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Division VII

DEVELOPMENT OF SEISMIC COUNTERMEASURES AGAINST CLIFF EDGES FOR ENHANCEMENT OF COMPREHENSIVE SAFETY OF NPPS PART 6: CONCEPT OF CLIFF EDGES FOR NPP AGAINST EARTHQUAKES

Tsuyoshi Takada[1], Tatsuya Itoi[2], Takenori Hida[3], Ken Muramatsu[4], Hitoshi Muta[5], Osamu Furuya[6], Keisuke Minagawa[7], Hidemasa Yamano[8], and Akemi Nishida[8]

[1] Professor, The University of Tokyo, Japan (takada@load.arch.t.u-tokyo.ac.jp)
[2] Assoc. Professor, The University of Tokyo, Japan
[3] Assist. Professor, The University of Tokyo, Japan
[4] Visiting Professor, Tokyo City University, Japan
[5] Assoc. Professor, Tokyo City University, Japan
[6] Professor, Tokyo Denki University, Japan
[7] Assoc. Professor, Saitama Institute of Technology, Japan
[8] Senior research engineer, Japan Atomic Energy Agency, Japan

ABSTRACT

The Fukushima accident in 2011 indicates that any possible events beyond design basis should have been explored deeper and been taken into consideration toward safety improvement of existing nuclear power plants (NPPs) against external hazards. This directly leads that the seismic safety of NPPs should be treated as whole systems with great consideration of interrelations among all constituent elements since the plants are very complex systems consisting of building structures, equipment, off-site surroundings and humans operating and managing all sub-systems (SSCH: Structures, Systems, Components and Humans). In this 3-year project, the NPP system is targeted in a cross-cutting approach, and the required performance of both the whole system and the constituent elements during earthquakes are clarified and finally integrated in a systematic manner, then the cliff edges relevant to each performance are identified and be quantitatively assessed. Various possible countermeasures for avoiding and mitigating the cliff edge effects are intensively developed. This paper proposes new concept of cliff edges (CEs); physical cliff CEs and knowledge-oriented CEs, then, demonstrates how to treat these cliff edges in conjunction with the required performance in a plant level during earthquakes. Finally, these cliff edges are integrated into the total plant safety and compared each other to secure the total safety of NPP against earthquakes.

1. INTRODUCTION

The Fukushima Daiichi NPP accident has brought up many important lessons for future safety enhancement of NPPs, as can be seen in current post-Fukushima activities being conducted in many countries. Key issues are implementation of risk-informed approaches, performance-based consideration of a total system as well as sub-systems, explicit inclusions of various underlying uncertainties associated with external natural hazards, behavior of huge and complex NPP systems including human actions. In order to capture the behavior of the total NPP systems subjected to earthquakes, multi-disciplinary approach from geotechnical, structural, mechanical and system engineering and human engineering, all of which are closely related each other for reducing the risk of NPPs. The Fukushima accident in 2011 indicates that any possible events beyond design basis should have been explored deeper and been taken into consideration toward safety improvement of existing nuclear power plants against external hazards. This directly leads that the seismic safety of NPPs should be treated as whole systems with great consideration of interrelations among all constituent elements since the plants are very complex systems consisting of building structures, equipment, off-site surroundings and humans managing all sub-systems (SSCH: Structures, Systems, Components and Humans).

The behaviour of the NPP system can be characterized in terms of the prominent cliff edges (CEs) in many aspects. Risk management is indeed a number of effective processes of avoiding and controlling potential CEs that the system possesses explicitly or implicitly. Some of CEs can be easily identified and could be controlled directly, but some can neither be even recognized nor be treated in an appropriate manner. Since external events like earthquakes have large uncertainty in nature to the safety of NPP, optimum combinations of countermeasures associated with each CE have to be sought. These are implemented at least three ranges of domains, design, accident management and disaster prevention domains.

In this 3-year project, the nuclear power plant system is analyzed in a cross-cutting approach, and the required performance of both the whole system and the constituent elements during earthquakes are clarified and finally integrated in a systematic manner, then the cliff edges relevant to each performance are identified and be quantitatively assessed. Various possible countermeasures for avoiding and mitigating the cliff edge effects are intensively developed. The paper, first of all, defines cliff edges either in a physical context or in a knowledge-related context, where the latter may be directly related to limitations of currently available knowledge, limitations of usable theories and analyses for complex phenomena. Then, the paper demonstrates how to treat these cliff edges in conjunction with the required performance in a plant level during earthquakes. Finally, these cliff edges are integrated into the total plant safety and compared each other to secure the total safety of NPP against earthquakes.

2. DEFINITION OF CLIFF EDGES

Definitions of CEs

Two kinds of CEs are first proposed and clearly defined as in the followings; physical CEs and knowledge-oriented CEs. The former CEs are the ones that have often been meant so far, while the latter are newly defined CEs that have been proposed first in this project. The Fukushima Daiichi accident could be understood as phenomenon un-experienced before, which stemmed from the limit of our imagination. When studying the safety of NPPs, these two kinds of CEs should be properly taken into consideration for almost all treatment of phenomena, modelling and data interpretation and so on (Takada et al.,2017).

Physical CEs

It is somewhat vague how the physical CEs are defined. According to the definition of the literature (NEI, 2013), the CEs represent the phenomenon that there occurs the significant increase of consequence due to a small amount of decrease of the occurrence frequency of the external event. In the earthquake situation, it implies the significant sudden change of the physical state of a system when the ground motion becomes slightly larger. This definition of CEs can be understood as depicted in the risk curve, i.e., a relationship between an occurrence probability and its consequence, as in the Fig. 1. The examples of the physical CEs are, occurrence of core damage due to a common cause failure brought by large earthquakes, the impact of base-isolated structure on the outer wall, etc.

Knowledge-oriented CEs

On the other hand, the other CEs are associated with the knowledge limitation within which we can deduce and make reliable decisions on the basis of our certain amount of knowledge and available information of an objective of interest. It relates the limit of our knowledge domain, the limit of our theory relied on, as expressed in Fig. 2. These CEs imply the deviation from the known domain to the unknown domain or phenomena unexpected.

A theoretical model representing physical states can be understood as an imaginary logical system depending on knowledge, idealization and many theoretical assumptions. The model in nature does not work well in the domain that our knowledge cannot cover, and the idealization and the assumptions cannot directly be applied to. Once the above condition cannot be satisfied, we encounter a kind of CE associated with our insufficient knowledge and poor modelling, and we may have significant consequence epistemologically as well as physically. Therefore, we cannot guarantee our confidence for elaborately built theoretical domain if the CEs are encountered. These CEs are related to the epistemic uncertainty in the current PRA procedure, which represents uncertainty due to the lack of information and insufficient knowledge, etc. In other words, emergence of the knowledge-oriented CEs result in the unexpected increase of uncertainty, which may invalidate basic assumptions and violate the theoretical basis.

These CEs may include nonlinear behaviour or complex behaviour of a system, which cannot be expressed appropriately with a simple linear model. A one-dimensional simplification assumption cannot justify three-dimensional behaviour of a system. Events and phenomenon beyond our imagined pre-specified basis can impair our basic assumptions, idealization and confidence in our analyses.

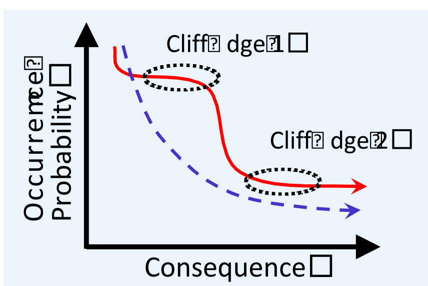

Figure 1: Physical cliff edges

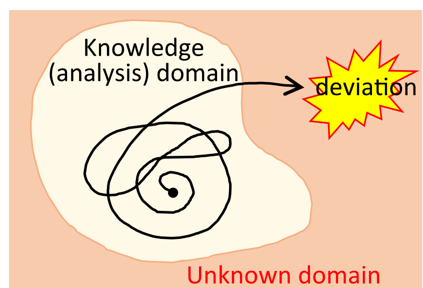

Figure 2: Knowledge-oriented cliff edges

3. CES IDENTIFIED IN FUKUSHIMA ACCIDENT

Phenomenological interpretation of the Fukushima Daiichi Accident identifies several CEs as a series of damage progression as in the followings. According to AESJ report (AESJ, 2014), accident sequences are (i) Off-site electric power was rendered impossible, and thus the plant's emergency diesel generators were activated and the emergency core cooling systems began operating. Approximately one hour later after the earthquake, a giant tsunami of about 14 meters in height hit the plant, (ii) incapacitating diesel generators and seawater pumps, (iii) making it impossible to remove the decay heat of the core fuel to cool it down. Then, (iv) the plant lost the on-site power, and then despite water injection into the reactors, fuel failure occurred. Some damage to the pressure vessels and containment vessels is deemed to have occurred, and (v) hydrogen explosions occurred due possibly to the accumulation of hydrogen within the reactor buildings. As a result, radioactive material had been released from the reactor buildings and reached areas outside the plant's premises. These are understood as a sequence of CEs which are categorized as physical CEs.

On the other hand, CEs can be also related to our limited knowledge. The NPP were considered to be well prepared to the past earthquake shaking since there were lots of earthquakes in Japan and special attention had been drawn for many years. However, unfortunately, there were rare experience of having a huge tsunami in the past. In the Tohoku coastal region, seismologists believed that no big earthquakes greater than M8.5 will occur on the basis of last 300 year data and even this region is one of the regions where earthquake occurrence pattern and characteristics were well known on the basis of ample earthquake data.

Figure 3, prepared by JSCE (2013), shows comparison of tsunami wave heights measured from the 2011 event (depicted by symbols) and simulated data of the past major earthquakes (Sanriku-oki EQ. (Mw=8.4, 1933), Miyagiken-oki EQ. (M=7.6, 1978), Meiji Sanriku-oki EQ. (Mw=8.0, 1896)). The simulated tsunami wave heights are drawn by red and green lines. It can be observed that along the coastal line from Hachinohe to Sendai, tsunami height around 20 meters are plotted due to Meiji Sanriku-oki earthquake, but less tsunami height were plotted at the coast near the Fukushima plant due to the past earthquakes. It leads that unfortunately there was not much experience of having greater tsunami at the Fukushima site in the past several centuries. This fortunate but scarce experience underestimates the threat of the tsunami. This can be categorized as knowledge-oriented CE.

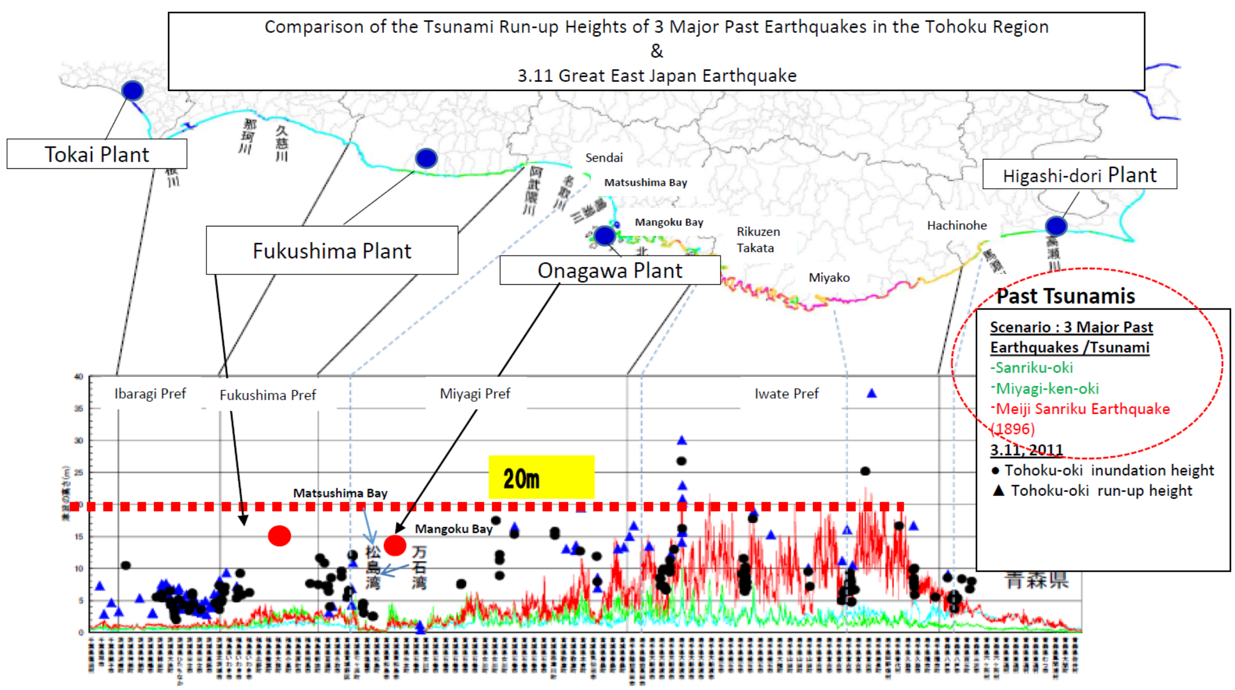

Figure 3: Tsunami height in 2011 event and simulated results of past major earthquakes (JSCE, 2013)

4. AVOIDANCE OF CES

Physical Defence-in-Depth (DiD) against Physical CEs

There is a concept of "Defense in Depth (DiD)" as a basic approach on ensuring safety against various uncertainties in the nuclear energy systems. This is applicable not only for the nuclear systems, but can be applied generally as concept of ensuring safety of safety critical facilities. And it is the fundamental point of safety principle for the countries possessing nuclear energy led by IAEA (1996). There are several different protection levels in the DiD, and even if one protection level was damaged, the overall safety must not be threatened by that. NPP must establish the protection measures for each domain, as mentioned above, domain of the design, domain of the management including response to an accident during operation and domain of the disaster prevention after the accident. The levels of DiD can be specified in terms of sudden change of system states, which may be called "cliff edge effects". Figure 4 illustrates some cliff edges which indicate critical states of interest from the NPP consequence. According to IAEA (1996), the following description on the DiD is now referred to herein and five levels of DiD are proposed as defined in Table 1.

Table 1: Levels of Defense in Depth (IAEA, 1996)

Level of DID	Objective	Essential means
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
Level 2	Control of abnormal operation and detection of failures	Control, limiting and protection systems and other surveillance features
Level 3	Control of accidents within the design basis	Engineered safety features and accident management
Level 4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequence of severe accidents	Complementary measures and accident management
Level 5	Mitigation of radiological consequences of significant releases of radioactive materials	Off-site emergency response

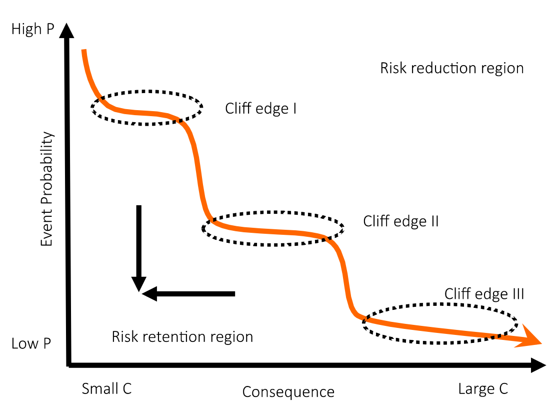

Figure 4: Relationship between CEs and DiD

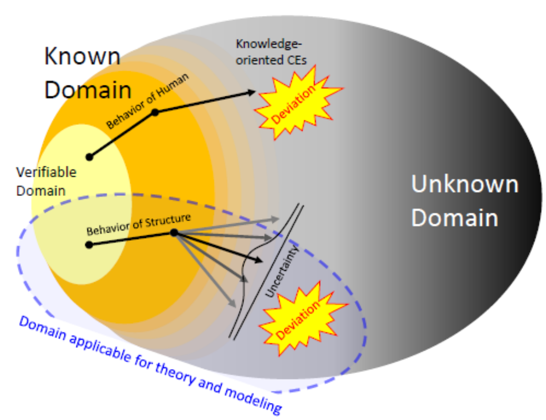

Figure 5: Knowledge domain and relevant CEs

As a proposed framework for securing NPP safety against earthquakes and tsunamis, risk concept and DiD concept are now integrated into risk management framework of NPP, as given in Fig. 6 (JAEE, 2015, which are partially refereed to from the literature made by USNRC (2013). It can be observed from the figure that the three domains; design, AM (accident management) and disaster prevention and mitigation, are clearly classified, and that each domain corresponds to the level of DiD as seen in the left vertical bar. In the probability-consequence diagram, the ranges of conventional Probabilistic Risk Assessment (PRA) levels are also overlaid, where the level 1 PRA focuses on the core damage frequency (CDF) , the level 2 PRA targets the containment failure frequency (CFF) and the level 3 PRA concerns the large early release frequency (LERF), along with the performance goal and the safety goal, both of which are expressed in terms of the annual frequency in the vertical axis. As discussed in 2.1, the first three levels of DiD ("stop", "cool" and "confine") have been clearly stated as fundamental safety principles with great confidence before the Fukushima Daiichi Accident. Additional two more levels (levels 4 and 5) in DiD are placed, namely, the appropriate management of accident beyond design basis, and prevention measure and emergency response for safety of the public and environment.

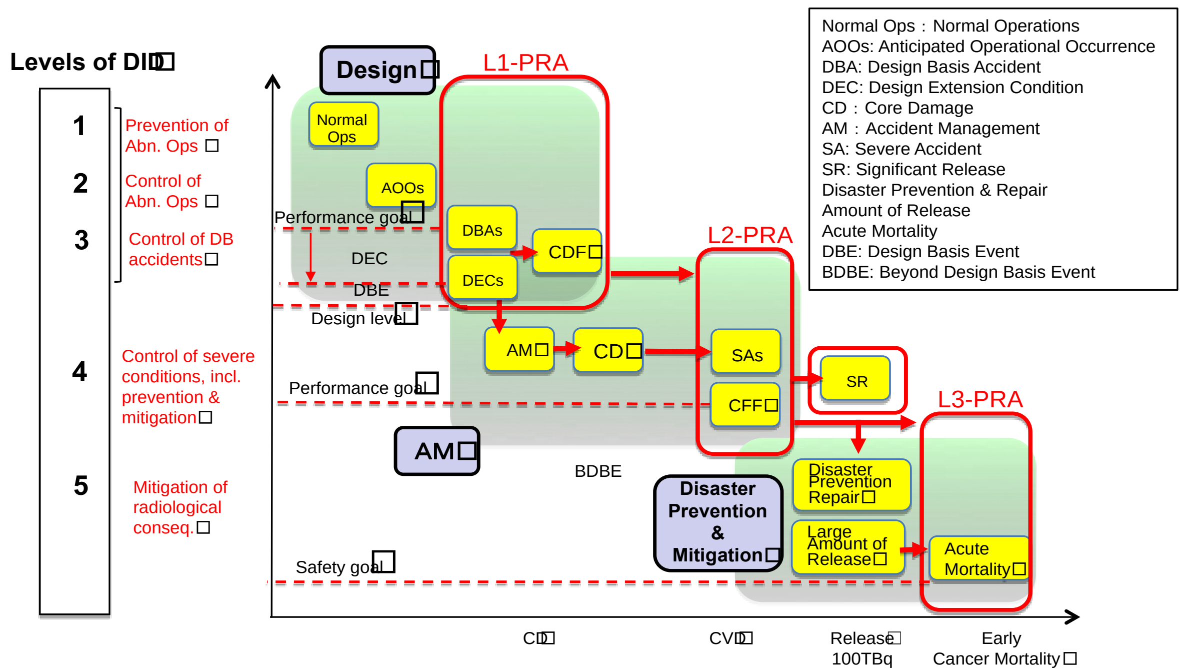

Figure 6: DID and Performance Requirement for NPP(JAEE, 2015)

Epistemic Defence-in-Depth (DiD) against Knowledge-oriented CEs

Concept similar to the above DiD can be firstly proposed in the case of knowledge-oriented CEs. Figures 5 shows the knowledge domain where the domain is divided into two domains; known and unknown domains, and verifiable domain is only a tiny part of the known domain. The domain surrounded by a dashed line indicates the domain where currently existing theories and models can work. System sometimes behaves beyond the known domain and results in uncertain consequence. There can be possible but not so easy countermeasures against the CEs, as in Figures 7 and 8. Figure 7 shows some possible ways on how to treat the knowledge-oriented CEs as follows,

(1) To widen and deepen our known domain by conducting experiments, observing real phenomena, accumulating our experience, relying on new methodologies such as AI, etc.,
(2) To introduce some special devices by which large uncertainty can be reduced, e.g., adoption of seismically isolated system, fail safe mechanism,
(3) To envelop results derived from different approaches.

Figure 8 shows the possible ways to control the system behaviour within controllable range as in the followings.

(4) To let systems not go beyond the controllable limit,
(5) To maintain slow and gradual transition from the known domain to the unknown domain.

These countermeasures, still in a conceptual stage, should be employed to prevent the knowledge-oriented CEs.

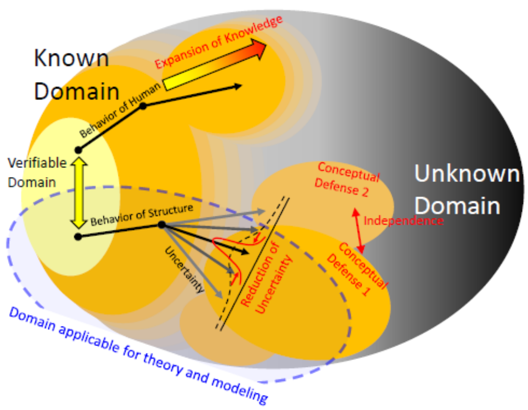

Figure 7: Countermeasure 1 against knowledge-oriented CEs

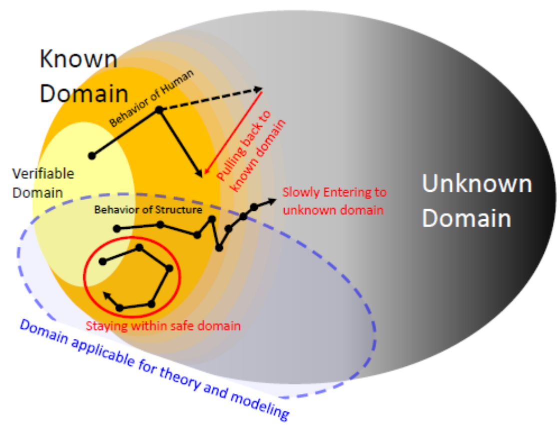

Figure 8: Countermeasure 2 against knowledge-oriented CEs

5. FUTURE CHALLENGES

Avoidance of Common Cause Failure

Common cause failure (CCF) effect is the biggest issue to keep each level of DiD independent during highly extremely severe condition. When a main system fails under large shaking condition, its back-up system may also fail. Therefore, the back-up system would be no more effective in this case. It is not easy to keep the levels of DiD independent under large seismic excitation condition. One proposes the three important characters of the levels of DiD; multiplicity, independence and diversity of relevant safety systems. Still it would be difficult to make the DiD concept fully effective under earthquake conditions, which is addressed as one of future challenges.

Consideration of Human Actions

After the Fukushima Daiichi accident on March 11, 2011, tremendous amount of recovery operations made by human beings in and around the site has been employed to stabilize the accident. These contributions by the human operations have never been counted in the conventional safety assessment so far. This human commitment should be appropriately taken into consideration in the safety assessment for more realistic assessment.

6. CONCLUSION

This paper presents the 3-year project on CEs of NPP systems against earthquakes, where the basis of treatment of the CEs, new definition of CEs, application of DiD concept and etc. are discussed briefly. Main features of the project are multi-disciplinary approach, unique treatment of CEs, performance-based consideration. The other companion papers under the same title will follow for more specific study in SMiRT25 conference.

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REFERENCES

IAEA (International Atomic Energy Agency) (1996). *INSAG-10 - Defence in Depth in Nuclear Engineering*

JAEE (Japan Association of Earthquake Engineering) (2015). *Tsunami Resistant Engineering for Nuclear Safety – Toward an Integrated Framework for Earthquake-Tsunami Protection-*

USNRC (2013). *NUREG-2150: A Proposed Risk Management Regulatory Framework, 2013*

Takada, T. and et. al. (2017). Development of seismic countermeasures against cliff edges for enhancement of comprehensive safety of NPPs - part 1: conceptual study on identification and avoidance of cliff edges of NPPs against earthquakes, Transactions, SMiRT24, 2017

Takada, T. and et. al. (2017). Risk-informed and Defence-in-Depth-based Safety Management Framework for Critical Facilities Subject to External Hazards, ICOSSAR2017, 2017

AESJ (Atomic Energy Society of Japan) (2014). *Fukushima Daiichi Nuclear Power Plant Accident: Its Facts and Agenda towards Tomorrow*, Final report, Maruzen Publisher, 2014.

JSCE (Japan Society of Civil Engineers) (2013). *The Great East Japan Earthquake Inundation Height and Run-up Height Research Conducted by Coastal Engineering Committee*, JSCE, 2013.