Revision of the AESJ Standard for Seismic Probabilistic Risk Assessment (2) Seismic Hazard Evaluation

Katsumi Ebisawa[a], Katsuhiro Kamae[b], Tadashi Annaka[c], Hideaki Tsutsumi[d] And Atsushi Onouchi[e]
[a]Tokyo City University, Tokyo, Japan
[b]Kyoto University, Kyoto, Japan
[c]Tokyo Electric Power Services Co., Ltd., Tokyo, Japan
[d]Former Japan Nuclear Energy Safety Organization, Tokyo, Japan
[e]Chubu Electric Power Co., Inc., Nagoya, Japan

Abstract: After the Atomic Energy Society of Japan was established seismic PRA implementation standard in 2007, some severe earthquakes which affect the seismic design of nuclear power plant have occurred. The most important earthquakes among them are the 2007 Niigata-ken Chuetsu-oki earthquake and the 2011 Tohoku-oki earthquake. In the later, the various new findings about the trigger earthquake and large aftershock caused by huge earthquake, the fault displacement and diastrophism due to the co-seismic and post-seismic slip, the joint effect of seismic motion and tsunami, and the effects of multi units and sites on the safety analysis were obtained. The new findings are incorporated into the revision of seismic hazard evaluation. This paper describes the overview of the Fukushima Dai-ichi nuclear power plant accident and lessons learned from its accident. The paper highlights the additional items based on lessons learned from various earthquakes such as Tohoku and NCO EQs after the 2007 version standard.

Keywords: Seismic PRA, Seismic hazard, Huge earthquake, Large aftershock, Combination of earthquake and tsunami

1. Introduction

The Atomic Energy Society of Japan (AESJ) had already established and published the implementation standard for Procedure of Seismic Probabilistic Risk Assessment (PRA) for nuclear power plants (NPPs) on 2007 (the 2007 version standard) through the discussions at the Seismic PRA Subcommittee under the Risk Technical Committee of the Standards Committee **[1]**. We had lessons learned from some earthquakes after the 2007 version standard. In particular, the lessons learned and new findings from the severe accidents of Fukushima Dai-ichi NPP (F1-NPP), which caused by Great East Japan Earthquake (Tohoku EQ) occurred on March 11 of 2011, were significant. In addition, those of Niigata-ken Chuetsu-oki Earthquake (NCO EQ) on July 17 of 2007 near Kashiwazaki-Kariwa NPP (KK-NPP) were also significant.

The objective of this paper, Part 2 seismic hazard, is to evaluate the seismic hazard for an accident sequence evaluation based on the following paper Part 4. The seismic hazard of the 2007 version standard was defined as the relationship between seismic motion and its exceedance frequency. The evaluation procedure was composed of the following seven sections, i.e. (1) process of seismic hazard evaluation, (2) handling of vertical motion and uncertainty factor, (3) setting of seismic source model, (4) setting of seismic motion propagation model, (5) formation of logic tree, (6) seismic hazard evaluation and (7) formulation of seismic motion for building and component fragility evaluation.

In revising the 2007 version standard, the definition of seismic hazard is also added the relationship between fault displacement and its exceedance frequency. Then the evaluation procedure is revised based on the new technological findings such as fault displacement, diastrophism, combination of seismic and tsunami events, multi units and is extended to the ten sections.

This paper describes the overview of the F1-NPP accident and lessons learned from its accident. The paper highlights the additional items based on lessons learned from various earthquakes such as Tohoku and NCO EQs after the 2007 version standard.

2. Overview of Fukushima NPP accident and lessons learned from Fukushima accident [2], [3]

2.1 Overview of F1-NPP accident

The F1-NPP is a multi-unit site with 6 BWRs as shown in **Fig. 1 (a)-(c)**. Figure 1(a) shows the location of each unit. Figure (b) and (c) are the cross and plan sections of reactor building (R/B) and turbine building (T/B) respectively. T/B stands directly by the sea. The emergency diesel generators are installed in the basement of these turbine buildings.

F1-NPP was overwhelmed by a tsunami about 46 minutes after the earthquake as shown in **Fig. 2**. The arrival time and tsunami height of the first large wave was 41 min after the main shock and O.P. of about 4 m, respectively. The arrival time and tsunami height of the second large wave were 8 min after the first wave with wave height. The tsunami height was so high that the experts estimated it to be more than 10 m from a photograph showing the overflow status of tsunami seawall (10 m) in **Fig.2**.

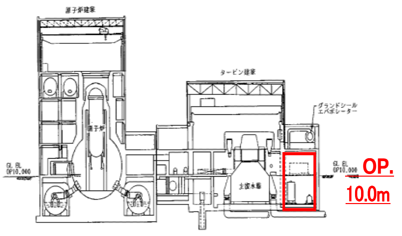
As to the sea water pump facilities for component cooling, all units were flooded by the tsunami as shown in **Fig. 2**. The Emergency Diesel Generators and switchboards installed in the basement floor of the reactor and the turbine buildings were flooded except for Unit 6, and the emergency power source supply was lost. Failure of reactor core cooling resulted in core damage in about 5 or 6 hours. Temperature and pressure in the primary containment vessel rose up, and radioactive materials were released through seals into the power plant and then the surrounding area. Consequently, a wide area was contaminated by the radioactive materials.

2.2 Lessons learned from the F1-NPP accident

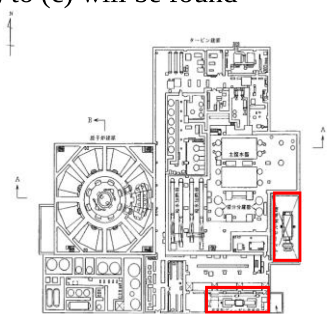
The important issues of seismic engineering based on lessons learned from F1-NPP accident and Tohoku EQ are as follows **[3]**;

(a) Occurrence of huge main earthquake and tsunami, a combination of seismic hazard and tsunami hazard,
(b) Consideration of huge aftershock and triggered earthquake,
(c) External events risk evaluation at multi units and sites,
(d) Combined emergency of both natural disaster and the nuclear accident,
(e) Core damage over a short period of time based on functional failure of support systems (seawater supply, power supply and signal systems),
(f) Common cause failure of multi structures and components and
(g) Dependency among neighbouring units.

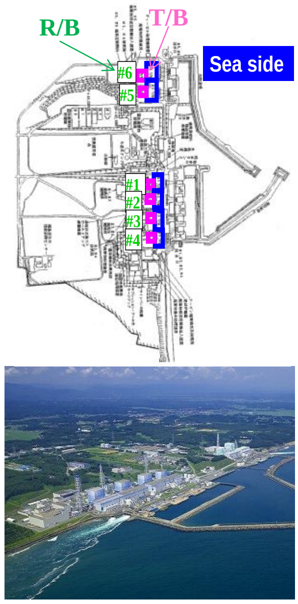
The contents related to the issues from (a) to (c) will be found in chapter **3 t**o **5** later.



(b) Cross section of Reactor Building (R/B) and Turbine Building (T/B))



(c) Plan section of R/B and T/B



(a) Location of F1-NPP

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

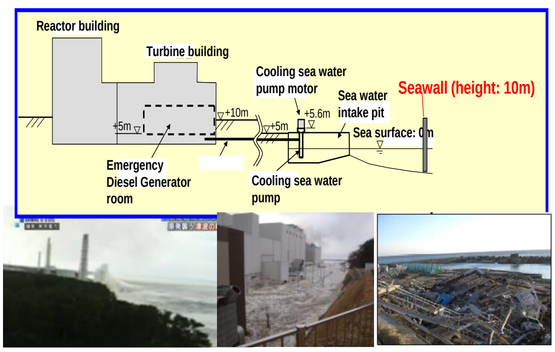


Fig. 2 Illustration of sea water supply system and situation of tsunami disaster at Fukushima Dai-ichi nuclear power plant (by Tokyo Elec. Power Co., 2011)

3. Policy for revising seismic hazard technology and additional items based on policy

3.1 Policy for revising seismic hazard technologies

The policy for revising seismic hazard technology is as follows;

(1) To analysis lessons learned from domestic and overseas some earthquakes after the 2007 version standard, to identify the important issues, and to consider them for the revised seismic hazard evaluation technologies,

(2) To analysis in detail especially lessons learned from NCO EQ (2007, Japan), Tohoku EQ (2011, Japan) and Aquila EQ (2010, Italy),

(3) To consider the consistency regarding the characteristics between seismic and tsunami sources.

(4) To consider the requirement from nuclear regulatory body based on F1-NPP accident and

(5) To describe in detail the examples that the 2007 version standard was applied to the safety inspection against NPP.

3.2 Additional items based on policy [3], [4]

The main additional items based on the above policy are as follows.

(1) The main target earthquakes are as follows.
- Domestic EQ: NCO EQ (2007), Iwate/Miyagi Prefecture EQ (2008), Tohoku EQ (2011) etc.
- Overseas EQ: Sichuan EQ (2008, China), Aquila EQ (2009, Italy), Christchurch EQ (2011, New Zealand) etc.

(2-1) Additional items From NCO EQ
- Treatment of stress concentrating zone (6.3)
- Hazard considering multi units (6.8)

(2-2) Additional items from Tohoku EQ
- Setting of source parameter of huge EQ (6.3)
- Treatment of trigger EQ caused by huge EQ (6.3)
- Hazard of large aftershock by huge earthquake (6.6)
- Hazard of Fault displacement (6.9)
- Hazard of diastrophism by huge EQ (6.9)
- Hazard by considering combination of earthquake and tsunami events (6.10)

(2-3) Additional item from Aquila EQ
- Administration responsibility of seismic expert (6.5)

(3) Consistency of tsunami hazard evaluation
- Consistency between seismic and tsunami sources (6.10)

(4) Requirements of nuclear regulatory body based on Tohoku EQ
- Evaluation of seismic motion generated by extremely near source (6.4)

(5) Application example on inspection using the 2007 version standard
- Seismic hazard evaluation at KK-NPP (6.5)

The number in ( ) corresponds the section numbers described in chapter 4 and 5 later.

4. Procedure of seismic hazard evaluation

The procedure of seismic hazard evaluation is described in chapter 6 of seismic PRA implementation standard. This procedure is composed of 10 sections considering the above additional items as shown in **Fig. 3**. These sections are divided into 3 parts, i.e. evaluation related to seismic hazard (including section 6.1), seismic motion hazard evaluation (including section 6.2 to 6.8) and fault displacement hazard evaluation (including section 6.9 to 6.10).

The technical contents of each section are as follows.

Section 6.1: Lessons learned from earthquakes after 2007 version standard and their reflection to procedure of seismic hazard evaluation

Section 6.2: Reflection of lessons learned from huge earthquake, treatment of uncertainty and validation and verification of seismic hazard evaluation

Section 6.3: Setting of source model

Section 6.4: Setting of seismic motion propagation model

Section 6.5: Generation of logic tree

Section 6.6: Evaluation of seismic motion hazard at bed rock

Section 6.7: Generation of time history wave due to fragility evaluation
Section 6.8: Notice items regarding seismic hazard evaluation at multi units
Section 6.9: Evaluation of hazard regarding fault displacement and diastrophism
Section 6.10: Multi hazard evaluation regarding external events

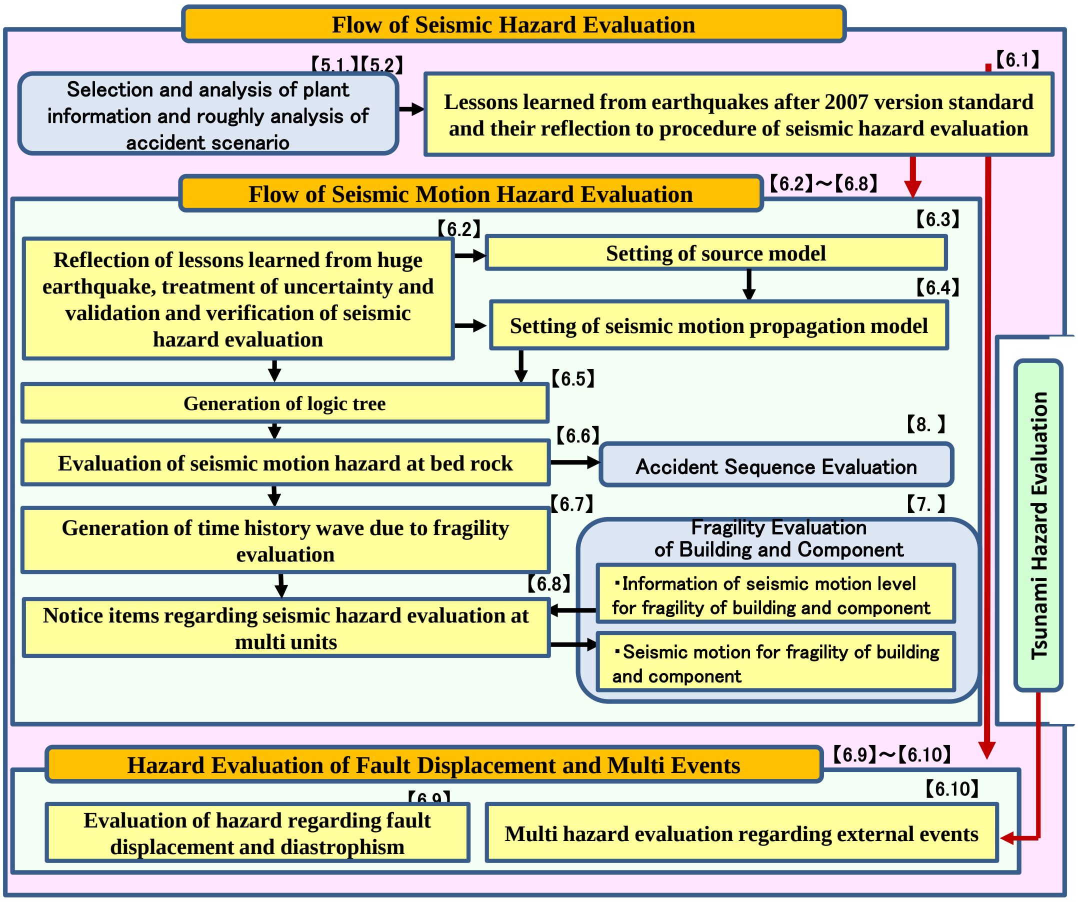


Fig. 3 Flow of seismic hazard evaluation

5. Additional items on each section

5.1 Additional items in section 6.1 "Lessons learned from earthquakes after the 2007 version standard and their reflection to procedure of seismic hazard evaluation

The additional items in section 6.1 are the following two them, i.e. (a) the contents of section 3.2 and (b) revised framework. In the above (a), the practical items are described in section 5.2 to 5.9 later. In (b), the practical framework is described as **Fig.3**.

5.2 Additional items in section 6.2 "Reflection of lessons learned from huge earthquake, treatment of uncertainty and validation and verification of seismic hazard evaluation"

The additional items in section 6.2 are the following two them, i.e. (a) Reflection of lessons learned from huge earthquake and (b) Validation & verification of seismic hazard evaluation. Here describes only (b).

In (b), it is described that the validation of seismic hazard evaluation is verified by referring the following evaluation example. This example compares the seismic motion level observed during time in a target area with the seismic motion level in seismic hazard curve corresponding to during time.

5.3 Additional items in section 6.3 "Setting of source model"

The additional items in section 6.3 are the following three them, i.e. (a) Setting of seismic source parameters for huge earthquake, (b) Treatment of triggered earthquake, (c) treatment of stress concentrating zone.

5.3.1 Setting of parameters for huge earthquake.

In the setting of seismic zone of huge earthquake, it is important to be not bound by preconceptions such as largest one in past data and to use imagination based on phenomena and physical investigation etc.

5.3.2 Treatment of triggered earthquake

The triggered earthquake (TE) caused by Tohoku EQ is shown in **Fig.4**. TEs occurred all over Japan including Nagano, Akita, Shizuoka and Fukushima Prefectures. TE occurred near the Idozawa fault belt approximately 50 km southwest of F1-NPP in the Tohoku region on April 11. The activated triggered earthquakes such as magnitude 6 to 7 approximately are included in frequent occurrence after Tohoku EQ. Influence of them upon seismic hazard has not been considered so far. Therefore, the expected considerations are described in below **[3]**.

It is probable that the case in consideration of TEs or not which occurred after the Tohoku EQ have different values of “a” and “b” on Gutenberug-Rihiter (G-R) Equation at the targeted area of seismic hazards evaluation. In order to confirm trend of probability, firstly, earthquake occurrence records can be accumulated and analysed in focusing for more ten years at least after the Tohoku EQ. Secondly, the values of “a” and “b” can be calculated by using data of the earthquake records for more ten years, besides trend of the values can be considered in view of before and after the Tohoku EQ **[3]**.

5.3.3 Improvement of b-value evaluation method in stress concentrating zone

The seismic activity around the NCO EQ hypocenter area is much high and so called ”Stress concentrating zone” as shown the red bold line in **Fig. 5**. The b-value evaluation on the”Stress concentrating zone” should be modified based on G-R Equation on seismic hazard of the region source **[4]**.

Fig. 6 shows the results of b-value between modified b-value model and exiting b-value model. From this figure, it is found that b-value of former model is larger than that of latter model.

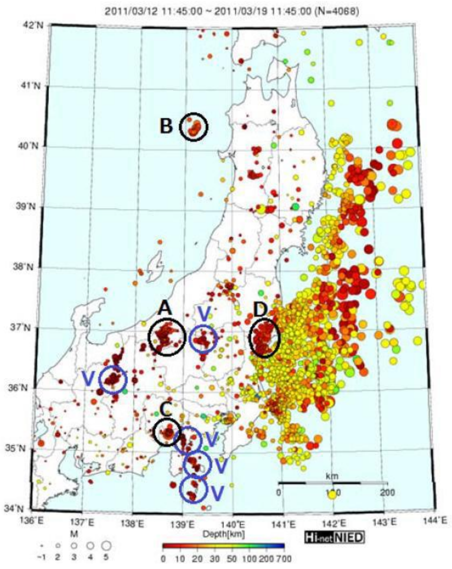


Fig. 4 Situation of occurrence of triggered earthquakes (symbol: ○) after 3.11 Tohoku earthquake

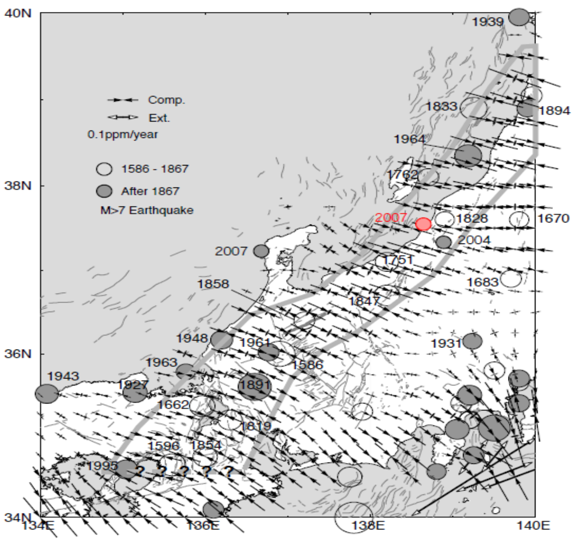


Fig.5 Example of stress concentrating zone around Niigata-ken Chuetsu-oki earthquake

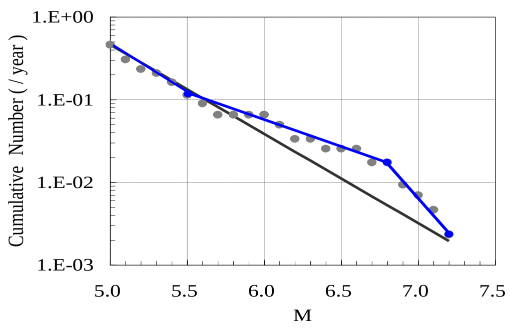


Fig.6 Example of the analysis results of b-value by both modified b-value model and exiting b-value model at stress concentrating zone

5.4 Additional item in section 6.4 “Setting of seismic motion propagation model”

The additional item in section 6.4 is the treatment for evaluating ground motions generated by extremely near sources. Nuclear regulatory body requires the above treatment.

Theoretical analyses show that the far-field terms are dominant in case of strong motion evaluations and the near- and intermediate-field terms are negligible. It follows that the simplification of the stochastic Green’s function method, which neglects the so-called near- and intermediate-field terms, is valid for near-source strong motion evaluations **[5]**.

The source model for an extremely near source, however, should reflect the complexity of the potential source rupture, especially the heterogeneous distribution of slip and rupture velocities. The rupture modelling method is good at characterizing these kinds of source effects and the seismic motions thus simulated are generally in a good agreement with the observation data even for those extremely near sources.

5.5 Additional items in section 6.5 “Generation of logic tree”

The additional item in section6.5 is the seismic expert responsibility related to the generation of logic tree. The background of this issue is as follows. In Aquila EQ (2009) in Italy, seismic experts were accounted for the administration responsibility.

It is described that the technical integrator, technical facilitator and experts take responsibility for only technical contents regarding seismic hazard evaluation. However they don’t take one for the results of seismic hazard evaluation and safety of NPP based on the above contents.

5.6 Additional items in section 6.6 “Evaluation of seismic motion hazard at bed rock”

The cumulated number of aftershocks after Tohoku EQ is 6 for M greater than 7 as shown in **Fig.7**. M of the largest aftershock was 7.7 at 15:15 on March 11.

The additional item in section 6.6 is the treatment of huge aftershock hazard. The magnitude 9.0 of Tohoku EQ obeys relationship between fault length and magnitude as shown in **Fig.8**.

The concept of seismic hazard evaluation for huge aftershock is proposed as shown in **Fig.9**.

(1) For evaluation of seismic hazard for huge aftershock of M9 class EQs, confirmation should be made whether the main shock (M9) would follow the characteristics of existing G-R Equation.
(2) If it follows characteristics of the equation, obtain new G-R equation including the main shock (M9) as shown in Fig. A.
(3) Obtain occurrence frequency ν (M9) of M9 using new G-R equation of (2).
(4) Obtain regression equation for aftershocks of M9 as shown in Fig. B.
(5) Obtain regression equation as conditional probability with ν (M9) of (3) and regression equation of (4) as shown in Fig. C.
(6) Obtain seismic hazard of aftershock using the regression equation of (5) as shown in Fig. D.

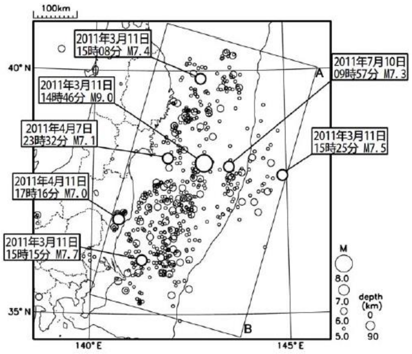


Fig. 7 Situation of occurrence of aftershock after 2011 Tohoku earthquake

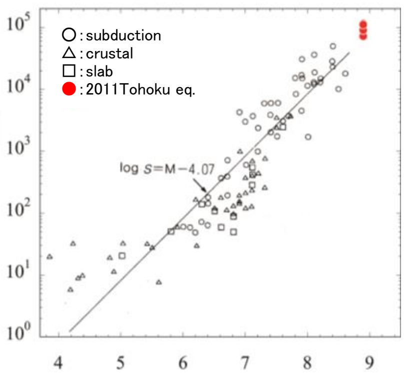


Fig.8 Relationship between fault length and magnitude including 2011 Tohoku earthquake

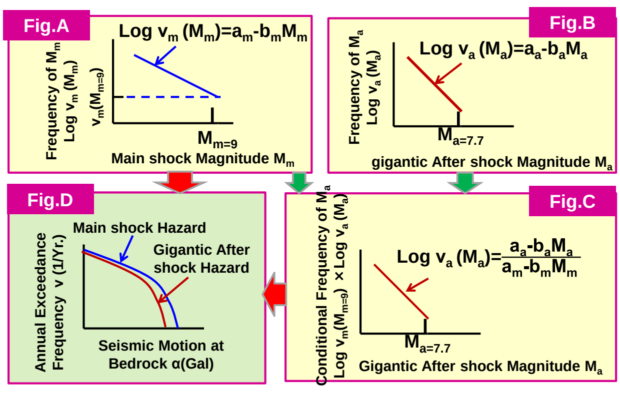


Fig.9 Procedure of seismic hazard evaluation for huge aftershock

5.7 Additional items in section 6.8 "Notice items regarding seismic hazard evaluation at multi units"

The additional item in section 6.8 is the seismic hazard at multi units and sites. NCO EQ occurred near KK-NPP. KK-NPP consists of 7 units as shown in **Fig.10**. In NCO EQ, the seismic motions that far exceeded those designed were observed at the building foundations of Unit KK1 to Unit KK7. In addition, the PGA at KK1 is about 2 times at KK5 because of the particular amplifying effect of irregular underground structure.

In seismic hazard evaluation, when seismic motions of all the target buildings and structures at a site are evaluated by using the same attenuation model, it shall be confirmed whether their seismic motions are similar value based on the seismic motion data observed at the site. If their data are not enough, its uncertainty factor needs to treat as the epistemic one. If their data are not different definitely, it is available to evaluate seismic motion by using the different attenuation model. In the fragility evaluation, it is advisable to confirm the response correlation between the target buildings and structures as shown in **Fig.11**.

5.8 Additional items in section 6.9 "Evaluation of hazard regarding fault displacement and diastrophism"

The additional items in section 6.9 are the following fault displacement and diastrophism hazards. In the former, a methodology for probabilistic fault displacement hazard evaluation was proposed by Youngs in 2003. This method established the evaluation formula on the basis of the surface earthquake faults that appeared when the normal faults moved. The evaluation formula based on the surface earthquake faults generated by reverse and strike faults in Japan were proposed. As a result of model case evaluations, the proposed evaluation formula gave a prospect for applicability in Japan **[6]**.

In the above method, the exceedance frequency of fault displacement hazard is evaluated as the sum of the frequencies of principal faulting and distributed faulting as shown in **Fig.12**. The example of evaluation result is shown in **Fig.13**.

Fig.10 Location of Kashiwazaki-Kariwa NPP with 7 units at Japan

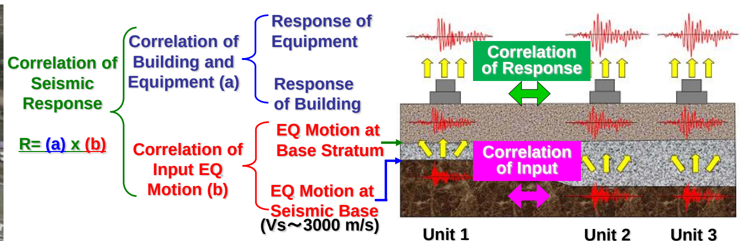


Fig. 11 Concept of Evaluation of response correlation

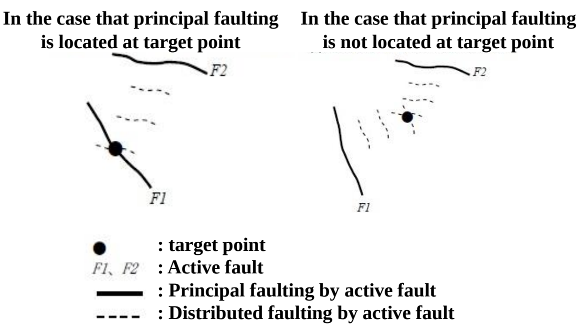


Fig. 12 Concept of displacement hazard evaluation

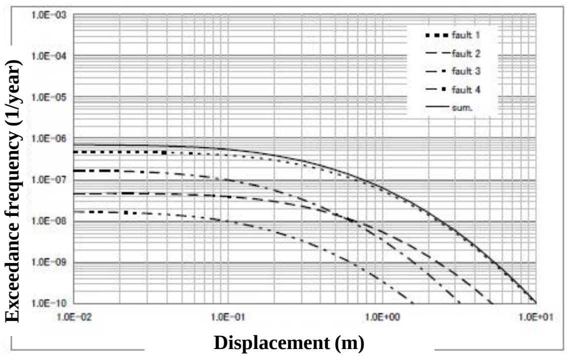


Fig. 13 Example of displacement hazard evaluation

5.9 Additional items in section 6.10"Multi hazard evaluation regarding external events"

The additional item in section 6.10 is the combination of seismic and tsunami hazards.

The seismic and tsunami hazard evaluations are practiced by developing hazard curves for seismic motion and tsunami height, respectively as shown in **Fig.14**. 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 **[3], [7]**.

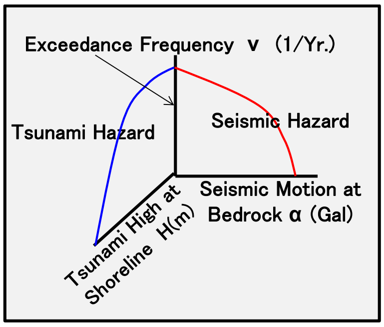


Fig. 14 Definition of hazard on seismic-tsunami PRA

6. Conclusion

This paper describes the overview of the F1-NPP accident and lessons learned from its accident. The paper highlights the additional items based on lessons learned from various earthquakes such as Tohoku and NCO EQs after the 2007 version standard.

Acknowledgements

This paper has drawn on significant contributions by participants in the seismic hazard evaluation working group and the seismic PRA subcommittee of the AESJ.

References

[1] Japan of Nuclear Atomic Society, "Seismic Probabilistic Safety Assessment Implementation Standards", (2009).

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

[3] K. Ebisawa et al., "Current issues on PRA regarding seismic and tsunami events at multi units and sites based on lessons learned from Tohoku earthquake/tsunami", Korean Nuclear Society, Nuclear Engineering and Technology, Korea, VoL.44, NO.5, pp.439-452, (2012).

[4] K. Ebisawa, "Current status and important issues on seismic hazard evaluation methodology in Japan", Korean Nuclear Society, Nuclear Engineering and Technology, Korea, Vol.41, NO.10, pp.1223-1234, (2009).

[5] Japan Nuclear Energy Safety Organization, "Guidelines on seismic motion evaluation for design basis ground motion development: Methodology and its application to extremely near sources, JNES-RE-2013-2044, (2014).

[6] M.Takao et al., "Application of probabilistic fault displacement hazard analysis in Japan", Japan Association for Earthquake Engineering, Vol. 13, NO.1, pp.17-36, (2013).

[7] K. Ebisawa et al., "Concept for developing seismic-tsunami PRA methodology considering combination of seismic and tsunami events at multi-units", Proceeding of the International Symposium on Engineering lessons Learned from the 2011 Great East Japan Earthquake, Tokyo, Japan, pp.1575-1585, (2012).