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Division VII

DEVELOPMENT OF SEISMIC COUNTER MEASURES AGAINST CRIFF EDGES FOR ENHANCEMENT OF COMPREHENSIVE SAFETY OF NUCLEAR POWER PLANTS PART 7 SEISMIC PERFORMANCE REQUIREMENT OF NPP

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ABSTRACT

After Fukushima-Daiichi nuclear power station accident, seismic events are considered as the most important risk, and consideration of enhancement of safety for these events are the major issues in Japan. This study presents the methodology for assessing Cliff Edge in consideration of nuclear facilities as total system, and proposes countermeasures to extracted Cliff Edge based on the concept of risk and defence in depth concept to secure and enhance the safety of nuclear facilities such as nuclear power plants.

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 layout. 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 Edge 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 buildings, systems, 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 RP Regarding to Physical Cliff Edge and Knowledge Oriented 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" (Fig.1). To establish the countermeasures to physical Cliff Edge, it should be needed to clarify the function to be activated and the level of performance to be demonstrated. For this reason, RP should be defined in this study. 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 expressed as performance index, i.e. the failure probabilities of SSCH. According to the definition of physical Cliff Edge, it can be defined as follow;

$$\text{Physical Cliff Edge}=\text{Max}[P'(\alpha)]. \tag{1}$$

Here,
P: Failure probability related to RP,
α: Strength of earthquake which can be express as peak ground acceleration.

The definition of knowledge oriented cliff-edge is either "Transition to the area beyond the scope of the analysis expected beforehand" (Fig.2). 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. The index can be expressed as knowledge amount. In some cases, it can be expressed quantitatively, however, it can only be expressed qualitatively in other cases. According to the definition of knowledge oriented Cliff Edge, it can be defined as follow;

$$\text{Knowledge Oriented Cliff Edge}=\text{Max}[K'(x)] \tag{2}$$

Here,
P: Knowledge amount related to RP,
x: Parameter such as PGA or range of scope.

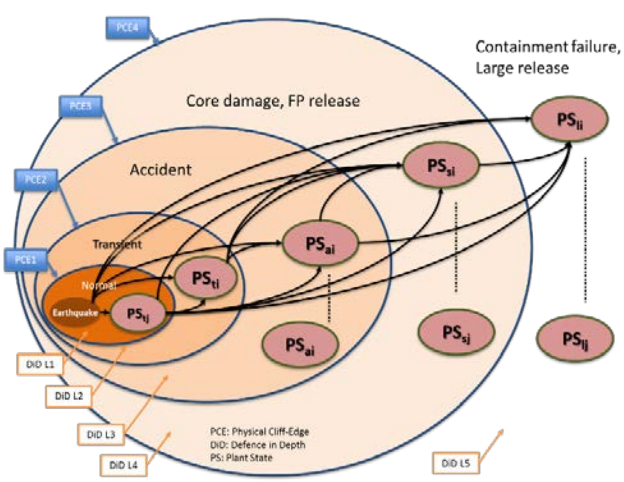


Fig.1 Concepts of Physical Cliff Edge

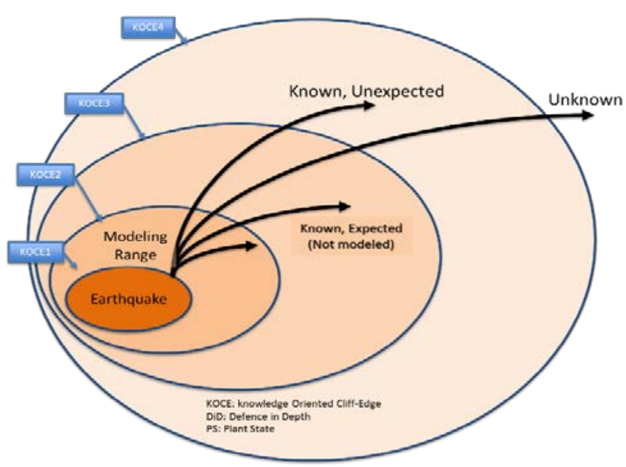


Fig.2 Concepts of Physical Cliff Edge and Knowledge Oriented Cliff Edge

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 (DBE) 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 Edge 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 Edge. Physical Cliff Edge should occur in the transition area between the levels of DiD, and they are realized in case that the conditions of loss of functions of each level of DiD are met.

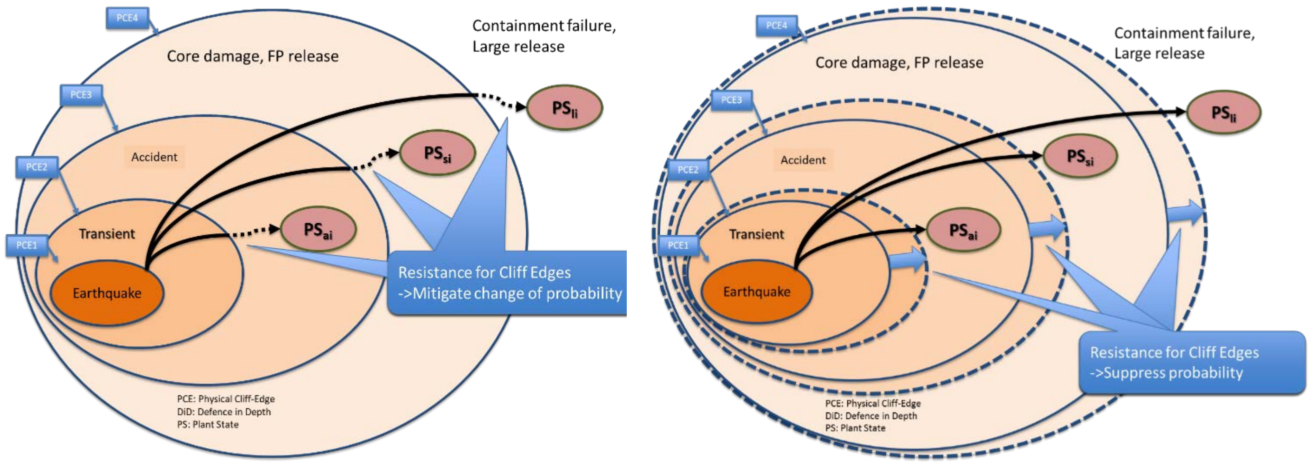
Table 1 The relationship among the Conditions of Loss of Functions of each Level of DiD and Physical Cliff Edge

DiD level	Definition	Physical Cliff Edge 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 Countermeasures against Physical Cliff Edge

According to the previous chapter, countermeasures against physical Cliff Edge can be considered in two ways shown in Fig.3. One is to mitigate the occurrence of physical Cliff Edge, i.e., to reduce the rate of change of the transition probability between any levels of DiD. For this purpose, it is very important to maintain the reliability of SSCH by redundancy and/or diversity as well as to consider the system design in which not only single component or system alone but also multiple systems correspond physical Cliff Edge. Fig.3(a) shows that the concept of mitigating physical Cliff Edge to reduce the probability change of the transition.

The other is to prevent the occurrence of physical Cliff Edge, i.e., to strengthen the capacity of the SSCH, in other words, to increase the median value of capacity. For this purpose, seismic design or isolation design will be introduced to reduce the transition probability between any levels of DiD. Fig.3(b) shows that the concept of preventing physical Cliff Edge to reduce probability of the transition.



(a) Mitigation of Cliff Edge (b) Prevention of Cliff Edge

Fig.3 Concepts of Countermeasures against Physical Cliff Edge

4. Knowledge Oriented Cliff Edge and RP

4.1 How to treat RP of Knowledge Oriented Cliff Edge

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 considered 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.

Knowledge oriented Cliff Edge which is different from physical Cliff Edge, is quite difficult to apply to logic model. However, above viewpoints are very similar to the concept of uncertainty categories. So The relationship among uncertainty categories and knowledge oriented Cliff Edge effect could be expressed as Fig.4. The RP of knowledge oriented Cliff Edge is knowledge amount, so the less knowledge, there should be the large knowledge oriented Cliff Edge.

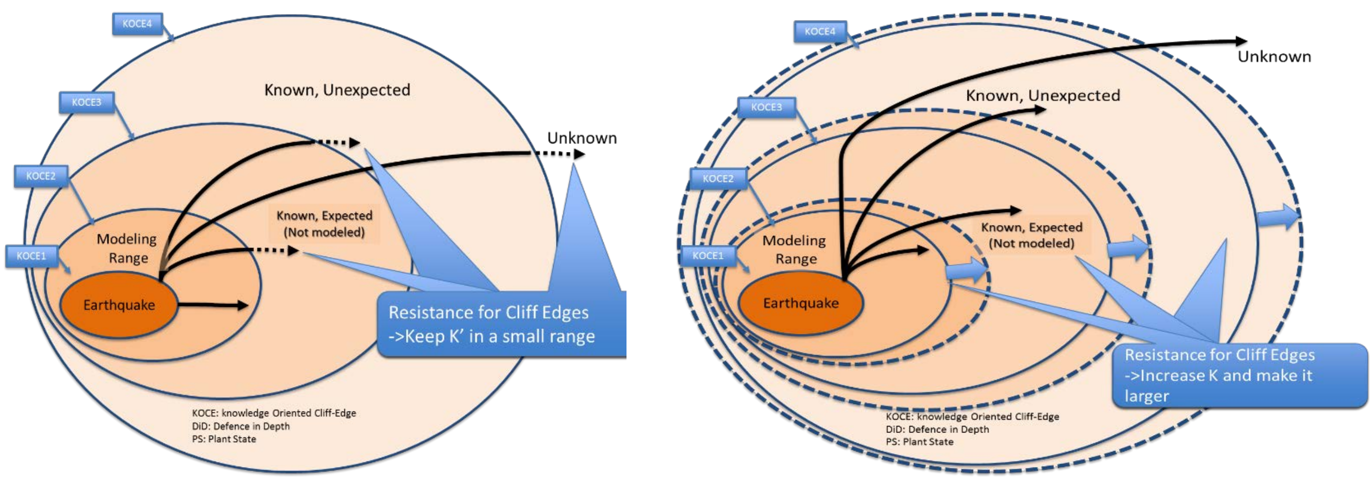
4.2 Countermeasures against Knowledge Oriented Cliff Edge

According to the previous chapter, countermeasures against knowledge oriented Cliff Edge can be considered in two ways shown in Fig.4. One is to mitigate the occurrence of knowledge oriented Cliff Edge, i.e., to avoid the sudden departure from the well-known area to the unknown area. For this purpose, it is very important to have findings as long as possible and fully understand such events. Fig.5(a) shows that the concept of mitigating knowledge oriented Cliff Edge.

The other is to prevent the occurrence of knowledge oriented Cliff Edge, i.e., to expand the well-known area of the capacity of the SSCH, in other words, to test the SSCH up to the area beyond design basis. For this purpose, to expand the seismic design scope over the design basis seismic intensity, or to introduce the isolation design to maintain SSCH within the design basis seismic intensity. Fig.5(b) shows the concept of preventing knowledge oriented Cliff Edge.

			knowledge Oriented Cliff-Edge
Known	Events within expected range	Within modeling	Small
		Out of modeling	
	Out of expected range	Out of modeling	
Unknown	Out of expected range	Out of modeling	Large

Fig.4 The Relationship among Uncertainty Categories
and Knowledge Oriented Cliff Edge Effect



(a) Mitigation of Cliff Edge (b) Prevention of Cliff Edge

Fig.5 Concepts of Countermeasures against Knowledge Oriented Cliff Edge

5. Quantification of Physical Cliff Edge Effect for Model Plant

According to categorized and reviewed RP of nuclear facilities, elements of physical Cliff Edge, 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 Fig.6.

Based on the structure explained in Fig.6, 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. Fig.7 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 Fig.8. 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 has been 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.

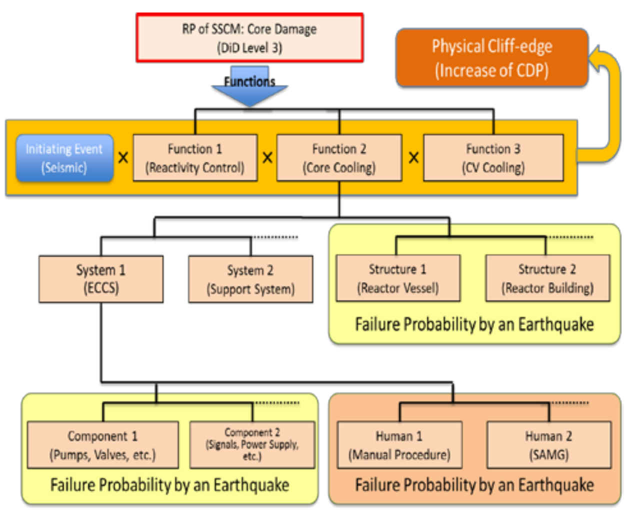


Fig.6 Structure of RP for DiD level 3

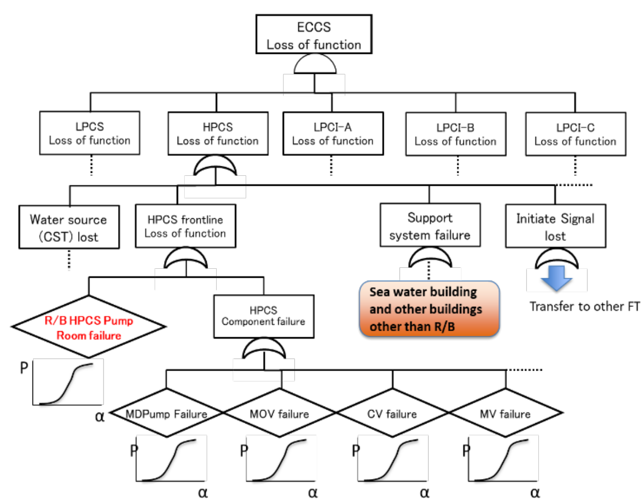


Fig.7 The Physical Cliff Edge Logic Model for DiD Level 3 Using Fault Tree

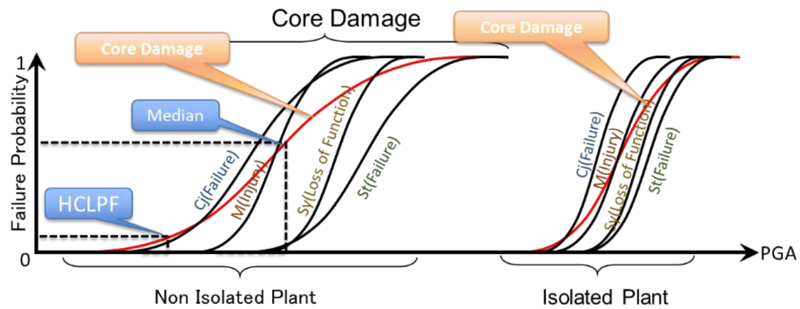


Fig.8 The Event Map of Core Damage

5.2 Quantification of Physical Cliff Edge Effect

Based on the methodology explained in the previous chapter, quantification of RP, i.e. core damage probability, of physical Cliff Edge regarding to the core damage sequence named AUV, which is the core damage scenario that loss of all of the core cooling systems subsequent to large LOCA, for BWR5 model plant has been done. Fig.9 shows that the result of quantification of RP in which black bold lines are the fragility curves of SSCH related to the core damage sequence explained above, and red bold line is conditional core damage probability (CCDP) for acceleration synthesizing related SSCHs. As the result, the median value of CCDP is 2,500 gal and physical Cliff Edge meaning Max[CCDP’(α)] is 1,230 gal.

As explained above, improvement of Cliff Edge effect can be achieved by introducing isolation design. Fig.10 shows the results considering to apply the isolation design to R/B to prevent the physical Cliff Edge effect, in which the meanings of lines are same as Fig.9. As the result, the median value of CCDP is 2,600 gal and physical Cliff Edge meaning Max[CCDP’(α)] is 1,710 gal.

From above, proposed methodology in this study can express the logic model using fault tree to quantify the RP and the physical Cliff Edge, and can show the improvement for introducing countermeasures to mitigate or prevent Cliff Edge effect quantitatively.

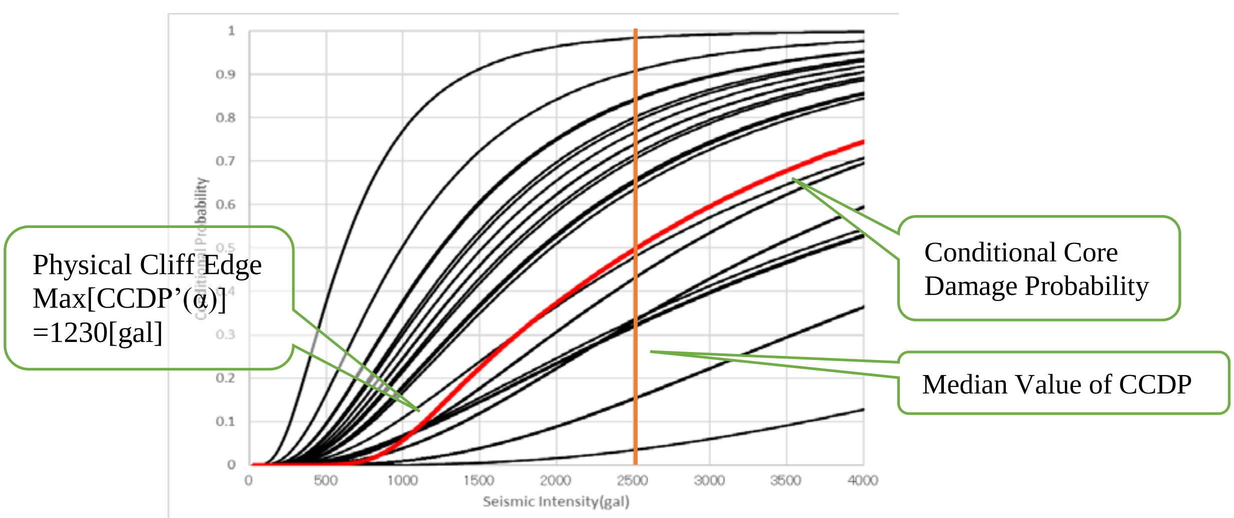


Fig.9 Example of Quantification Combining Component and Structural Failure

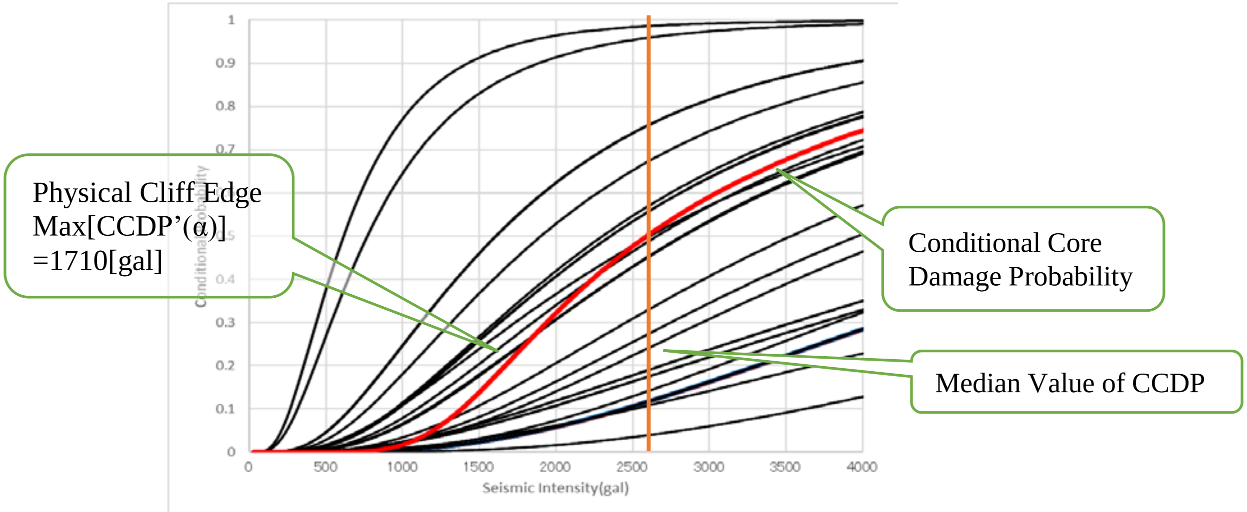


Fig.10 Example of Quantification Combining Component and Structural Failure with R/B Isolation

6. Conclusion

This study presents the methodology for assessing Cliff Edge in consideration of nuclear facilities as total system, and proposes countermeasures to extracted Cliff Edge based on the concept of risk and defence in depth concept to secure and enhance the safety of nuclear facilities such as nuclear power plants.

Fig.11 is the concept of measures avoiding both Cliff Edge effect. Basically, the areas in which knowledge oriented Cliff Edge is large are very dangerous because it is impossible to control the situation since lack of knowledge regarding to the event, even physical Cliff Edge is small. So the transition from knowledge oriented Cliff Edge large area to knowledge oriented Cliff Edge small area should be needed. Still knowledge oriented Cliff Edge small but physical Cliff Edge area is difficult to control, however, much better than those dangerous areas. Finally, the transition to both small area is achieved, it is possible to control the situation and to maintain the event controllable. The proposed idea and methodology are expected to contribute to secure the safety through the seismic related event in nuclear facilities.

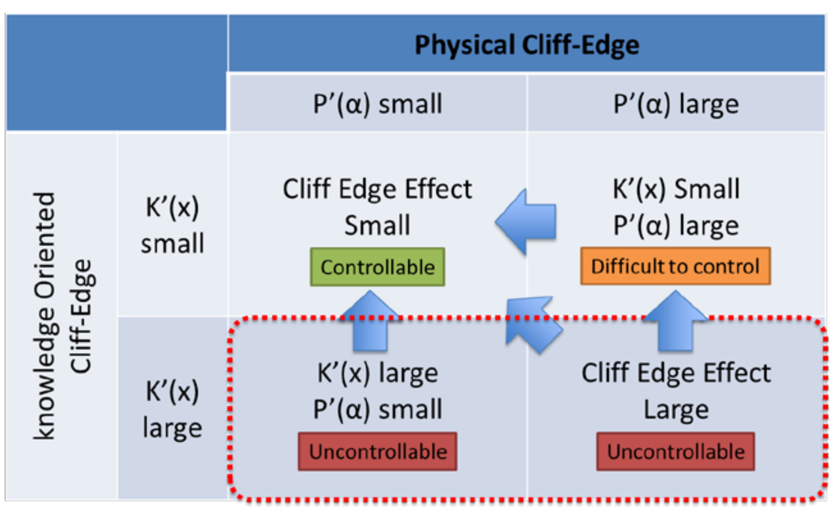


Fig.11 Concept of Measures Avoiding Cliff Edge Effect

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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.

Hitoshi Muta, Ken Muramatsu, Tsuyoshi Takada and Tatsuya Itoi, “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,” SMiRT-24, August 2017.