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Development of Fault Displacement PRA

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ABSTRACT

A Standard for Procedure of Fault Displacement Probabilistic Risk Assessment (PRA) for Nuclear Power Plants (AESJ-SC-RK009:2021) has been established and issued by the Standards Committee of the Atomic Energy Society of Japan (AESJ). As an implementation standard, this standard specifies the requirements for the PRA to assess the risk from accidents triggered by fault displacements at nuclear power plants during power operation. This paper describes the motivation of developing the standard for the fault displacement PRA and the outline of procedures of Probabilistic Fault Displacement Hazard Analysis (PFDHA), fragility analysis and accident sequence analysis, which are main parts of this standard.

BACKGROUNDS AND OUTLINE OF THE STANDARD

Through the lessons learned from the nuclear accidents at Fukushima Dai-ichi in 2011, it has been recognized that quantitative risk assessment and analysis of risk profiles for external hazards are important and essential for nuclear safety in Japan. Japan is prone to earthquakes and existence of a large number of faults has been confirmed. Therefore, during the site investigation of nuclear power plants, geological, geographical, soil and seismological conditions are investigated in detail to assure safety. To minimize the possibility of encountering unforeseen circumstances in case faults beneath safety-critical facilities would be forced to slip due to activities of active faults nearby the site, it is important to assess the scenarios, the likelihood and consequences of accidents induced by such fault displacements. The Standards Committee considered it important to establish a standard for the fault displacement PRA procedure in a timely manner.

For safety assessment of nuclear power plants against fault displacement, it is necessary to conduct fragility analysis in addition to hazard analysis. The risk assessment that includes both hazard and fragility analysis will be utilized to confirm the effectiveness and adequacy of safety design, plant operation management, accident management and related safety regulations, identification of residual risk, and the risk informed decision making of safety improvement activities.

Based on the above-mentioned understanding, the Standard Committee of AESJ established and issued "AESJ-RK009:2021 Standard for Procedure of Fault Displacement Probabilistic Risk Assessment."

In the process of establishing this standard, the findings from recent researches related to fragility analysis and accident sequence analysis were taken into consideration in addition of those related to hazard analysis. These findings were analysed and reviewed to summarize the latest knowledge as concepts, requirements, practical procedures, etc. in a structured manner.

Chapters 1 to 4 are the scope of the standard, related codes and standards, definition of terms, and overall process of fault displacement PRA, respectively. Structure of this standard from Chapters 5 to 9 is shown in Figure 1. Requirements for each technical elements of the PRA, which are the main contents of this standard, are described in chapters of “Investigation of plant and site information and identification of accident scenarios”, “Fault displacement hazard evaluation”, Building and component fragility evaluation” and “Accident sequence evaluation”. Following sections describe major contents of each part.

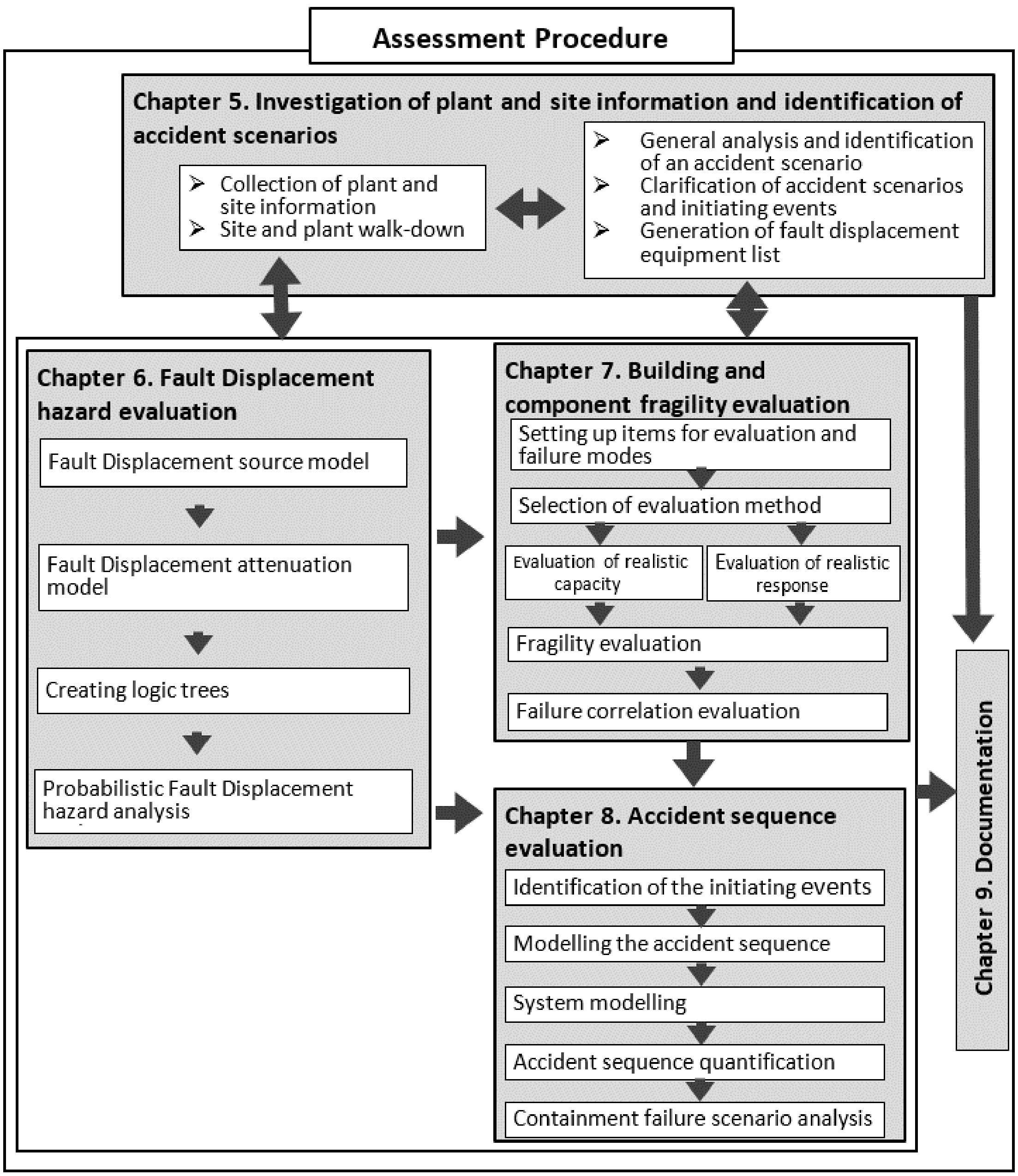

Figure 1 Structure of the Standard

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The provisions of individual contents such as hazard evaluation, fragility evaluation, accident sequence evaluation, etc. will be described later, but before that, the major characteristics of this standard are described.

SSHAC GUIDE APPLICATION to FRAGIITY EVAUATION

Senior Seismic Hazard Analysis Committee (SSHAC) guide such as NUREG-2118 (USNRC 2012) and NUREG-2213 (USNRC 2012) are generally considered as a guide for PSHA (Probabilistic Seismic Hazard Analysis) to capture the CBR of TDI (Centre, Body, Range of Technically Defensible Interpretation) for the seismic hazard model. The reason behind is that seismic PRA has been applied for several decades and we have gained a lot of data and experiences except for hazard analysis whose uncertainty seems relatively larger than other study contents of PRA.

On the other hand, fault displacement PRA is completely new methodology and there are only few study cases in the past. Therefore, it is described in this standard that SSHAC guide should be applied to fragility assessment in addition to hazard assessment to capture CBR of TDI of fragility model. Considering the fact that SSHAC guide will be applied to a wider range of studies, the system of participatory peer review should also be applied according to the SSHAC guide.

SUPERPOSITION OF OTHER HAZARDS

Fault displacement usually appears along with strong seismic motion, but this standard basically treats only fault displacement as a target hazard. Main reason is that handling a superposition of both hazards is still in the development stage. Considering the current situation, AESJ considered that it is better to develop the standard for the fault displacement PRA without waiting for the establishment of methodology to handle superposition of hazards. After accumulation of case studies of fault displacement PRA, we should consider the priority of assessing superposition of hazards depending on the quantitative risk level as a single hazard. In case there is a pressing need for the evaluation of both hazards, this standard describes simplified method of handling both fault displacement and seismic motion, although it is a little conservative.

INVESTIGATION OF PLANT AND SITE INFORMATION AND IDENTIFICATION OF ACCIDENT SCENARIOS

As an initial step of the PRA, the analyst collects plant and site information for the hazard analysis, fragility analysis and accident sequence analysis. After then, a general analysis of accident scenario is carried out to depict various accident scenarios that can potentially occur as a result of a fault displacement events at the site. Important aspects of plant and site information collection and the accident scenario identification are provided below.

Collection of Plant and Site Information

Gathering information is an iterative process carried out as the assessment evolves, and types of information gathered varies with the technical elements (e.g., hazard analysis, fragility analysis, and accident sequence analysis) of the PRA. Sources of plant and site information are such as plant design drawing and documents, licensing and basis documents for the construction plan approval, and plant procedures. Analysts should also gather information on proceeding fault displacement PRA studies and reports on domestic and international fault displacement disasters that have occurred not limited to nuclear facilities.

Plant walkdowns should be performed to collect information that cannot be gathered or identified from documents. Another objective of walkdown is to confirm the design documents reflect the as-build and as-operated structures, systems and components (SSCs). Important viewpoints during the fault displacement walkdown, but not limited to, are as follows:

- No apparent corrosion or crack in joints between the support and SSCs
- Anchor bolt are adequately tightened and controlled
- Assumptions used in the determination of fault displacement failure modes (i.e., failure cause by component inclination, relative displacement of buildings, or uplift/subside of longish foundation) is consistent with the as-built SSCs
- Possibility of secondary effects caused by collapse, damage or falling of SSCs located near the SSCs taken credit in the PRA
- Possibility of losing access route or portable equipment carrying passage due to structure collapse or landslides

Identification of Accident Scenarios

The goal of the accident analyses at this stage is to identify generic accident scenarios that could be risk important and develop a fault displacement equipment list as an input to fragility and accident sequence analysis. This process starts from gaining a generic understanding of the accident scenario that can be in triggered by the fault displacement event, considering the geological and plant structure characteristics at the site. The impact of fault displacements on SSCs are unique in the point that it could be locally limited to certain SSCs, in contrast with seismic events where the seismicity is not a local but experienced in the entire site. Accident scenarios involving such localized damages caused by fault displacement, as well as accident scenarios involving damage of important large SSCs and secondary effects resulting degradation of safety functions must be clarified when credible.

FAULT DISPLACEMENT HAZARD EVALUATION

Probabilistic Fault Displacement Hazard Analysis (PFDHA) is applied to fault displacement hazard evaluation. In PFDHA, a displacement of the ground along a fault plane, that is, a dislocation, is to be evaluated as a "fault displacement". It should be noted here that the fault displacement in PFDHA is not the displacement obtained by integrating the seismic acceleration in PSHA twice. It is necessary to adopt evaluation formulae that can consider the characteristics of the evaluation site, including evaluation formulae based on the fault displacement data of the ground surface due to earthquakes occurred in Japan. In this case, evaluation methods based on overseas data may be referred to. The fault displacements evaluated in PFDHA are classified into a primary (principal) fault and a secondary (distributed) fault. Figure 2 shows a conceptual diagram of the primary and the secondary fault. The primary fault is the fault that is considered to be an extension of the earthquake source fault. It should be added here that the primary fault includes a splay fault that connects to the earthquake source fault. The secondary fault is the fault that occurs secondarily or subordinately due to an activity of the primary fault at a location distant from the primary fault. In the fault displacement hazard evaluation, faults that are confirmed near the ground surface are considered. Hereafter, terms "principal" and "distributed" are used instead of "primary" and "secondary" respectively following some papers on the PFDHA.

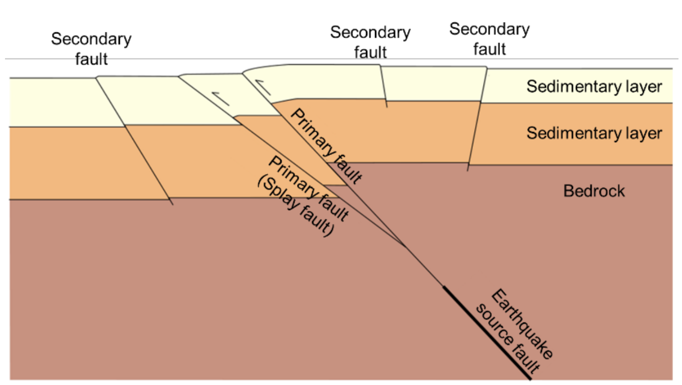

Figure 2. Conceptual diagram of primary and secondary fault

Procedure of Fault Displacement Hazard evaluation

In general, the fault displacement hazard evaluation should be performed in the order described below.

(A) Evaluating fault displacement hazard curves on the ground surface
- Setting fault displacement models (A1)
- Setting distance attenuation models of fault displacement (A2)
- Developing logic trees (A3)
- Evaluating fault displacement hazard curves (A4)

(B) Transforming the fault displacement hazard curves on the ground surface to the free bedrock surface

Basically, the aforementioned (A) should be proceeded based on the same procedure as the previous PFDHA. The feature of the AESJ standard, however, is that the (A) includes not only identified sources but also unidentified sources based on the diffuse seismicity regions similar to Probabilistic Seismic Hazard Analysis (PSHA).

Setting fault displacement models (A1)

Both the identified sources and the unidentified sources are to be examined, and the displacement approach and/or the earthquake approach will be applied for the identified sources. The displacement approach, which is also called the direct approach, utilizes the fault displacement characteristics observed at the evaluation site. The displacement approach is applied when there is sufficient survey information related to the displacement amount and activity, etc. of the fault in the site and/or in the vicinity of the site regardless of whether the fault is a principal fault or a distributed fault. On the other hand, the earthquake approach is employed when the aforementioned survey information is not sufficient.

When setting the parameters of the fault displacement models for the unidentified sources based on the diffuse seismicity regions, the parameters of Gutenberg-Richter law (GR law) and occurrence probability of the principal fault in the region without identifying earthquake sources are to be set according to the seismotectonic characteristics of the region and the data of past earthquakes around the evaluation site. When calculating an annual exceedance rate of principal fault displacement, the same method as the identified sources may be applied. However, as for the evaluation formulae for the occurrence probability and the fault displacement amount of the principal fault, evaluation formulae have been proposed based on the data of the surface ruptures that appeared in the area where active faults have not been identified. These formulae may be applied as references for the unidentified sources based on the diffuse seismicity regions.

Setting distance attenuation models of fault displacement (A2)

There are two types of distance attenuation formulae for an evaluation of fault displacements, namely, one is for the principal fault and the other is for the distributed fault. Since it is known that the fault displacement amount of the principal fault changes depending on the position along the principal fault, a suitable formula should be selected according to the purpose. As for the distance attenuation formulae for the occurrence probability of distributed fault, a formula that depends on a magnitude of an earthquake and a formula that depends on the horizontal size (cell size) of the evaluation structure have been proposed. Therefore, it is necessary to choose a suitable formula according to the case. Regarding the distance attenuation related to the occurrence probability of distributed faults, the cell-size dependency has a greater impact on the occurrence probability than the magnitude. Therefore, the judgment should be made based on the degree of influence of those parameters. In addition, when considering the cell-size dependency, the distance attenuation formula for the occurrence probability of the distributed fault, which was obtained using a cell size close to the horizontal size of the building/structure, should be applied.

Developing logic trees (A3)

In the process of the setting of the fault displacement models and the distance attenuation models of the fault displacement, the PFDHA evaluator should consider items for which opinions are divided, items for which there are two or more evaluation methods, and so on. The logic tree needs to be developed reflecting all possible epistemic uncertainties. Examples of the epistemic uncertainties are as follows;

- Identified sources
  - (a) Displacement approach; capability of the fault, average recurrence period, average slip rate, average displacement amount per one time, and parameters of the probability density function (standard deviation, shape parameter, scale parameter, etc.)
  - (b) Earthquake approach for principal fault; (in addition to (a)) fault length, fault width, dip angle, fault mechanism (normal, reverse or strike-slip), magnitude, displacement distribution (including uniformity/non-uniformity), and differences among various evaluation formulae
  - (c) Earthquake approach for distributed fault; the distance from the principal fault, differences among various evaluation formulae, and parameters of the probability density function (standard deviation, shape parameter, scale parameter, etc.)
- Unidentified sources
  - (d) Earthquake approach for principal fault; (in addition to (b)) coefficients of GR law, maximum magnitude to which GR law is applied, and differences among evaluation formulae.
  - (e) Earthquake approach for distributed fault; the same as (c)

Evaluating fault displacement hazard curves (A4)

Based on the groups of the fault displacement hazard curves obtained from the logic trees, the fractile fault displacement hazard curves are to be evaluated, and the distribution profile of the uncertainties in the fault displacement hazard evaluation should be confirmed. Figure 3 shows an example of hazard curves obtained from PFDHA and the 0.05 to 0.95 in the legend are fractile hazard curves. In this example, assuming that three faults are distributed around the site, the magnitude of earthquakes due to the active faults and the average recurrence period of the active faults were considered in the analysis as epistemic uncertainties. For one fault, whether the fault is an active fault or not was also taken into account as an epistemic uncertainty.

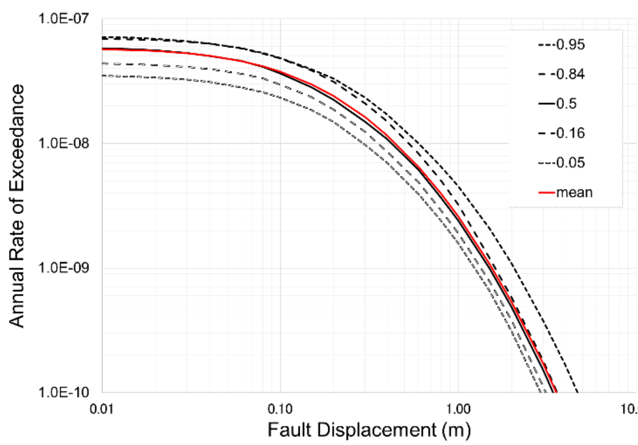

Figure 3. Example of hazard curves

Regarding the median hazard curve or the mean hazard curve, the validity as the representative of the fault displacement hazard curves should be examined in consideration of the obtained distribution profile. If it is judged to be invalid, some of aggregate fault displacement hazard curves may be adopted as the representative of the fault displacement hazard curves. It should be noted that the fault displacement hazard curve gives only the scalar of the displacement, not the vector. Therefore, in the evaluation for a building and/or a structure, it is desirable to consider an evaluation method that can take into account information such as strike and dip obtained from the fault survey results at the evaluation site.

Transforming fault displacement hazard curves on the ground surface to the free bedrock surface (B)

In order to carry out the fault displacement PRA, when transforming the fault displacement hazard curves on the ground surface to the input position of the fault displacement of the building/structure, the ground transmission ratio related to fault displacement should be adopted for transforming the fault displacement hazard curves on the ground surface to those on free bedrock surface. In this occasion, it can be assumed that an annual exceedance rate of the fault displacement on the free bedrock surface is the same as before transformation. It should be added that the reason for defining the fault displacement on the free bedrock surface is to prepare for the superposition with seismic ground motion in the future.

BUILDING AND COMPONENT FRAGIITY EVALUATION

The purpose of building and component fragility evaluation is to quantify their conditional failure probability for accident sequence analyses with fragility-input fault displacement hazard on free bedrock surface described in the previous section. Conceptual image of relationship between hazard and fragility analysis under fault displacement is shown in Figure 4. Similar to other external hazards such as seismic PRA and tsunami PRA, building and component fragility evaluation under fault displacement hazard shall be performed in the following procedures.

- Setting up items for evaluation and failure modes
- Selection of evaluation method
- Evaluation of realistic capacity
- Evaluation of realistic response
- Fragility evaluation
- Failure correlation evaluation

Technical elements of the building and component fragility evaluation under fault displacement hazard are described below.

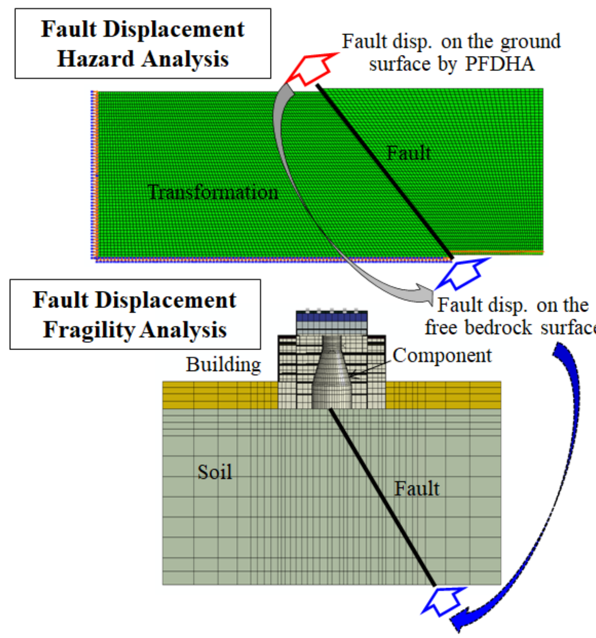

Figure 4. Conceptual image of relation between hazard and fragility analysis under fault displacement

Setting up items for evaluation and failure modes

First, based on the fragility information collected and analysed described in the previous section and also the fault displacement equipment list, buildings and components for fragility evaluation should be determined focusing on the initiating events and mitigation systems. Secondly, the potential failure mode and area for each building and component should be derived for fault displacement fragility evaluation, and accordingly damage indicators related to the failure mode should be evaluated. Finally, uncertainty factors regarding realistic capacity and response should be investigated for the evaluated SSCs or categories, and furthermore, aleatory and epistemic uncertainties should also be broadly classified.

Selection of evaluation method

Fragility evaluation method should be selected depending on the intended purpose and the degree of accuracy that is required. In particular, the fragility model should be validated with actual damage cases due to fault displacement hazard and also be considered with the epistemic uncertainties corresponding to each evaluation method using expert judgments.

Evaluation of realistic capacity

Capacity in the required limit state of each SSC corresponding to the failure mode and area under fault displacement hazard should be evaluated realistically as a stochastic quantity. As for the evaluation methods of realistic capacity, there are the empirical method including experiments, the theoretical method including analyses, and engineering judgments based on both methods.

Evaluation of realistic response

Responses of each SSC corresponding to the failure mode and area under a number of scales of fault displacements in assumed exceedance rates should be evaluated realistically as a stochastic quantity. Fragility-input fault displacement with both uncertainties of soil-structure interaction should be evaluated based on the results of PFDHA on free bedrock surface without soil-structure interaction.

Fragility evaluation

Building and component fragility curves under a number of scales of fault displacements in assumed exceedance rates should be calculated through any of the methods mentioned above. These building and component fragility curves are used in the accident sequence analyses in the next chapter. Moreover, when accident sequence analyses are performed to distinguish initiating events directly leading to core damage such as reactor building collapse, reactor containment vessel collapse and reactor pressure vessel major failure, from other initiating events related to local failure of components, fragility curves should be quantified to distinguish failure modes directly leading to core damage and other failure modes. As for the references regarding examples of fault displacement fragility curves, nuclear power plant (NPP) building fragility curves on various types of supporting rocks are given by H. Tsuji et al. (2018) and also NPP component fragility curve such as main steam crossover piping evaluated by R. Haraguchi et al. (2020) is shown in Figure 5.

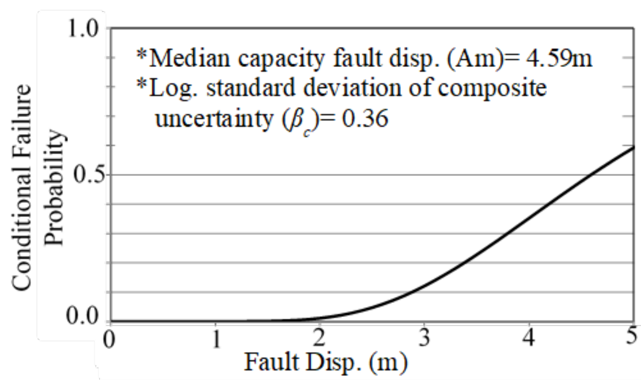

Figure 5. Example of component fragility curve

Failure correlation evaluation

Under a large amount of fault displacement, it is assumed that so called common-cause failure will occur, where multiple components fail at the same time. Therefore, similar to seismic PRA, the correlations of failure between multiple components should be considered in the following accident sequence evaluation.

ACCIDENT SEQUENCE EVALUATION

The purpose of accident sequence evaluation is to develop accident sequences for the initiating events that can occur following an initiating event, and quantify the frequency of the accident sequences. Methodologies used for the accident sequence evaluation in seismic PRAs are basically applicable to fault displacement PRA, with additional consideration of plant response and operator action impacts that are characteristic to fault displacement events. Technical elements of the accident sequence evaluation are described below.

Initiating event analysis

Initiating events subjected to accident sequence evaluation should be defined based on the set of initiating events identified by the accident scenario analysis. For each initiating events or initiating event groups, SSC failures that cause the initiating event, functions necessary to mitigate the initiating event, and condition of the containment vessel should be clarified. To assess the impact of combined impact of multiple initiating events caused by the fault displacement event, a hierarchy initiating event tree can be used (Figure 6).

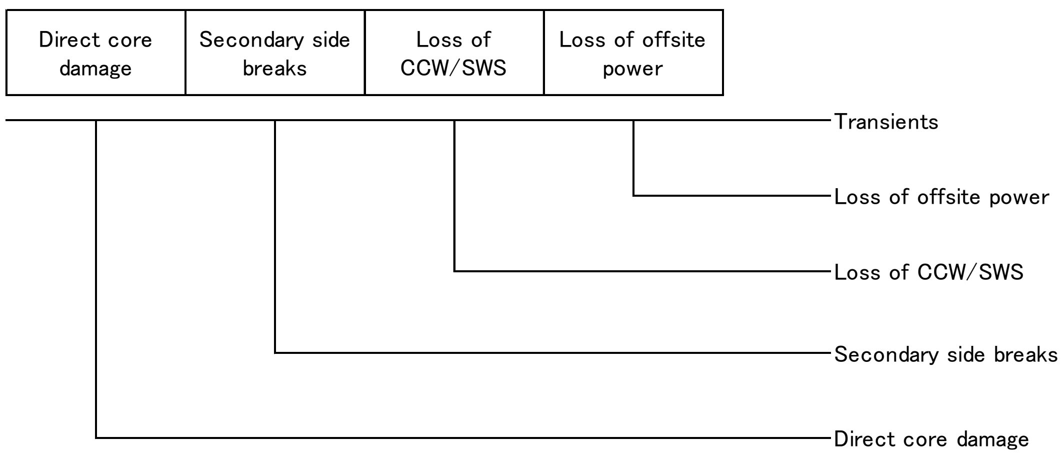

Figure 6 Example of an initiating event tree

Accident sequence modelling

Event trees are developed for each of the initiating event groups. Initiating events that involve large structural failures and those of which the plant response is not clear (e.g., reactor building failure event and containment vessel failure event), can be treated as events directly leading to core damage. However, the impact of such accidents on the level 2 PRA analysis, such as containment failure frequency and source term, should be investigated.

Systems modelling

Fault tree analysis can be used to quantify the reliability of mitigation functions and systems. Functional failures, structural failures resulting in loss of function, structural failure resulting in loss of boundary of the system, and structural failures causing secondary effects on other functions or systems should be considered. The fault displacement event can add high stress to the operators and/or impact accessibility to equipment, so the impact on mitigation actions should be considered in the human reliability analysis.

Accident sequence quantification

Frequency of the accident sequences should be quantified, and uncertainty analysis, sensitivity analysis and importance analysis against the core damage frequency should be performed. In the accident sequence quantification, correlation of fault displacement induced failures should be considered. Since the region of impact of the fault displacement events are relatively limited compared to seismic events, it is important to consider the spatial relation of SSCs that fail. Failures cause by relative displacement of buildings, such as structural failure of piping crossing two buildings may be highly correlated.

Containment failure scenario analysis

Analysis of containment failure scenarios should be performed to clarify the impact of fault displacement accident sequences on scenarios resulting to release of fission products. Core damage accident sequences should be categorised and grouped considering the similarity in plant response, success criteria, and availably of mitigation system or actions to prevent release. Containment event trees are developed to identify and clarify the probable containment failure scenarios.

CONCLUSION

AESJ established the implementation standard for the fault displacement PRA as a first procedure guidance for fault displacement PRA in the world. As stated in the IAEA safety standards, fault displacement is usually discussed as a critical siting issue. We hope this standard will be utilized, not only in Japan but also internationally, for risk-informed decision making for safety of existing nuclear installation as well as for updating siting criteria for new installation.

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