Transactions, SMiRT-24
BEXCO, Busan, Korea - August 20-25, 2017
Division VII

Development of seismic countermeasures against cliff-edges for enhancement of comprehensive safety of nuclear power plants
Part 4: Avoidance of Cliff-edge of Safety-Related Systems

Hitoshi Muta[1], Ken Muramatsu[2], Tsuyoshi Takada[3], and Tatsuya Itoi[4]

[1] Associate Professor, Department of Nuclear Safety Engineering, Tokyo City University, Japan
[2] Visiting Professor, Department of Nuclear Safety Engineering, Tokyo City University, Japan
[3] Professor, Department of Architecture, The University of Tokyo, Japan
[4] Associate Professor, Department of Nuclear Engineering and Management, The University of Tokyo, Japan

ABSTRACT

Nuclear power plant is the huge complicated system which consists of several types of buildings, systems, components, surrounding environments, infrastructure, instruments and control systems including human operators. When discussing about seismic safety of nuclear power plant, it should be very important to understand the whole system comprehensively considering mutual correlations and dependency properly.
This study presents how to treat the nuclear power plant as a whole system including ground, buildings, system, components and human operators, clarification of “Required Performance” of a whole plant system, identification of cliff-edge related to “Required Performance” and development of techniques to avoid cliff-edge effects.

1. Background and objective

In 2011, severe accidents occurred in the unit 1, 2 and 3 of Fukushima Dai-ichi nuclear power station because of station blackout caused by Tsunami induced by the large earthquake. Causes of this severe accident are multiple failures of systems and components such as emergency power sources, inadequacy of accident management procedures during loss of AC and DC power and training plans for above situation, and inappropriate design of plant design. Namely, various kinds of numbers of factors related to Structures, Systems, Components and Human (SSCH) brought the severe accident, and these are causes of being in the cliff-edge condition of nuclear power plant.
Since nuclear power plant is the huge complicated system which includes buildings, systems, components, surrounding environments, human operators and so on, it should be very important to analyse nuclear power plant as the whole system comprehensively. Then, Structure, System, Component and Human, as the factors consisted of the whole system, are defined as SSCH.
In case that severe accident such as core damage occurs, contamination of environment caused by the release of fission products is one of the main problems. This means implementation of broad disaster prevention plan considering the impact of the nuclear disaster which affects inside the nuclear power station site as well as outside, should be expected.
Therefore, identification of cliff-edges related to not only nuclear reactor building but also whole plant system, the human operators who control the plant and the impact to the society, and establishment of the techniques to avoid cliff-edge effects are essential.
This study presents how to treat the nuclear power plant as a whole system including ground, buildings, system, components and human operators, clarification of “Required Performance” (RP) of a whole plant system, identification of cliff-edge related to RP and development of techniques to avoid cliff-edge effects.

2. Definition of Cliff-edge Effect

In this study, cliff-edges of nuclear power plant such as operational continuity, core damage and so on, will be identified. Moreover, RP related to them will be clarified and SSCH will be modelled broadly to consider the plant as the whole system. Extraction of insights that cannot be obtained unless the whole plant system is analysed considering seismic correlation and relationship among specific component behaviour, is expected.
Cliff-edges can be categorized into "physical cliff-edge" and "knowledge oriented cliff-edge". These cliff-edges are defined as follows.

2.1 Physical Cliff-edge

The definition of physical cliff-edge is "the physical condition in which the consequence of severe accident changes dramatically even in case that excess probability of ground motion changes slightly". Figure 1 shows graphical image of physical cliff-edge. Cliff-edges are considered to be realized by simultaneous loss of multiple functions such as structures, systems components and human factors. For example of physical cliff-edges, core damage caused by seismic common cause failure, collision to the retaining wall of the isolation building and so on.

2.2 Knowledge Oriented Cliff-edge

The definition of knowledge oriented cliff-edge is either "occurrence of unexpected event" or "transition to the area beyond the scope of the analysis along with increase of ground motion". Namely, cliff-edge can be described as the occurrence of unexpected behaviour during earthquake, or the transition to the unknown area which cannot be identified based on the experience so far. Figure 2 shows graphical image of knowledge oriented cliff-edge.

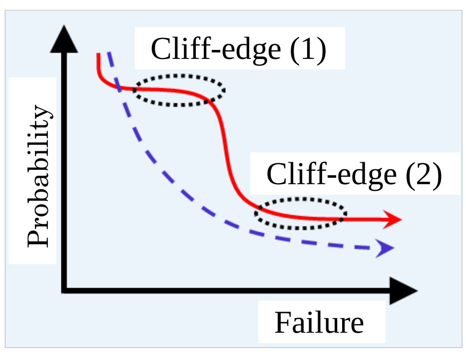

Figure 1 Graphical Image of Physical Cliff-edge

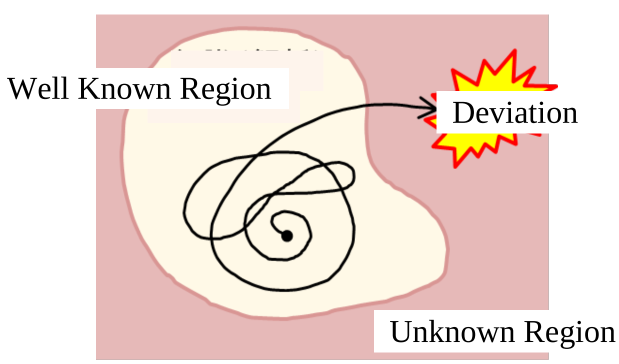

Figure 2 Graphical Image of Knowledge Oriented Cliff-edge

2.3 Definition of RP Regarding to Cliff-edges

To establish the countermeasures to cliff-edges, it should be needed to clarify the function to be activated and the level of performance to be demonstrated. For this reason, in this study, RP should be defined. The definition is “required performance of the specific function of the specific component to satisfy the specific purpose”. And this index should be expressed along with the degree of satisfaction of function to the index.
For physical cliff-edge, RP can be categorized into two index, the one is expressed as the design specification index such as the capacity of design basis earthquake considered and evaluated in the stress test for example, and the other is performance index expressed as the failure probabilities of SSCH for example, which should be the object of this study.
For knowledge oriented cliff-edge, RP is the boundary of the scope or the range related to the plant behaviour and/or event which are assumed in the design stage or analysis. In some cases, the index can be expressed quantitatively. However, in other cases, the index can only be expressed qualitatively.

2.4 Categorisation of Cliff-edge Effect and RP of each Category

As mentioned above, physical cliff-edge is physical event in which the condition of the plant changes dramatically, and examples are failures of components related to the plant system and core damage. “Near Term Task Force” by USNRC defines the cliff-edge effect for flooding hazard as “safety consequence of a flooding event may increase sharply with a small increase in flooding level”.
In general, cliff-edge effect is characterized to be realized by simultaneous loss of SSCH. Therefore, RP of physical cliff-edge is expressed as the occurrence probability of the event, i.e. failure probability of SSCH. This means that avoidance of physical cliff-edge can be manageable by improvement of SSCH reliability to seismic.
On the other hand, knowledge oriented cliff-edge is the event in which the condition of the plant deviate out of the scope or the range expected in advance, and examples are strong nonlinear behaviour, brittle fracture and the behaviour out of the design scope. Therefore, RP of knowledge oriented cliff-edge is expressed as follows;

- Physical quantity of ground motion such as displacement or acceleration regarding to the soundness of SSCH
- Targeted detail plant behaviour for the design and analysis
- Scope of modelling and degree of the details

Therefore, this means that avoidance of knowledge oriented cliff-edge can be manageable by appropriate configuration of seismic response within assumption and/or reduction of unexpected range.

3. Physical Cliff-edge and RP

3.1 RP Based on Defence in Depth Concept

Safety design of nuclear power plant is based on “Defense in Depth” (DiD) concept. The systems regarding to prevent and mitigate design basis event such as transients and accidents that are physical events in which the condition of the plant changes dramatically, are designed according to DiD concept. Therefore, physical cliff-edges needed to be considered can be specified by clarification of relationship among each level of DiD, physical cliff-edge and RP.
At first, the conditions of loss of functions of each level of DiD should be clarified. Table 1 shows the relationship among the conditions of loss of functions of each level of DiD and physical cliff-edges.

Physical cliff-edges should occur in the transition area between the levels of DiD, and they are realized an case that the conditions of loss of functions of each level of DiD are met.
RP to physical cliff-edge can be expressed as follows;

- Cliff-edge for DiD level 1:
  The probability of failure of any part of SSCH of nuclear power plant.
- Cliff-edge for DiD level 2:
  The probability of failures of SSCH related to the functions of emergency reactivity control and safe shutdown.
- Cliff-edge for DiD level 3:
  The probability of core damage accident caused by multiple failures of SSCH related to prevention of design basis accident, including incomplete of emergency procedures.
- Cliff-edge for DiD level 4:
  The probability of containment failure caused by simultaneous occurrence of core damage accident, loss of SSCH related to maintain the function of containment, SAMG, emergency support centre and related infrastructure.

Table 1 The relationship among the Conditions of Loss of Functions
of each Level of DiD and Physical Cliff-edges

DiD level	Definition	Physical Cliff-edges and The conditions of Loss of DiD levels
Level 1	Prevention of Abnormal Events	Abnormal event **Any part of SSCH failure**
Level 2	Prevention of Progression of Abnormal Events and Accidents	Accident **Loss of Reactor Primary Coolant Boundary**
Level 3	Abnormal Release of Fission Product	Core damage, Abnormal release of FP **Loss of Functions of Emergency Safety Features**
Level 4	Accident Management for Severe Accident	Loss of Containment Function **Incompleteness of Accident Management**
Level 5	Emergency Evacuate Plan for Nuclear Disaster	

3.2 Relationship among Physical Cliff-edge, DiD levels and SSCH

Based on the idea described in the previous chapter, SSCH which realize the functions of defined RP for each DiD level can be assigned. Table 2 shows SSCH Realizing RP for each DiD Level. To analyse the degree of satisfaction to each RP, it should be clarified how to treat the SSCH such as reactor building, containment vessel and reactor vessel which are categorised into multiple levels of DiD. Moreover, the functions and roles expected in the DiD concept, are different from each other. However, the functions should be independent from other levels of DiD based on DiD concept.
This means that catastrophic failure of reactor building by an earthquake causes simultaneous loss of levels of DiD, i.e. level 1, 2, 3 and 4. One of the ideas how to treat the containment vessel is to divide the reactor building into the part regarding to its functions of each level of DiD instead of treating the reactor building as one structure as well as one function.
On the other hand, such kind of consideration could confirm the independency among the levels of DiD in a viewpoint of impact of an earthquake.
Therefore, DiD level 5 is under the situation of large release of fission product, and in this stage, the effort to mitigate the radiation impact should be made. This means that RP of DiD level 5 should be considered based on the context which is quite different from that of DiD level 4 and cliff-edge.

Table 2 SSCH Realizing RP for each DiD Level

DiD Level	Structure(S)	System(S)	Component(C)	Human(H)
Level 1	Reactor Building (R/B), Containment Vessel (CV) and Reactor Vessel (RV)	-	-	-
Level 2	Reactor Building (R/B), Containment Vessel (CV) and Reactor Vessel (RV)	Reactor Shutdown, Reactivity Control, Reactor Cooling, Support Systems	Sensors, Logic Circuits, etc.	Manual Shutdown Operation, Operation of Decay Heat Removal, Monitoring, etc.
Level 3	Reactor Building (R/B), Containment Vessel (CV) and Reactor Vessel (RV)	Emergency Safeguard Features, Accident Management Facilities, Support Systems	Pumps, Valves, Control Circuit, Power Supply, etc.	Emergency Procedures (EOP,EPG, etc.)
Level 4	Reactor Building (R/B), Containment Vessel (CV), Emergency Support Facility, Infrastructures	Accident Management (AM), Severe accident Countermeasures, Support Systems.	AM Related Component, Movable Components, etc.	SAMG, Other Related Procedures.
Level 5	-	-	-	Emergency Evacuation.

4. Knowledge Oriented Cliff-edge and RP

Knowledge oriented cliff-edge is defined as the cliff-edge brought from the lack of knowledge regarding to RP of the plant system, and is the orthogonal concept of physical cliff-edge. Knowledge oriented cliff-edge should be studied in following viewpoints;

a. Out of the modelled scope
   A kind of event not considered in traditional seismic PRA model such as assumption of completely dependency among any kinds of the components which invalidate the effect of redundancy and diversity.
b. Out of the analysis methodology
   Events difficult to be modelled, for example, simultaneous multiple events, dynamic event and so on.

c. Out of the event considered
These events are impossible to be considered.

Regarding to limitation of modelling, for example, physical phenomena in Containment Vessel, human behaviour and human factor during and after an earthquake are mentioned. Moreover, regarding to “Out of the analysis methodology” at this moment, for example, aftershock, seismic induced tsunami event, unknown physical phenomena and human factors during and after an earthquake.
Knowledge oriented cliff-edge which is different from physical cliff-edge, is quite difficult to apply to logic model. Therefore, at first, it should be noted what kinds of knowledge oriented cliff-edges. Then, Derived cliff-edges should be categorized and analyzed qualitatively, and countermeasures as well.

5. Analysis of Physical Cliff-edge Effects for Nuclear Power Plant

According to categorized and reviewed RP of nuclear facilities, elements of physical cliff-edges, such as occurrence probability of core damage and containment failure, failure probability of SSCH at certain ground motion acceleration, and integrity of nuclear facilities and infrastructures, should be extracted. To clarify the relationship between the physical cliff-edge and RP using the logic models such as event tree and/or fault tree, cliff-edge for seismic event will be analysed as RP index for current nuclear facilities.
In this chapter, Structure of RP and Construction of Logic Model for DiD Level 3 is presented and explained as an example.

5.1 Structure of RP and Construction of Logic Model for DiD Level 3

In DiD level 3, avoidance of core damage caused by seismic motion should be required, and seismic core damage probability will be introduced as the index of RP. This index, i.e. core damage probability, is consisted of three safety functions such as reactivity control, core cooling and containment cooling. These functions have some of SSCH, for example, reactor building and reactor vessel as structure, ECCS as system, components such as pumps and valves, and human. Structure including these items can be expressed as Figure 3.

5.2 Concept of Event Map for Each DiD Level

Based on the structure explained above, to define the capacity to seismic motion for each element and human reliability, the RP to DiD level 3, i.e. failure probability of SSCH consisted of minimal cut-set which is the combination of events inducing core damage, can be analysed. Figure 4 shows the image of physical cliff-edge logic model for DiD level 3 using fault tree. Using this logic model and according to the logic formulations, probabilities of combinations of SSCH, which lead to core damage, can be converted to the event map of the whole plant system for DiD level 3 shown in Figure 5. And the cliff-edge can be expressed as the cumulative probabilities to the ground motion acceleration.
The event map for DiD level 3 usually contains the redundancy or diversity of safety functions, expressed as logical AND, and these kinds of configuration can contribute decrease of failure probabilities of SSCH and the RP for DiD level 3. This is the one of the means of Avoidance of Cliff-edge effect.
On the other hand, isolation of building is the other mean to avoid cliff-edge effect, which can improve failure probability to seismic motion for the whole plant system. Application of this technique is now being studied by other parties in this project. And their results will be adopted to the SSCH logic model to analyze the effectiveness of avoidance cliff-edge effect.

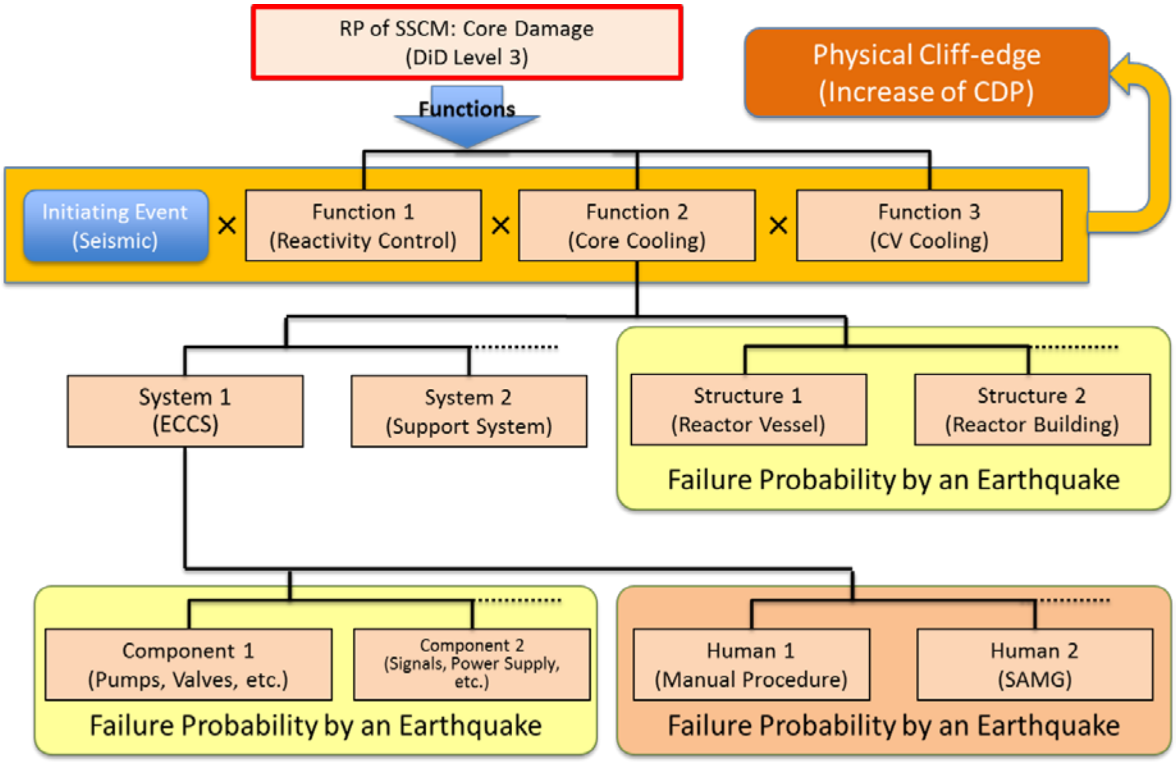

Figure 3 Structure of RP for DiD level 3

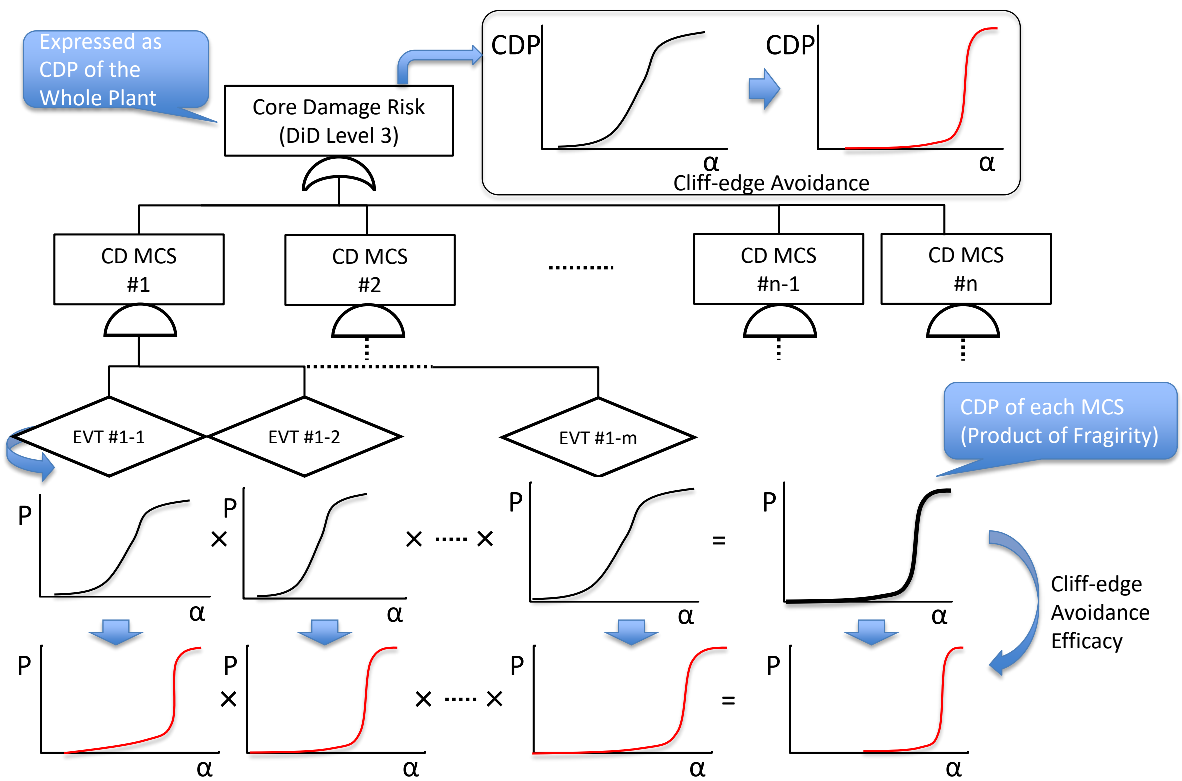

Figure 4 The Physical Cliff-edge Logic Model for DiD Level 3 Using Fault Tree

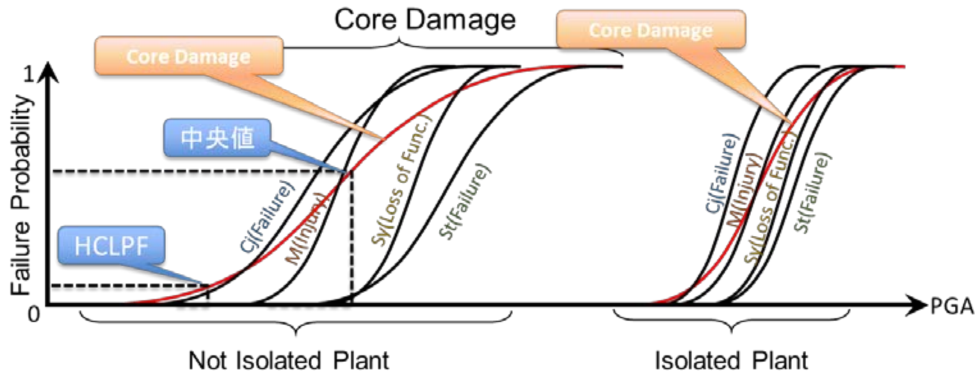

Figure 5 The Event Map of Core Damage

6. Conclusion

This study presents how to treat the nuclear power plant as a whole system including ground, buildings, system, components and human operators, clarification of "Required Performance" of a whole plant system, identification of cliff-edge related to "Required Performance" and development of techniques to avoid cliff-edge effects.

This study also presents the definition of required performance (RP), RP of physical cliff-edges and knowledge oriented cliff-edges and the relationship between RP and SSCH.

For physical cliff-edges, cliff-edge for each DiD level were defined and SSCH were configured regarding to each DiD level. For knowledge oriented cliff-edge, mainly cliff-edges out of the modelled scope and out of the analysis methodology were studied so far.

REFERENCES

U.S.NRC, NUREG-1150, Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants, December, 1990.

Qiao LIU, Ken MURAMATSU, Tomoaki UCHIYAMA, JAERI-Data/Code 2008-005, "User's Manual of SECOM2-DQFM: A Computer Code for Seismic System Reliability Analysis," Japan Atomic Energy Agency, March 2002.

Tetsukuni OIKAWA, Masahiko KONDO, Yoshinobu MIZUNO, Yuichi WATANABE, Hiroshi FUKUOKA, Ken MURAMATSU, "Development of systems reliability analysis code SECOM-2 for seismic PSA." Reliab Engng Syst Safety 1998;62: 251 – 71.

Yuichi WATANABE, Tetsukuni OIKAWA, Ken MURAMATSU, "Development of the DQFM method to consider the effect of correlation of component failures in seismic PSA of nuclear power plant," Reliab Engng Syst Safety 2003;79: 265-279.