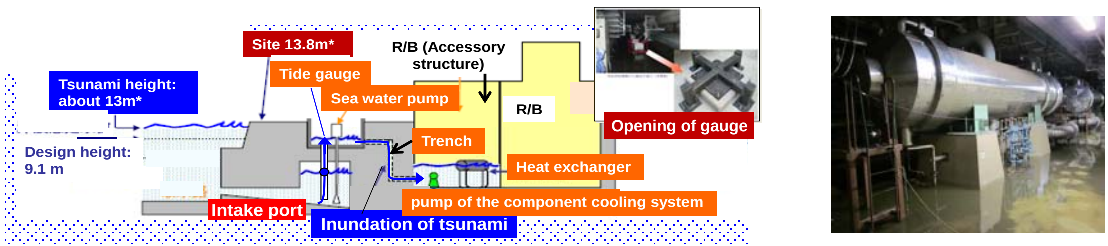


Figure 4. Illustration of sea water supply system and situation of tsunami disaster at Tokai Dai-ni nuclear power plant

Onagawa district is featured with a sawtooth coastline. In this area, lessons learnt from historical tsunami disasters have taken root as a local climate. To apply for establishment permit, Tohoku Elec. Power Co. listened from many local residents on tsunami run-up height and damage, and reflected them in the site height of 14.8 m. The design tsunami height (13.6m) is larger than the observed height (13m). The site height (13.8 m) considering the 1m ground subsidence is larger than the observed height (13m).

Component cooling system consists of intake channel/seawater pump/ seawater pump room/ heat exchanger room as shown in Fig. 5 (a), (b). The seawater pump room was designed as the height of 14.8 m and about 100 m away from the coast to prevent the inundation by run-up tsunami as shown in Fig. 5 (a). Inside the room, the tide gauge is installed with an opening. Tide gauge is to allow the automatic stop of the seawater pump in short of seawater due to the backrush of a tsunami. The tsunami did not attack the seawater pump room directly. The seawater overflowed in the room through the opening of gauge. Then the seawater flowed from the pump room, via the trench, into the basement floors of the reactor buildings, causing the heat exchanger room of the component cooling water system in the second basement to be submerged as shown in Fig. 5 (b). The component cooling water pump of Unit 2 was also submerged, which thereby caused the cooling function of EDGs to be lost, with two units stopped out of those three generators.



(a) Sea water supply system

(b) Disaster of heat exchanger room

Figure 5. (a), (b) Illustration of sea water supply system and situation of tsunami disaster at Onagawa nuclear power plant (by Tohoku Elec. Power Co., 2011)

Tohoku Elec. Power Co. Inc. took measures to prevent the piping penetrations and the cable tray penetrations from the seawater pump room to the trench. They would set up a flood barrier around the seawater pump room. Then the seawater flowed from the pump room, via the trench, into the basement floors of the reactor buildings, causing the heat exchanger room of the component cooling water system in the second basement to be submerged.

The component cooling water pump of Unit 2 was also submerged, which thereby caused the cooling function of EDGs to be lost, with two units stopped out of those three generators.
Tohoku Elec. Power Co. Inc. took measures to prevent the piping penetrations and the cable tray penetrations from the seawater pump room to the trench. They would set up a flood barrier around the

seawater pump room.

The Onagawa NPP where inundation was slight and light enough were able to avoid total loss of the terminal heat sinks.

3. OUTLINE OF TSUNAMI PRA

3.1 Procedure of the Tsunami PRA

The procedure of tsunami PRA consists of 4 steps as shown in Fig. 6 (Sugino, 2008).

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

3.2 Collection of plant information and setting of accident scenario

In the collection of information and setting of accident scenario as shown in Fig. 7, 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. 7.

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

- Functional loss of sea water pump
- Functional loss of power supply system
- Functional loss of DG oil tank
- Functional loss of sea water intake pit
- Functional 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

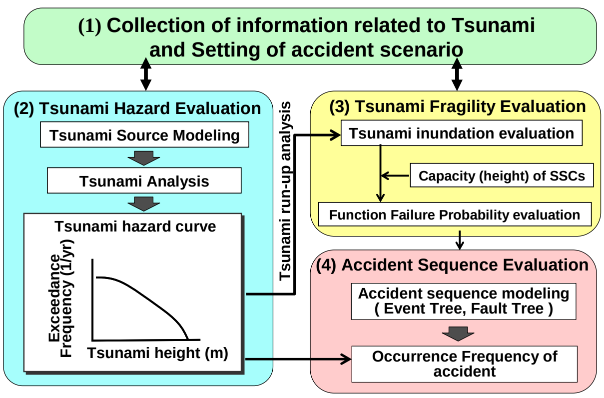


Figure 6. Procedure of tsunami PSA

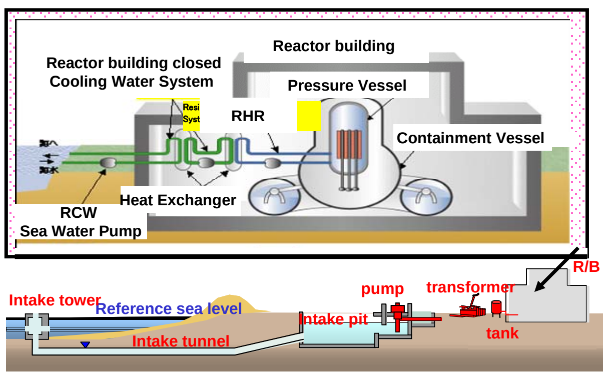


Figure 7. Collection of plant information and setting of accident scenarios

3.3 Tsunami hazard evaluation

The tsunami hazard evaluation is shown in Fig. 8. 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 logic trees (LTs) are developed by considering uncertainties of tsunami source models, ocean floor topographic models and onshore topographic models. Tsunami simulation is conducted for paths of each LTs, and tsunami hazard curve is obtained. The tsunami hazard curve is needed to obtain in cases of both tsunami run-ups and tsunami backwash.

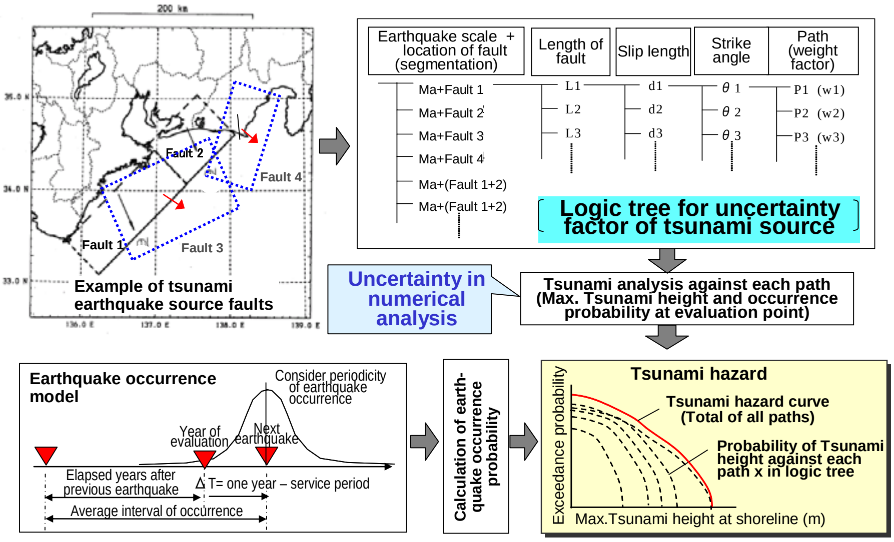


Figure 8. Procedure of tsunami hazard evaluation

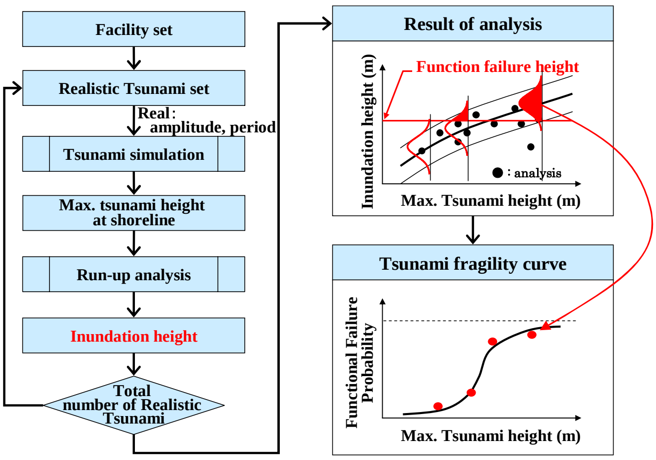


Figure 9. Procedure of tsunami fragility evaluation

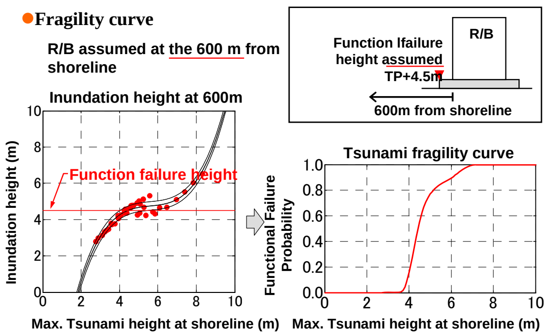


Figure 10. Example of tsunami fragility

3.4 Tsunami fragility evaluation

3.4.1 Procedure of tsunami fragility evaluation

The Fig. 9 shows the procedure of tsunami fragility evaluation. 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 the figure.

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

3.4.2 Damage part, damage mode and its physical quantities for evaluation of tsunami fragilities
It is important to identify the parts and 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.

3.4.3 Examples of Fragility Evaluation
The Fig. 10 shows an example of fragility evaluation. The results on analysis of onshore run-ups of tsunami are shown for targeted point in the Fig. 10. The Fig. 10 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.

3.5 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 3.2. The evaluation procedure as shown in Fig. 11 is the same as that of Seismic PSA (Hirano, 2008). The accident scenarios of tsunami are developed in cases of both tsunami run-ups and tsunami backwash.

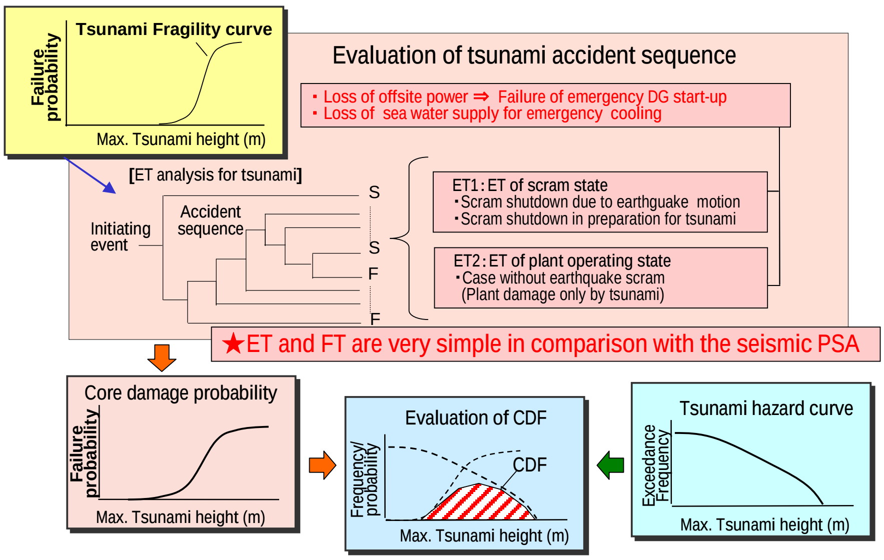


Figure 11. Procedure of tsunami accident sequence evaluation

4. USABILITY OF TSUNAMI PSA

4.1 Identification results of accident scenario by tsunami PRA

The accident scenarios of tsunami were identified in cases of both tsunami run-ups and tsunami backwash in the above section 3.2. In the tsunami run-up, the inundation of primary outdoor facilities was considered; e.g., the loss of cooling function due to the inundation of the seawater pump, the loss of the offsite power due to the inundation of the power supply system, the loss of the function of the emergency diesel generator due to the inundation of the oil tank. On the other hand, in the backwash, if the seawater pump level decreased below the minimum pump-able level in the storage pit, the cooling systems lost its function (Sugino, 2008).

Fig. 12 shows the event tree based on an accident scenario for tsunami run-ups in a BWR. The accident scenario starts from the function failure of facilities outside buildings spreads out to functional failure inside buildings, and finally reaches core damage. When the outdoor facility is submerged in water causing seawater pumping function loss, RCIC and HPCI are able to provide cooling function to the reactor core temporarily so that the reactor core will not suddenly break down. However, if the pumping system is not recovered for long period, the reactor core will get damaged.

Fig. 13 shows the event tree of an accident scenario for the backwash in which case water draws back causing water level decrease (Sugino, 2008).
If the mitigation system in both the run-up and the backwash cannot be recovered within a short time, the reactor core will get damaged. Approximate time from system malfunction until core damage is calculated in this case. As a result, this time is about 100 minutes (Sugino, 2008).

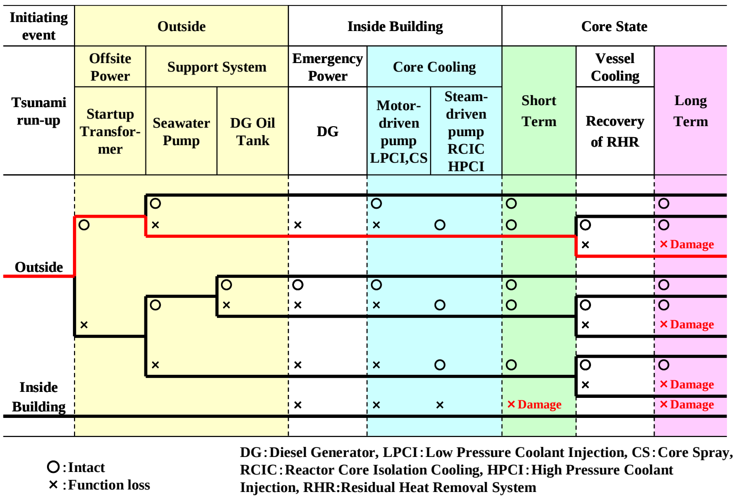


Figure 12. Example of event tree based on accident scenario of tsunami run-up

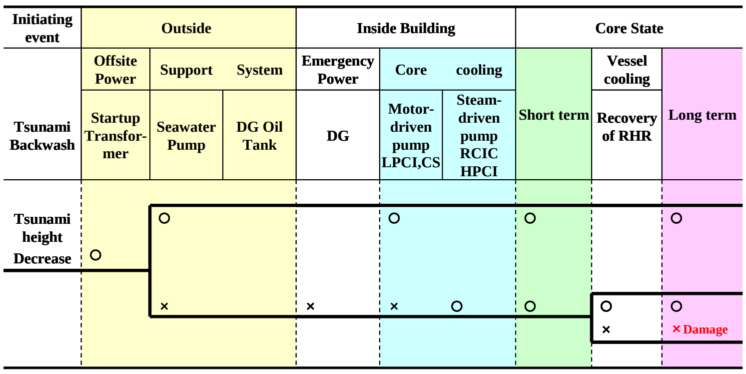


Figure 13. Example of event tree based on accident scenario of tsunami backwash

4.2 Contents of accident at F1-NPP

The contents of accident at F1-NPP show in Fig. 14 as follows (Ebisawa, 2012, Takamatsu, 2012).

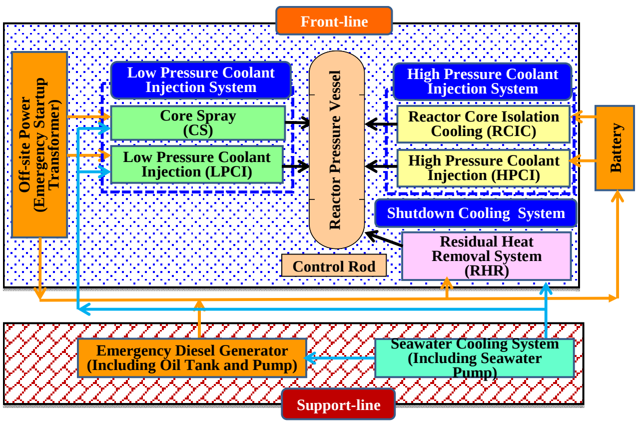
- (i) Functional failure of seawater supply system (seawater pump, switchboard (switchgear) / signal-processing board (motor control)) for seawater pump
- (ii) Functional failure of emergency power supply system (diesel generator (DG), DG switchboard (switchgear) / signal-processing board (motor control)) for emergency power
- (iii) Functional failure of breakers and emergency transformer in the switchyard
- (iv) Functional failures of transmission line tower out of the site and offsite power supply

(v) Function failure of interconnected power supply between neighboring Units (Units 1 and 2, Units 3 and 4, and Units 5 and 6).

(i) All of seawater supply systems and (ii) emergency power supply systems were lost in function simultaneously. These results from (i) to (v) led to loss of all AC power (Station blackout). As a consequence, functions of reactor cooling system was lost, core damage occurred and radioactive materials were released to the off-site area.

4.3 Comparison between accident scenarios by PSA and accidents at F1-NPP

The table 1 shows the comparison results between the accident scenarios by tsunami PRA in 4.2 and accidents at F1-NPP in 4.3 (Ebisawa, 2012). The contents of tsunami PRA developed more than a year ago identified well about the points occurred at the F1-NPP. It clearly showed further usability of tsunami PRA method.



Accident Scenarios	Accidents at F NPPs
(1) Failure of Sea Water Pump	Occurred
(2) Failure of Power supply	Occurred
(3) Failure of emergency DG	Occurred
(4) Failure of Transformer at outdoor	Occurred
(5) Inundation of reactor building	Unconfirmed
(6) Inundation of turbine building	Occurred

Figure 14. Illustration of contents of accidents at Fukushima Dai-ich nuclear power plant and comparison between accident scenarios by tsunami PRA

5. FUTURE ISSUES

5.1 Application of tsunami PRA method to F1-NPP accidents and its verification and improvement

The authors will apply the tsunami PRA method to F1-NPP accidents and verify the method. In the application and verification evaluation, the issues will be identified. The tsunami PRA method will be improved through the resolution of the issues.

5.2 Development of Seismic-tsunami PSA

In risk evaluation practice for seismic and tsunami events, no consideration have been taken on dependency of seismic motion effects and tsunami effects, and seismic PRA and tsunami PRA have been developed independently. Based on the lessons learned from the accident of F1-NPPs, development of seismic-tsunami PRA considering combination of seismic motion and tsunami effects is urgently required (Ebisawa, 2012).

5.3 Development of tsunami design technical guideline

The authors will develop and improve tsunami design technical guideline based on lessons learned from F1-NPP accidents and fragility of seismic-tsunami PRA.

6. CONCLUSIONS

The summarizations of this paper are as follows.

(1) Usability of PSA

1) The authors have been developing the tsunami PSA method since 2004 and identifying the important accident scenarios, accident sequence, system and components for safety before Tohoku earthquake in March 11, 2011.
2) The Tohoku earthquake occurred and the gigantic tsunami attacked F1-NPP. The function of the reactor cooling system was lost, core damage occurred and radioactive materials were released to the off-site area.
3) The accident scenarios by tsunami PRA identified well about the accidents at the F1-NPP. It clearly showed further usability of tsunami PRA.
4) PRA is a usable method to identify important accident scenarios, accident sequence, system and components for safety and these results are candidates to take countermeasures for accident managements (AMs). PSA is an effective measure to evaluate AM's effectiveness.

(2) Improvement and application of tsunami PRA method

1) The authors will apply the tsunami PSA to F1-NPP accidents and verify the method. In the application and verification evaluation, the important issues will be identified. The tsunami PRA method will be improved through the resolution of the issues.
2) The authors will develop and improve seismic-tsunami PRA method considering combination of seismic and tsunami events.
3) The authors will develop and improve tsunami design technical guideline based on lessons learned from F1-NPP accidents and fragility of seismic-tsunami PRA.

ACKWNOWLEGEMENT

The authors would like to express their appreciation to the valuable suggestions and recommendations in various fields on this work from Prof. Emidiety K. Kameda and Prof. M. Hirano.

REFERENCES

Ebisawa, K., Kameda, H. and Hirano, M. (2012). Concept for developing seismic-tsunami PSA methodology considering combination of seismic and tsunami events at multi-units, One Year after the 2011 Great East Japan Earthquake – International Symposium on Engineering Lessons Learned from the Giant Earthquake -, Kenchiku-kaikan, Tokyo, Japan, March 1-4.

Hirano, M., Nakamura, T., and Ebisawa, K. (2008). Outline of seismic PSA implementation standards on the Atomic Energy Society of Japan, The 14th World Conf. on Earthquake Engineering, Oct. 12-17, Beijing, China.

Japanese government, (2011). Report of Japanese government to the IAEA ministerial conference on nuclear safety.

Japanese Society Civil Engineering. (2002). Tsunami evaluation technology guide.

Kameda, H. (2012). Engineering agenda on earthquake-tsunami safety of nuclear power plants raised by the 2011 Great East Japan Earthquake disaster, Proceeding of the One Year after 2011 Great East Japan Earthquake – International Symposium on Engineering Lessons Learned from the Giant Earthquake-, Tokyo, 3-4 March.

Sugino, H., Iwabuchi, Y., Nishino, M., Tsutsumi, H., Sakagami, M. and Ebisawa, K. (2008). Development of probabilistic methodology for evaluating tsunami risk on nuclear power plants, The 14th World Conf. on Earthquake Engineering, Oct. 12-17, Beijing, China.

Takamatsu, N., Kameda, H., and Ebisawa, K. (2012). Fragility enhancement in seismic-tsunami risk reduction for nuclear power plants, Proceeding of the One Year after 2011 Great East Japan Earthquake – International Symposium on Engineering Lessons Learned from the Giant Earthquake-, Tokyo, 3-4 March.

Tohoku Electric Power Company (Tohoku EPCO) (2011), "Damage listing of major equipments", home page of Tohoku EPCO. (http://www.tohoku-epco.co.jp/ ICSFiles/afieldfile/2011/05/30/ab5.pdf)

Tokyo Electric Power Company (Tokyo EPCO) (2012), home page of Tokyo EPCO. (http://www.tepco.co.jp/nu/fukushima-np/f1/images/f12np-gaiyou_1.pdf)