Proceedings of the International Symposium on Engineering Lessons Learned from
the 2011 Great East Japan Earthquake, March 1-4, 2012, Tokyo, Japan

FRAGILITY ENHANCEMENT IN SEISMIC-TSUNAMI RISK REDUCTION FOR NUCLEAR POWER PLANTS

Naotaka TAKAMATSU[1]、Hiroyuki KAMEDA[2] and Katsumi EBISAWA[3]

[1] Deputy Director General, JNES, Tokyo, Japan takamatsu-naotaka@jnes.go.jp
[2] Professor Emeritus, Kyoto University and Technical Counselor, JNES, Tokyo, Japan kameda2@minuet.plala.or.jp
[3] Associate Vice President, JNES, Tokyo, Japan ebisawa-katsumi@jnes.go.jp
(JNES: Japan Nuclear Energy Safety Organization)

ABSTRACT: As major engineering tools for seismic-tsunami risk reduction at nuclear power plants, we propose a framework of fragility enhancement of plant structures, systems, components. A key issue is to eliminate cliff-edge effects at electrical devices under tsunami actions. It is pointed out that fragility enhancement is achieved by realizing "smooth fragility" and/or "safe re-location". It is proposed to consider many other types of components that are subjected to various load effects such as inundation, hydrodynamic forces, scouring, buoyancy, and uplift. Engineering options with "Water Proof, Structural Resistance and Dry Siting" are proposed.

Key Words: Multi-units, Tsunami Design, Seismic-Tsunami PSA, Fragility, Cliff Edege

1. INTRODUCTION

The Tohoku earthquake (Mw9.0) occurred at 14:46 on March 11, 2011, and caused a huge tsunami. strong seismic ground motion was observed at the Fukushima Dai-ichi nuclear power plant (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 components of the water intake systems 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. 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).

As major engineering tools for seismic-tsunami risk reduction at NPPs, we propose a framework of fragility enhancement of plant structures, systems, components (SSCs). A key issue is to eliminate cliff-edge effects at electrical devices under tsunami actions. It is pointed out that fragility enhancement is achieved by realizing "smooth fragility" and/or "safe re-location" later. It is proposed to consider many other types of plant components that are subjected to various load effects such as inundation, hydrodynamic forces, scouring, buoyancy, and uplift. Engineering options with "Water Proof (WP), Structural Resistance (SR) and Dry Siting (DS)" are proposed. It is pointed out that combined action of strong seismic motions and tsunami attack with a time lag should be considered.

These notions are closely related to the experience of the 2011 Tohoku earthquake and tsunami disaster and the performance of NPPs in the disaster area, where some "failed catastrophically" but some "failed gracefully".

This paper describes the overview of tsunami disaster of NPPs by Tohoku earthquake and tsunami and various types of load effects by tsunamis. The outline of fragility evaluation on tsunami PSA is also described. Then the paper represents the proposal of concept of "Tsunami Resistant Technology" as fragility enhancement of SCCs. Further based on the above concept, typical examples of SSC design and enhancement for tsunami protection of NPP and example of implementation of WP, SR and DS are described.

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

2.1 Nuclear power plants

(1) Fukushima Dii-chi NPP

The tide level observation system consists of the tide gauge (quiet area in the harbor) 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 /tsunami height of second big wave were 8 min after the first big wave the water level is unknown due to tide gauge failure, max. scale of the gauge is 7.5 m respectively. The tsunami height was more than 10 m that the experts estimated to be more than 10 m from the picture showing the overflow status of tsunami seawall (10 m).

Tokyo Elec. Power Co. (TEPCO) evaluated the design tsunami height based on Japanese Society Civil Engineering (JSCE) guide (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).

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.1**. 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 was flooded, but one DG installed on the first floor of DG building was not flooded and the EPP supply was possible.

F1-NPP was inundated heavily beyond its tsunami protection capabilities, and lost all of them.

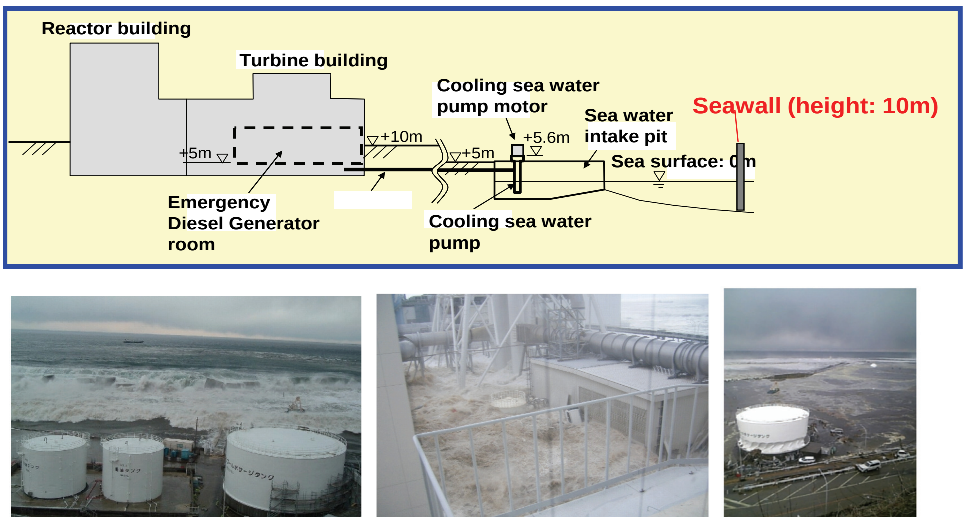


Fig.1 Illustration of sea water supply system and situation of tsunami disaster at Fukushima Daiichi nuclear power plant

(2) Tokai Dai-ni NPP

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.2**. 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.

(3) Onagawa NPP

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.

Onagawa district is featured with a ria-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 Com. 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.3**. 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. 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. 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.

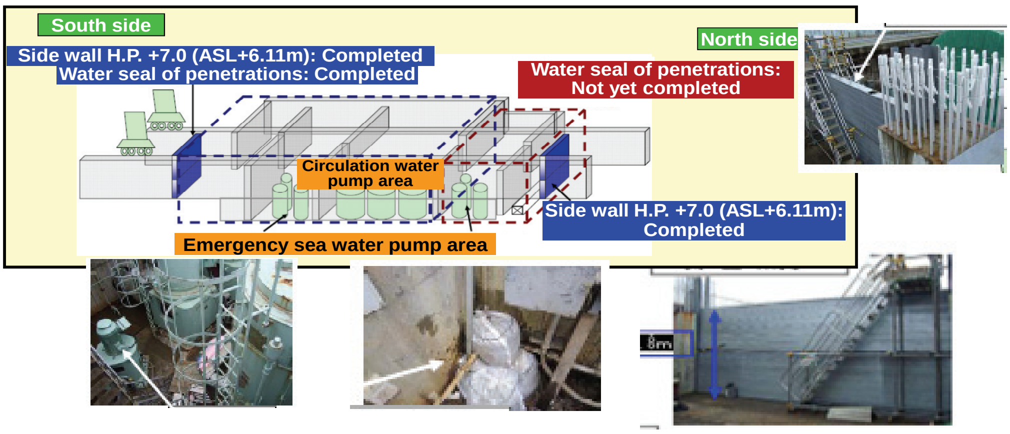


Fig.2 Illustration of sea water supply system and situation of tsunami disaster at Tokai Daini nuclear power plant

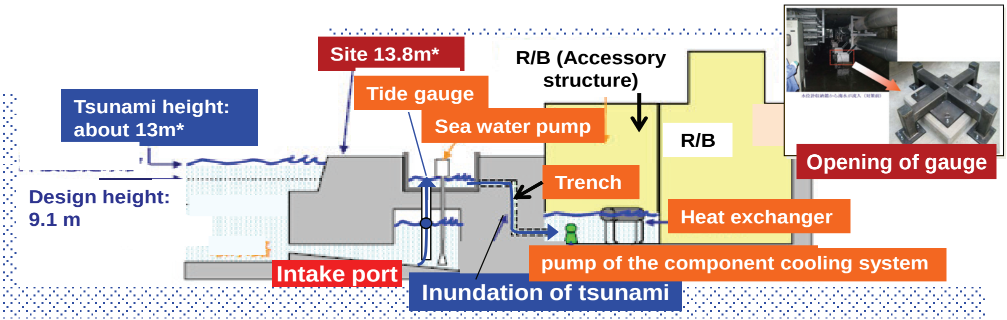


Fig.3 Illustration of sea water supply system and situation of tsunami disaster at Onagawa nuclear power plant

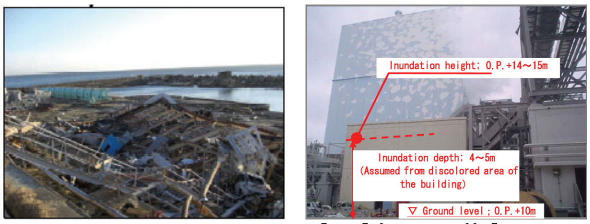


Fig.4 Inundation at Fukushima Daiich NPP

Fig.5 Inundation at Onagawa NPP

Tohoku Electric Power Comp. 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 Electric Power Comp. 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 NPPs where inundation was slight and light enough were able to avoid total loss of the terminal heat sinks.

2.2 Various types of load effects by tsunamis

The authors have investigated seismic and tsunami disaster caused by Tohoku earthquake. Based on this investigation results, various types of load effects by tsunami are described. We must be aware that there are various types of load effects by tsunami to be considered: inundation, hydrodynamic forces (impulsive, sustained in push-pull), scouring, buoyancy, and uplift.

(1) Inundation

The **Fig.4** shows the inundation at F1-NPP. The **Fig.5** shows the inundation that the seawater flew in the basement of reactor building through intake tunnel-pump pit-trench due to siphon effects at Onagawa NPP. We must be careful. Seawater flowed into the basement of the reactor building through the intake tunnel, pump, pit and trench due to siphon effects. So we must be aware that water creeps in anywhere if there are accessible paths and head difference.

(2) Effects of hydrodynamic forces

The **Fig.6 (a)-(c)** shows another very different picture of water-related hazards from ground motion effects. The **Fig.6 (a)** is the effects of the hydrodynamic forces were bent steel pillars in Onagawa town. The **Fig.6 (b)** is the seawall gate in Miyako city, this is a very strong one but was destroyed by the impulsive tsunami force. The **Fig.6 (c)** is the tsunami flew over the tsunami wall of 15.5 m at Fudai River in Fudai village. It broke maintenance girders like the photo, but the main structure remained intact.

(3) Scouring, buoyancy and uplift

The **Fig.7 (a)-(d)** shows about scouring, buoyancy and uplift. We can observe that this seawall toppled because of scouring as shown in the **Fig.7 (a)-(b)**. The **Fig.7 (c)** is the condition that the fuel tank floated and dislocated at Onagawa NPP. We can say so because this space has not been disturbed at all. The **Fig.7 (d)** is concrete from a bridge. It was not dislocated like the photo, but it was uplifted once and then transported. We can say so because of many evidences of multiple failures, so uplift effects are also these ways.

(a) Bent steel pillars at Onagawa town

(b) Sea wall gate destroyed by impulsive tsunami force at Miyako city

(c) Tsunami flew over the tsunami wall across Fudai River (TP+15.5m), and broke maintenance decks / main structure stayed intact at Fudai village

Fig.6 Effects of hydrodynamic forces

(a) Seawalls toppled due to scouring at Miyako city

(b) Seawalls toppled due to scouring at Miyako city

(c) Fuel tank floated and dislocated (Tohoku EPCO) at Onagawa town

(d) Bridge decks pulled up from the piers and transported (by K.Kawashima) at Rikuzen-Takada city

Fig.7 (a)-(d) Scouring, buoyancy & uplift

2.3 Success example of tide embankment, and ancient instruction and observance

The authors have investigated seismic and tsunami disaster caused by Tohoku earthquake and confirmed success example of tide embankment, and ancient instruction and observance.

The 10m-high tide embankment in Taro district with a local nickname of “the Great Wall of China”, was destroyed by the 15m-high tsunami as shown in **Fig.8(1)**. However the 15.5m-high tide embankment in Otabe district in Fudai village was constructed according to the village chief’s strong willing as shown in **Fig.8(2)**. This blocked the 15 m-high tsunami and successfully protected the houses in this district. As a lesson learnt from great damages caused by the past tsunamis, local wisdom against a15m high tsunami has been widely disseminated. In contrast to the failure of disaster prevention in the former 10 m-high embankment case, the construction of the latter 15.5 m embankment with the local wisdom led to “a peace consequence” (Japanese government 2011).

The stone monument stands at the Aneyoshi district in Miyako city as shown in **Fig.9(1)**. As lessons learnt from past experience of the tsunami disaster, the inscription reads as “Do not build any house below this stone”. Run-up height of 38.9 m by Tohoku earthquake was observed as shown in **Fig.9(2)**. Thanks to having followed this ancient instruction, Tohoku earthquake did not claim a single casualty in this district. It is seen that the fate depended on whether this kind of previous tsunami lessons had been reflected in tsunami design or not (Japanese government 2011).

(1) Tao district in Miyoko city

(2) Ohtabe district in Fudai village

Fig.8 Success example of tide embankments

(1) A photo from the village’s point of view (Average height of district: about 60 m)

(2) A photo from a viewpoint of facing the village taken at the spot slightly below the stone monument

Fig.9(1)-(2) Ancient instruction and observance in Miyako city

3. PROCEDURE OF TSUNAMI FRAGILITY ON TSUNAMI PSA

3.1 Procedure of the Seismic PSA

The procedure of tsunami PSA consists of 4 steps as shown in **Fig.10** (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

3.2 Tsunami fragility evaluation

(1) Procedure of tsunami fragility evaluation

The **Fig. 11** 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.

(2)Damage part, damage mode and its physical quantities for evaluation of tsunami fragilities

It is important to identify the modes (inundation, hydrodynamic forces (impulsive, sustained in push-pull), scouring, buoyancy, and uplift) 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)Examples of Fragility Evaluation

The **Fig. 12** shows an example of fragility evaluation. The results on analysis of onshore run-ups of tsunami are shown for targeted point in the **Fig.12**. The **Fig.12** 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.

3.3 Concept of seismic-tsunami PSA methodology

The concept and important issues for developing seismic-tsunami PSA methodology considering the combination of seismic and tsunami events at multi-units has been examined (Ebisawa 2012). This concept and important issues consists of the following four viewpoints; setting of accident scenarios, seismic-tsunami hazard evaluation, seismic-tsunami fragility evaluation and seismic-tsunami accident sequence evaluation.

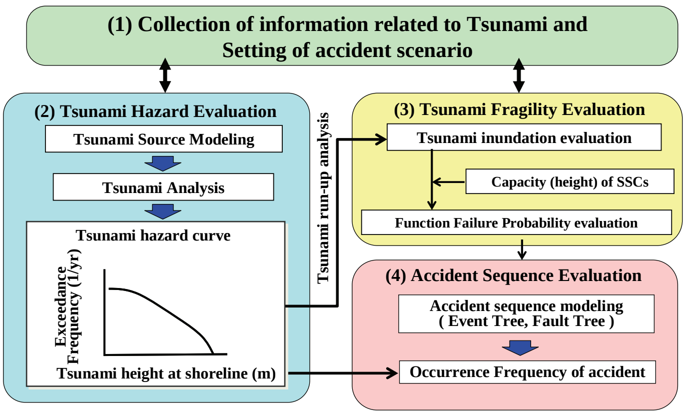


Fig.10 Procedure of tsunami PSA

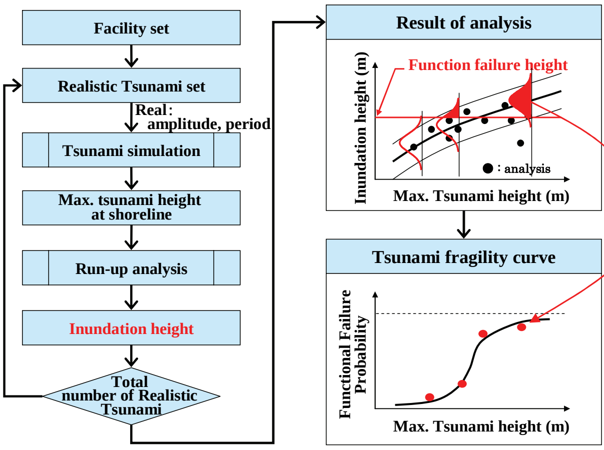


Fig.11 Procedure of fragility evaluation

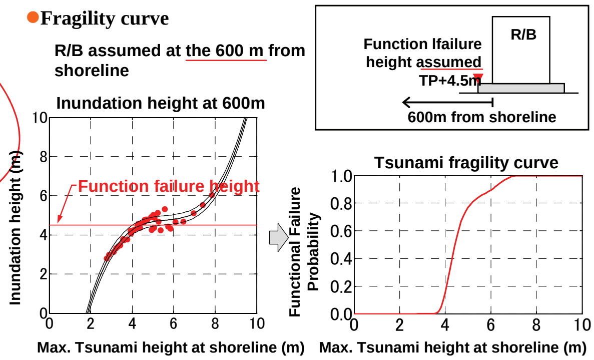


Fig.12 Example of tsunami fragility evaluation

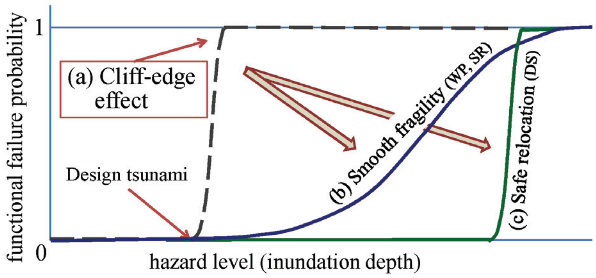


Fig.13 Enhancement of fragility under tsunami threat（Kameda 2011, Kameda 2012）

4. PROPOSAL OF "TSUNAMI RESISTANT TECHNOLOGY" AS FRAGILITY ENHANCEMENT OF SSC

4.1 Proposal of "Tsunami Resistant Technology" as fragility enhancement of SCC

The practical risk reduction is realized through the enhancement of fragility function. This is the most important engineering practice. Of course, hazard assessment and accident scenario evaluation are also important. But the most direct way to enhance the risk reduction is the enhancement of fragility (Kameda 2011, Kameda 2012).

Vulnerability of electric devices to water intrusion (like switch boards, motors for seawater pumps, cables, etc.) should be drastically improved. This is a very specific feature of tsunami protection, compared to ground motion protections. We have seen the cliff-edge effects drastically as shown in **Fig.13**. If the tsunamis exceeded the design, then we suddenly get 100% malfunction. This is extreme dangerous, so eliminating the cliff-edge effect through making smooth fragility or relocating to a safe location. We need to do this kind of enhancement.

4.2 Elements of Tsunami Resistant Technology

We need elements of tsunami-resistant technology to avoid the cliff-edge, considering various load effects of tsunamis. The key issue is the elimination of cliff-edge effects. The objective is smooth fragility and/or safe relocation. We can come up with some elements of engineering protection methods. We came up with three key areas as follows(Kameda 2011, Kameda 2012);

- Water Proofing (WP: isolated from direct contact with water),
- Structural Resistance (SR: withstand hydrodynamic tsunami forces) and
- Dry Siting (DS: located at high elevation).

The proper combination of WP, SR and DS is particularly important to existing plants where the site elevations are prefixed.

5. Typical examples of SSC design and enhancement for tsunami protection of NPP and implementation of waterproof, structural resistance and dry siting

5.1 Example of paths of tsunami intrusion

The **Fig. 14 (1)-(2)** shows how the water came in and crept into NPPs. The paths of tsunami intrusion are as follows.

(1) Sea water pumps inundated at flooded sea water pit

(2) Critical facilities submerged by flooding in the buildings intruding through carry-in entrances, ventilation louvers, etc. Then the seawater is spread in the building through hatches and openings. EDG, electric devices, pumps, etc. are inundated.

Detailed problem identification should be made on tsunami effects on plant safety, on which basis protection works should be enacted using WP, SR and DS technology.

5.2 Typical examples of SSC design and enhancement for tsunami protection of NPP

The **table 1** shows how we can classify them into the three areas (WP, SR and DS). We may classify them in these ways. We would like to propose this kind of framework.

We developed this kind of table of what should be the major methods to protect from tsunami. We need a seawall and residual heat removal function following reactor shutdown. We need to protect pumps for residual heat removal and so forth. We need a core cooling system, emergency power supply system, emergency component cooling system, electric devices, equipment for emergency management, building components (like doors to the buildings) and the possible paths of intrusion. As actions, for example of seawalls, we need strong walls, a strong foundation, sea bed consolidation.

5.3 Example of implementation of waterproof, structural resistance and dry siting

Actions are already being taken at Hamaoka NPP by Chubu Electric Power as shown in **Fig.15 (1)-(3)** because Hamaoka is extreme difficult situation. They anticipate a Tokai earthquake. They are going to complete it by December 2012 as shown in **Fig.15**.

(1) Protection from inundation of the site

(2) Protection from inundation of buildings

(3) Protection of core-cooling function under emergency

For example, they are making a tsunami wall with a very strong wall and foundations with a length of 1.6 km like **Fig.15(1)**. The doors and the partitions to enter the building and the internal partitions are to be strengthened and watertight (so waterproof and structural resistance) like **Fig. 15(2)**. Two emergency gas turbine generators are to be installed at an altitude of 25 m like **Fig. 15(3)**, so it's dry siting. This kind of framework should be established.

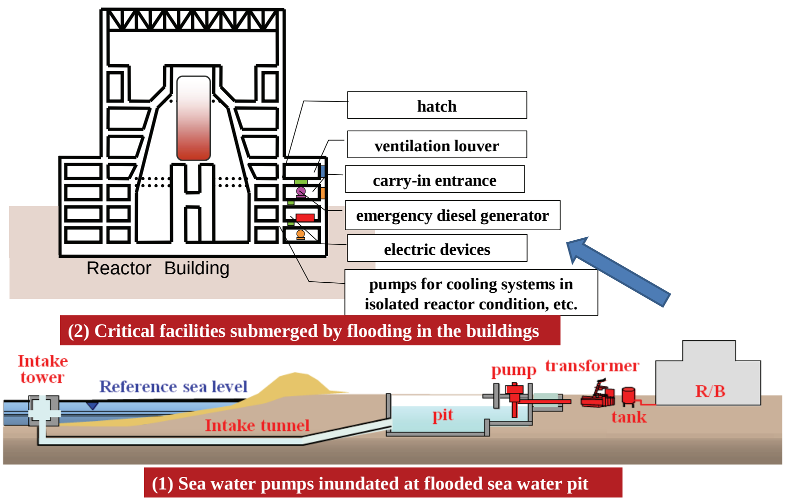
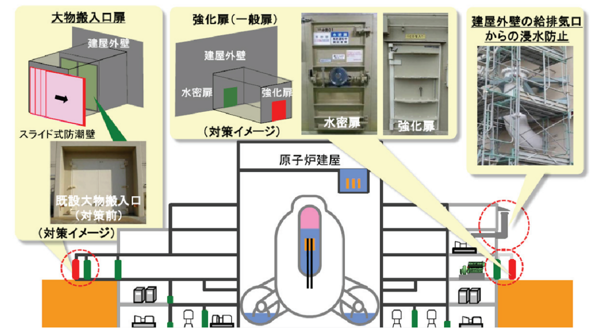


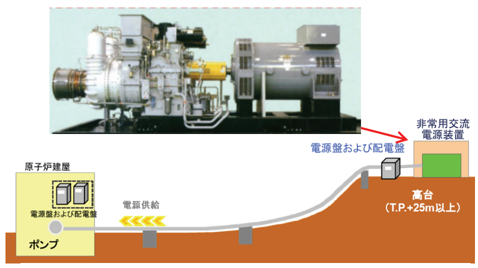
Fig. 14 (1)-(2) Water came in and crept into NPPs

Table 1 SSC design and enhancement for tsunami protection of NPP

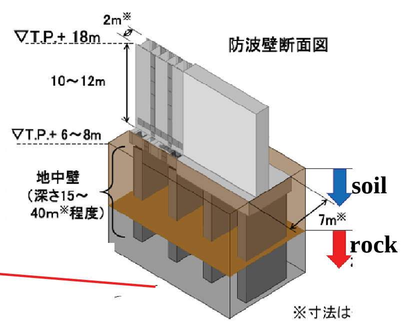
Structures, Systems, Components (SSC)		Location	Actions (e.g.)	WP	SR	DS
***Seawall**		*outdoor *facing the open sea	***strong walls *strong foundation *sea bed consolidation**		○	
***Residual heat removal function following reactor shut down (scram)**	*Pumps for the residual heat removal system , etc.	*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.**	○		



(2) Watertight doors at entrance to RB and waterproof internal partitions (WaterProof & Structural Resistance)



(3) Emergency gas turbine generator to be installed at T.P,+25m (Dry Siting)



(1) Tsunami wall construction (T.P.+18m, 1.6km length, RC wall, RC foundations) (Structural Resistance)

Fig. 15Action plan at Hamaoka NPP by Chubu Electric Power Co.

6. CONCLUSINS

The summarization of this paper is as follows.

(1) Performance of NPPs in the Tohoku earthquake 11 March 2011 reviewed: some failed catastrophically, some failed gracefully.

(2) Critical lessons for future nuclear safety were proposed:

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.

(3) It is seen that the fate depended on whether this kind of previous tsunami lessons had been reflected in tsunami design or not.

(4) Agenda for tsunami PSA were proposed in terms of enhancement of tsunami fragility to eliminate cliff-edge.

(5) "Tsunami resistant engineering" was proposed for NPP safety. The key issue is to eliminate cliff edge effects in the fragility of SSC by realizing "smooth fragility" or "safe relocation".

(6) A scheme of engineering components "Water Proof", "Structural Resistance", and "Dry Siting" was proposed.

REFERENCES

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

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.

Ebisawa, K., Kameda, H. and Hirano, M. (2012), “Concept of seismic-tsunami PSA under combined ground-motion and tsunami effects on multi-unit 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 2012.

Kameda, H. (2011), "Earthquake engineering agenda for safety of nuclear power plants," Bulletin of Japan Association for Earthquake Engineering, No.15, Special issue on the Great East Japan Earthquake Disaster, October 2011, pp.97-102. (in Japanese)

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.