Improvement of Fault Displacement PRA Methodology and Concept of its Application to a Hypothetical NPP

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Abstract: The authors have developed a concept of fault displacement (FD) probabilistic risk analysis (PRA) methodology, through application to a hypothetical nuclear power plant (NPP).

Core damage frequency and its uncertainty of a hypothetical NPP was evaluated using FD hazard, FD fragilities of building and components, and fault tree and event tree models. Important initiating events, accident sequences, components and structure failures, as well as the range of the fault displacement that characterize the core damage risk profile were identified. Through the study, the authors confirmed the feasibility of the methodology, and also identified the important source of uncertainties within the methodology that require further development. Risk insights obtained from the FD PRA can be used to investigate countermeasures to reduce FD risk.

Keywords: Fault displacement PRA methodology, Improvement of methodology, Concept of methodology application, Hypothetical NPP.

1. INTRODUCTION

The Chi-Chi Earthquake, a magnitude of 7.6, occurred in Taiwan in Sept.1999. During the event, dam and buildings collapsed by surface fault displacement, and the influence of FD on structures has been brought to attention. Recently in Japan, interest on the impact of principal and secondary FDs on nuclear facilities has increased, and it is currently recognized as an urgent issue for investigation. The current status regarding FD probabilistic risk analysis (PRA) methodology in Japan is as follows. The Atomic Energy Society of Japan (AESJ) is conducting two activities [1], [2]. Japan Society of Civil Engineers published research report of FD evaluation that included investigation of Fault and FD, FD evaluation based on numerical analysis and experiment etc. [3]. With regards to international activities, an international workshop, with participants from nuclear industry, has been recently held to discuss the latest studies on fault displacement hazards [4]. The authors were conducting analysis and examination for developing fault displacement PRA methodology [5].

Under this context, the authors established a methodology concept as part of the development of fault displacement PRA. To confirm the feasibility of the methodology, CDF and uncertainty analysis have been performed through application to a hypothetical NPP. Important initiating events, accident sequences, components and structure failures, as well as the range of the fault displacement that characterize the core damage risk profile were identified. Through the study, the authors confirmed the feasibility of the methodology, and also identified the important source of uncertainties within the methodology that require further development. In addition, investigations on the evaluation of the impact of superposition of seismic acceleration and FD, and consideration of measures to reduce FD have been performed.

In this paper, concept of the FD PRA is described in section 2. The CDF and uncertainty analysis performed against a hypothetical NPP is described in section 3. Sections 4 and 5 describe the treatment of combined seismic motion and FD hazard, and consideration of measures to reduce risk from FD, respectively.

2. Concept of FD PRA methodology

2.1. FD PRA basic approach

An effective approach for the FD PRA, is to focus on the credible plant behaviour analysis against fault displacement in the beginning, rather than a detailed CDF analysis, since the impact of FD event on NPP risk may not be significant to justify performing a fully detailed PRA. If the event is deemed to have significant impact on the NPP, a detailed investigation will be performed focusing on aspects that have large uncertainty. To focus on the important accident contributors, screening is applied at the FD equipment list development stage, initiating event identification stage, and fragility analysis stage.

2.2. Basic evaluation process

The FD PRA process consists of accident scenario identification, hazard evaluation, fragility evaluation and accident sequence evaluation as shown in Figure 1. The evaluation process is basically the same with the framework of seismic PRA and tsunami PRA.

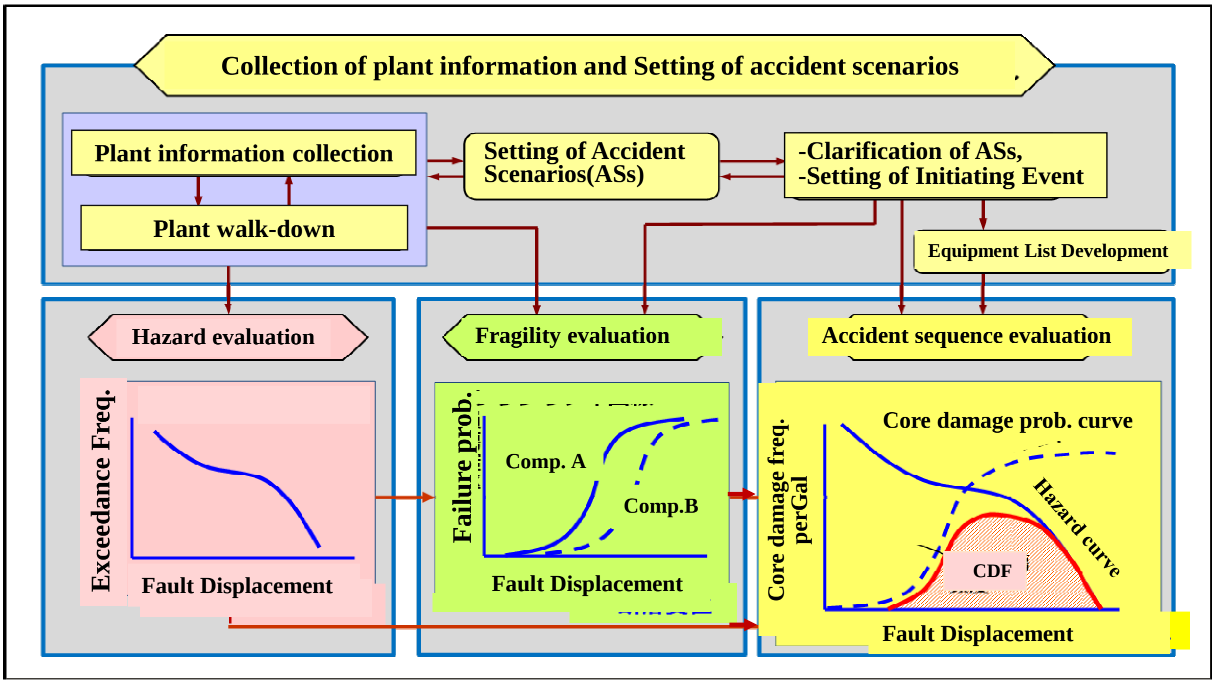


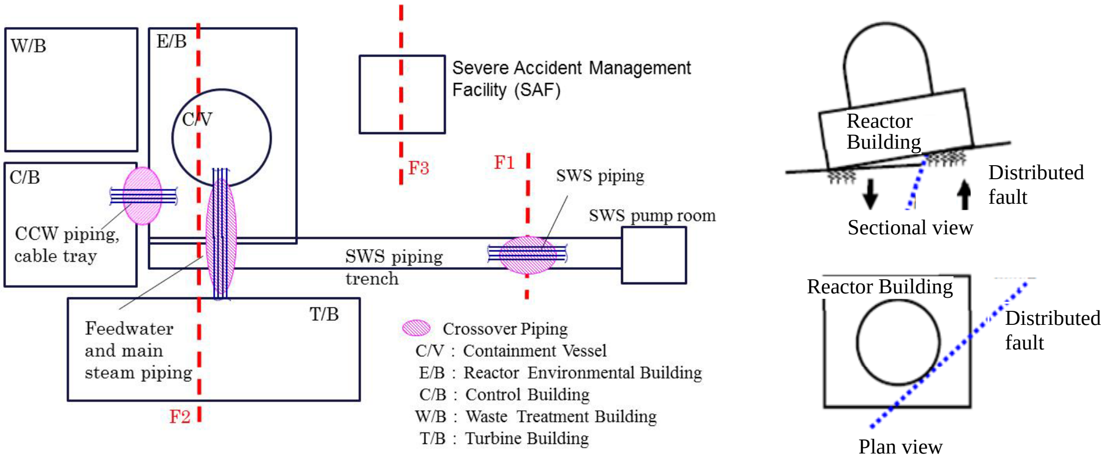
Figure 1 Evaluation process of FD PRA

3. Application of the method to the hypothetical NPP

3.1. Hypothetical NPP and FD hazard of interest

A pressurized water reactor (PWR) plant consisting of civil structures such as containment vessel (C/V), reactor environmental building (E/B), control building (C/B), turbine building (T/B), waste treatment building (W/B), sea water system facility (SWS), severe accident management facility (SAF) has been set as a hypothetical plant of interest. The plant layout drawing is shown in Figure 2 (a). As shown in the figure, piping that cross buildings, such as component cooling water system (CCWS) piping, sea water system (SWS) piping, and main steam line are also considered.

A reverse fault of the distributed fault has been assumed, as show in Figure 2 (b). Three locations (F1, F2, and F3) of which the surface displacement interacts with the structures were considered. F1 represents a surface FD that locates underneath the E/B, C/V and T/B. F2 represents a surface FD that crosses the SWS sea water piping trench. And F3 represents a FD located underneath the centre of the SAF basemat.



(a) Layout of the hypothetical NPP (b) Point of action at building

Figure 2 Hypothetical NPP and distributed FDs assumed in the study

A hypothetical FD hazard, based on the Japanese FD hazard study has been applied in this study. Takao et al. [6] has reported a FD hazard considering the FD conditions in Japan. The FD hazard evaluated by the Takao et al., shown in Figure 3, was used in this study for the three distributed FDs of interest.

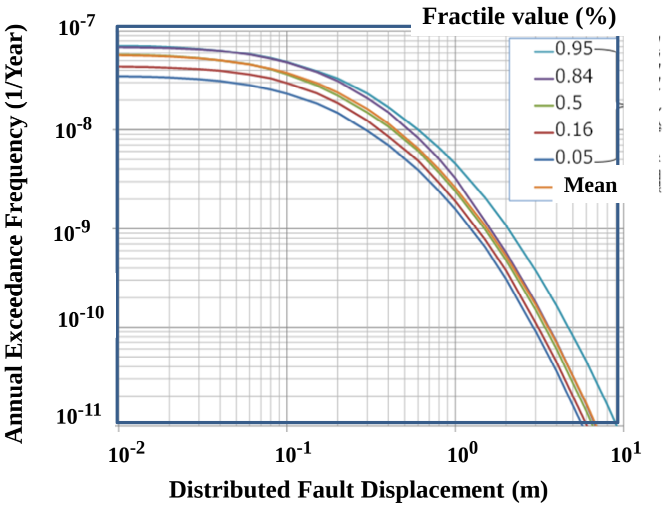


Figure 3 Distributed FD hazard use in this study

3.2. Identification of FD equipment and initiating events

(1) FD equipment list

A FD equipment list is developed to identify the SSCs affected by the FD of interest. This process is important to demonstrate the completeness of the FD induced initiating events, and the failure modes to be considered in the FD PRA.

With consideration that the FD event is a local event, the development of the FD equipment list starts with the identification of the building and structures affected by the postulated FD. Building and structures directly affected by the FD are identified by the geometrical condition between the FD and the structure of interest. The initial FD equipment list includes all SSCs within the building that is directly affected by the FD. Failures of equipment caused by relative displacement of two structures or buildings are also important. Displacement of adjacent buildings, caused by the FD, also need to be considered to identify potential failures of piping and cables that cross the buildings.

The equipment list of structures and equipment is screened with consideration of their anticipated impact to FD risk, using insights from generic hazards and fragility analysis. This process will reduce the number of equipment to be subjected to detail fragility analysis and also allow the PRA to focus on the important risk contributors. Potential failure modes and their screening condition are presented below.

- Functional failure caused by inclination
  Inclination angle of buildings, caused by a credible FD, is small and their impact is considered not sufficient to affect the functionality of active components.
- Loss of support caused deformation of floor
  Deformation of floor is likely to occur at the base floor. Floors above the base floor, which have no direct contact with the FD surface or the slab effected, are unlikely to cause local deformation. For FDs that cause significant deformation of the building, the effect will be captured in the building fragility.
- Stress caused by building displacement
  If the amount of creditable building displacement, evaluated from hazard analysis, is considerably small to cause failures of equipment that cross buildings, this failure mode can be screened out.

With consideration of the screening shown above, a FD equipment list has been developed for the hypothetical plant. Figure 4 shows the equipment layout in the base floor of the hypothetical plant. Equipment effected by the deformation of the base mat identified from the equipment layout at the base floor and the location of the FD, where deformation of the floor is expected to occur. In this case FD is anticipated to cause displacement to the E/B and T/B, causing stress to the crossover piping and cables that reach out from the effected buildings. For the components installed in the SAF, portable pumps, emergency mobile power supply unit, and fire pump trucks were identified as equipment that can be effected by FD F3.

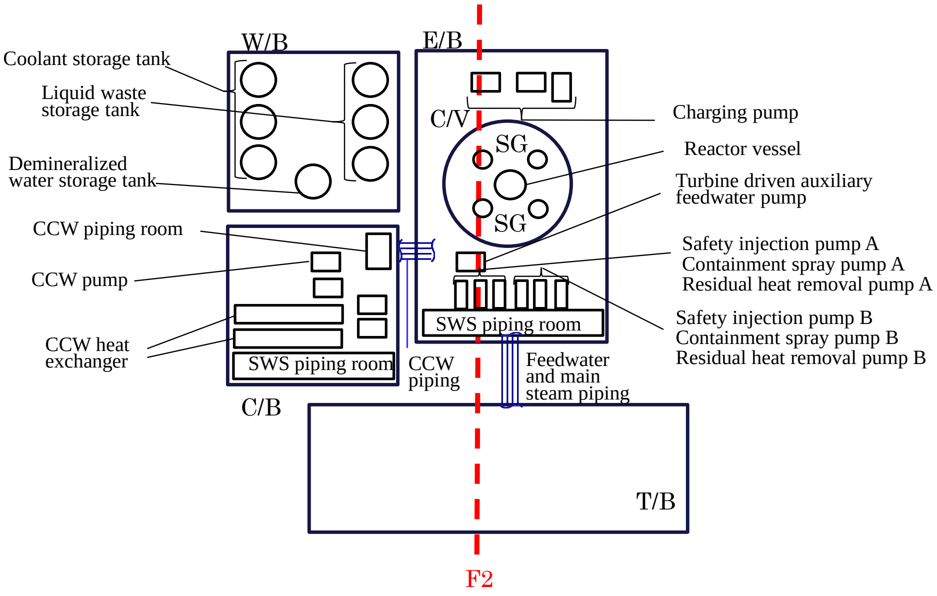


Figure 4 Conceptual Layout drawing of building and equipment

(2) Initiating event identification

For each component in the FD equipment list, the initiating events triggered by the postulated failure as well as the impact on the mitigation functions were investigated. Table 1 shows samples of equipment in the equipment list of those that have the potential to fail by deformation of floor in the hypothetical plant. Deformation of the floor at the vicinity of sea water system piping may cause a partial or total loss of sea water system initiating event. Deformation of the floor located at the turbine building has the potential to cause loss of feed water or secondary side break initiating events.

Table 2 shows sample of equipment that cross buildings and have the potential to fail by building displacement. Piping and cable trays that cross buildings have the potential to fail when either of the buildings experience displacement.

Table 1: Equipment with potential to fail by deformation floor and their impact on plant response

Equipment/Component	Initiating Events	Effected Mitigation Function
Charging pump A	—	RCP seal cooling, charging injection
Safety injection pump A	—	Safety injection, Feed and bleed
Containment spray pump A	—	Containment spray
Residual heat removal pump A	—	Residual heat removal, Low head injection
T/D auxiliary feedwater pump	—	SG cooling
SWS piping	Partial or total loss of SWS	Component cooling
Turbine building internal equipment	Loss of main feedwater, Secondary side breaks	SG cooling, Primary side depressurization using SGs

Table 2: Equipment with potential to fail by relative replacement between buildings and their impact on plant response

Equipment/Component	Initiating Events	Effected Mitigation Function
SWS piping	Partial or total loss of SWS	Component cooling
CCW piping	Partial or total loss of CCW	
Main steam piping	Secondary side breaks	SG cooling, Primary side depressurization using SGs
Main feedwater piping	Secondary side breaks	
Cable tray	Transients	Plant monitoring and control

3.3. Fragility analysis of structures and components

(1) Screening of components

In order to select components for quantification of their fragilities from the FD equipment list, screening based on structure and function of each component is conducted. If a component has sufficiently large capacity compared to the influence of the FD, and its failure probability is negligible within the range of a credible FD, it is screened out from the fragility evaluation. And if failure of a component is considered to be enveloped by failure of other systems structures and components (SSCs), the component is also screened out.

As a result of the above mentioned screening process, cross over piping between the buildings, seawater piping placed in the seawater trench and severe accident countermeasure components (e.g., emergency mobile power supply unit and mobile pumps) were selected from the equipment list for quantification of their fragility.

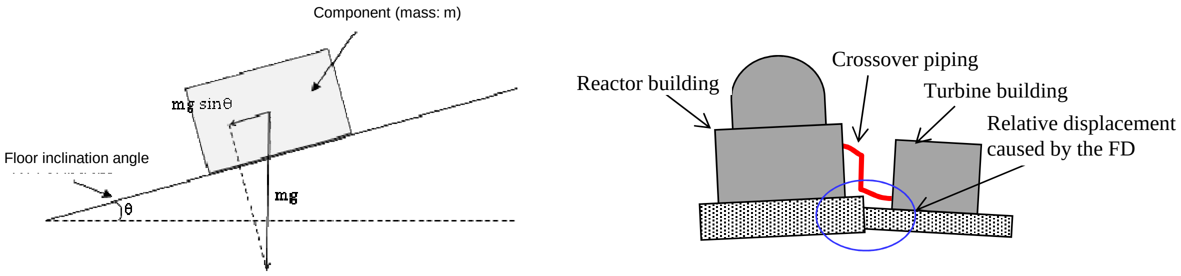
(2) Method and condition of the fragility evaluation

Fragilities of components are evaluated by applying separation of variables method of the seismic PRA [5] [7]. The fragility is evaluated using the amount of the FD as a measure and the results is expressed as median capacity displacement A_m, aleatory uncertainty β^R_r and epistemic uncertainty β^R_u.

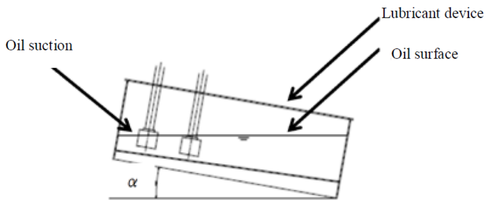
In this study, influences on the SSCs caused by inclination or displacement by the FD are considered for the fragility evaluation and superposition with the load by seismic motion is not considered. And for the evaluation of failure and fragilities of the components, layout of the hypothetical NPP (PWR) shown in section 3.1 is considered.

(3) Results of the fragility evaluation

Fragility of each component is evaluated based on its dominant failure mode such as structural failure and functional failure. Structural failure is evaluated based on load on the component's member generated by inclination of the floor (Figure 5 (a)). However, actual load generated by the inclination is significantly small comparing with the capacity of the component's member and its failure probability is obviously negligible [5]. Therefore, this failure mode is screened out as mentioned in section 3.4(1). In the case of crossover piping between buildings, large relative displacement between the buildings is thought to be caused by the FD (Figure 5 (b)). Therefore, its failure probability is not negligible and fragility is evaluated based on distortion load on the crossover piping generated by the relative displacement. Functional failure of dynamic components is evaluated from a view point of operation continuity under the condition of inclination by the FD. Therefore, functional failure of dynamic components are evaluated focusing on the inclination angle which the lubricant device can maintain its function (Figure 5(c)) [5].



(a) Concept of the structural failure mode　　(b)Failure of the crossover piping

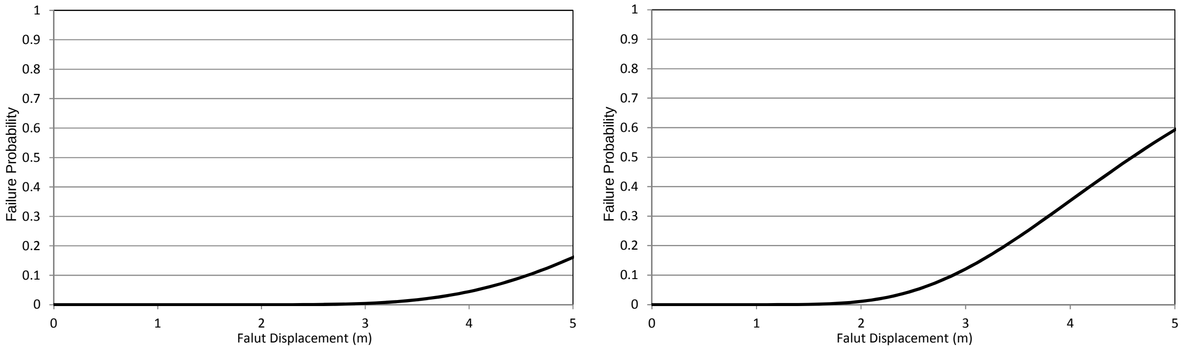


(c) Concept of the functional failure mode

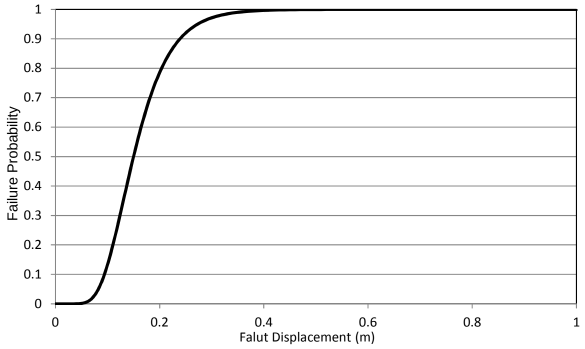
Figure 5　Failure modes considered in the fragility evaluation

A result of fragility evaluation of a horizontal pump is shown in Figure 6 (a) as an example. Failure mode of the pump is a functional failure by loss of lubrication supply. Median functional capacity (inclination angle) C_m of the lubrication oil suction is 5˚. As a result of the evaluation, median capacity displacement (A_m) is 6.84m, aleatory uncertainty β^R_r is 0.10, epistemic uncertaintyβ^R_u is 0.30 and HCLPF is 3.54m.

Results fragility evaluations of main steam and CCW crossover piping are also shown in Figure 6 (b) and (c) respectively, as examples of the cross over piping. Failure of the crossover piping is evaluated from the viewpoint of distortion generated by the relative displacement at the piping member midway between the buildings. As a result of the evaluation of the main steam crossover piping, median capacity displacement (Am) is 4.59m, aleatory uncertainty β^R_r is 0.10, epistemic uncertaintyβ^R_u is 0.35, and the resulting HCLPF is 2.22m. And the result of the CCW crossover piping is an example of the most severe case, median capacity displacement (Am) is 0.15m, aleatory uncertainty β^R_r is 0.10, epistemic uncertaintyβ^R_u is 0.35, and the resulting HCLPF is 0.07m.



(a) Horizontal pump (b) Main steam crossover piping



(c) Component cooling water crossover piping

Figure 6 Examples of fragility evaluation results

3.4. Accident sequence analysis and core damage frequency evaluation

(1) Analysis condition

An initiating event tree to address the various FD induced initiating events was developed, based on the FD equipment list and the FD initiating events identified in section 3.2. The initiating event tree is shown in Figure 7. The initiating event tree is development in a manner similar with the initiating event tree for seismic PRAs. The initiating event with the largest impact on plant response is considered in the event heading just after the initiating event. The impact of support system and frontline system failures on plant response is addressed in fault trees used in the plant response event tree, which is linked to each of the end states of the initiating event tree. Since the FD induced support system failures in the accident sequences will be evaluated through the fault trees in the plant response event tree, in the initiating event tree, there are no branches representing support system failures in the sequence where secondary side break has occurred.

Fault trees were developed for each event tree headings of the plant response event tree. SSCs considered in the fault trees were limited to representative active and components of the front line system necessary to achieve the mitigation function, and the components of support systems (i.e., CCW, SWS and Electrical system) that support the frontline systems. Failure modes considered in the fault trees were random failures, human errors, FD induced failures and failures due to seismicity. The concept of the fault tree structure is shown in Figure 8.

Considering that the distributed FDs at a site may occur simultaneously, or independently (only one occur), sequence analysis has been conducted for four cases: a case assuming that distributed FDs all occur simultaneously with the same magnitude, and three cases each assuming independent occurrence of the three different FDs (F1,F2 and F3).

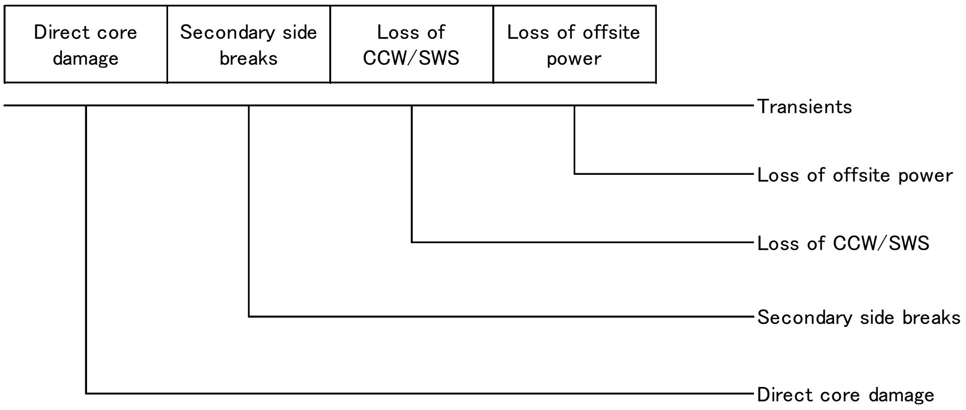


Figure 7 Example of the initiating event tree

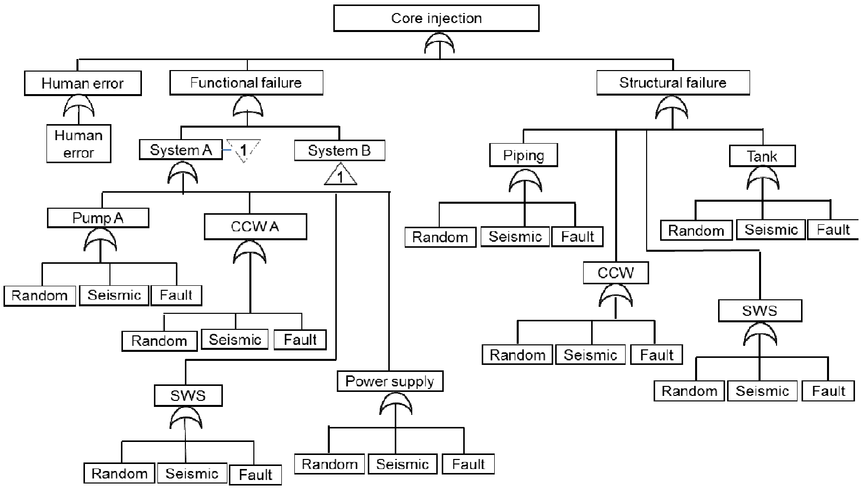


Figure 8 Concept of the fault tree for FD PRA

(2) Point estimate of the Core damage frequency

Core damage frequency (CDF) quantifications using the FD hazard curve, event tree and fault tree models have been carried out using the Risk Spectrum® PSA code. Component failure by seismicity is not considered in the CDF quantification. Point estimates of the CDF for the four cases are shown in Table 3. The CDF for the scenario assuming that all FDs activate simultaneously, is $3.3x10^{-8}$ /yr. The dominating initiating event for this in this scenario is the total loss of CCW and SWS initiating event, and the other initiating events have contribution a little less but similar.

The CDF evaluations for separate FDs show that F2, the event in which the FD takes place underneath the E/B and the TB, has the highest risk contribution. The dominating core damage scenario for F2 involves total loss of CCW and SWS initiating event caused by FD induced failure of CCW piping that cross the E/B and C/B. When the this initiating event involves a structural failure of cable trays that also cross the buildings, a loss of auxiliary feed water function with no mitigation functions available will occur, and the core will be damaged. The large CDF contribution from F2 indicates that the FD induced failures caused by F2 are the dominant risk contributors when the FD actuate simultaneously.

The CDF contributions from each FD height intervals, for the case assuming simultaneous actuation of the FDs, are shown in Table 4. The conditional core damage probability (CCDP) for each FD height intervals are also shown in the table. The CCDP increases from above 0.1 m, which corresponds to the bin that covers the median capacity of cable trays and piping that cross buildings. The most risk significant FD height range is meters 0.2 to 0.4 m, and the CCDP for the bin exceeds 0.8. For FD height ranges above, the CDF contribution decreases as result of decreasing hazard frequency.

Table 3: CDF contribution per initiating event

Initiating event	Distribute FD of interest			
	F1	F2	F3	F1, F2, F3 Simultaneous
Direct core damage	0.0E+00	8.1E-09	0.0E+00	8.1E-09
Secondary side breaks	0.0E+00	5.4E-09	0.0E+00	5.4E-09
Loss of CCW/SWS	3.5E-09	1.6E-08	0.0E+00	1.6E-08
Loss of offsite power	1.2E-10	3.6E-09	1.6E-10	3.6E-09
Total	3.6E-09	3.3E-08	1.6E-10	3.3E-08

All units are in /yr

Table 4: CDF contribution per FD height （F1, F2, F3 Simultaneous case）

	0.01m-0.05m	0.05m-0.1m	0.1m-0.2m	0.2m-0.4m	0.4m-0.7m	0.7m-1.0m	1.0m-1.5m	1.5m-3.0m	3.0m-5.0m	total
CDF (/yr)	2.4E-11	5.9E-10	5.7E-09	1.3E-08	6.6E-09	2.9E-09	1.7E-09	1.8E-09	3.3E-10	3.3E-08
Contribution	<0.1%	1.8%	17.4%	39.7%	20.2%	8.9%	5.2%	5.5%	1.0%	
CCDP	0.002	0.06	0.47	0.84	0.82	0.84	0.97	0.98	1.00	

(3) CDF uncertainty analysis

Uncertainty analyses have been carried out for the four cases of which CDF point estimates have been performed. The uncertainties considered in the analyses are the uncertainty of the hazard curve, FD fragility, and random failures including human error. Uncertainty distributions were assigned to each frequency and probability values and were propagated through the model using Risk Spectrum® PSA code.

The results of the uncertainty analyses are shown in Figure 9. Uncertainty of the FD hazard characterized the uncertainty of the CDF values, resulting in small variation in the uncertainty band among the four cases evaluated.

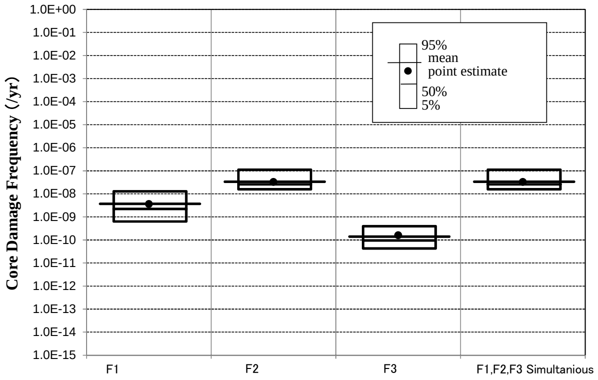


Fig.10 CDF uncertainty results

4. Consideration of seismic acceleration superposition and countermeasures to reduce risk

4.1. Consideration of superposition of seismic acceleration and FD

For the purpose to obtain a prospect of the idea to evaluate superposition of seismic motion and FD, a sensitivity analysis has been performed. The variation of the CCDP given superposition of seismic motion and FD has been analysed using the PRA model developed. For the systems modeled in the FD PRA, seismic fragilities of the components were considered in addition to FD fragilities. Seismic fragilities were considered for SSCs that can cause an initiating event as a result of FD, but from the limitation of using the PRA model developed in the previous sections, initiating events specific to seismic failure were not considered.

Variation of CCDPs for given combinations of seismic acceleration and FD are shown in Figure 11. The CDF is sensitive to the superposing seismic acceleration at FD hazards less than 0.2m, where the CCDP from FD itself is relatively small. On the other hand, the CDDP becomes insensitive to the superposing seismic acceleration at FDs larger than 0.2m, where the CCDP become close to one regardless of the superposing seismicity.

The analysis show that the evaluation of CCDP as a function of seismic acceleration and FD can provide insights on the hazard range where the superposition of hazards become important. Accordingly, if hazard analysis can show the hazard range, where superposition of the hazards is important, has sufficiently low frequencies, the combined seismic and FD hazard may not important. In such cases, the risk insights from PRAs assuming independent hazards could be sufficient to identify the dominant risk contributors and CDF.

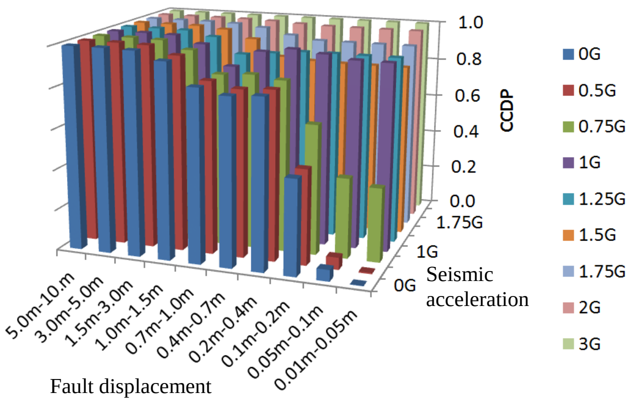


Figure 11 CCDP evaluation for combined seismic and FD hazard

4.2. Examination of countermeasures to reduce FD risk

The authors are currently investigating countermeasures to reduce FD risk. In the case shown in section 3.4 (2), the PRA has identified that the dominant accident sequences are triggered by the failure of cross over CCW piping and cable trays caused by relative displacement of the buildings. Concept of countermeasures to reduce risk of such scenarios has been examined. One of the countermeasures to reduce risk is to add means to prevent containment failure, such as the use of portable equipment, and prevent large release. For instance, for this specific scenario, establishing alternate containment spray injection and providing water to the containment heat exchangers using portable pumps to establish containment heat removal, could be an option to prevent containment failure.

5. Technical area subjected to further methodology improvements

Areas that require further improvement of the FD PRA are the following.

1) Examine refinement of the logic tree addressing the uncertainty of FD hazard. While the current FD hazard represents expected motion at the ground surface, seismic hazard represents the expected motion at the free-field. To evaluate the combined seismic and FD hazard, the FD hazard should also be developed to represent the motion at the free-field, to be the same as the seismic hazard.
2) The uncertainty factors related to the FD ground propagation evaluation should be refined in relation with item 1).
3) Fragility analysis considering the uncertainty factors of item 1) and 2) should be reexamined.
4) With consideration of research results on verification methodology of FD fragility (presented in PSAM 14), formulate the improved fragility analysis methodology.
5) Improve the accident scenario analyses to consider the geometrical relation of distributed FD and nuclear power plant of interest.
6) Perform CDF sensitivity analyses in relation with items 4) and 5), and identify the important uncertainty factors. Also assess the impact of FD specific failures, such as failure of piping crossing buildings, on the plant response.

6. Conclusion and future plans

The results of this study are as follows.

1) Basic concept of FD PRA methodology has been developed.
2) CDF and uncertainty analysis to confirm the feasibility of the methodology have been conducted through application to a hypothetical plant. The analysis provided insights on important initiators, dominant accident sequences, important failure modes and range of FD height that has high CDF contribution.
3) Concepts on how to consider the risk contribution from superposing seismic acceleration, and countermeasures to reduce risk have been examined.
4) Areas of uncertainty that require further methodology improvement have been identified.

The author plans to further develop the FD PRA methodology for practical application through research on the areas pointed out in chapter 5.

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