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Analytical Study on Fragility Evaluation against Fault Displacement for Nuclear Power Plant Buildings

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Abstract

Japan Nuclear Safety Institute had recently reported the pioneering deterministic approach for nuclear power plant against fault displacement [1]. But the uncertainty of fault displacement based on probabilistic hazard analysis is considered to be greater than that of other natural phenomena e.g. earthquake ground motions or seismic acceleration vibration in the report. Furthermore, for plant-wide risk assessment against fault displacement hazards beyond design basis displacement level, it is seriously necessary to promote a series of fundamental studies and develop the standard procedures regarding not only accident sequence analysis but also fragility analysis of buildings and structures as well as components and piping systems.

Based on the above background, the objective of this study is focusing to obtain basic fragility data for the aleatory and epistemic uncertainties of structural responses for nuclear power plant buildings against fault displacement. A number of nonlinear soli-structure finite element analyses against relatively large fault displacement are performed with not only the randomness of soil and building materials but also the uncertainty of fault hazards such as fault types and geometries. Their quantitative results for fragility data are shown in this paper.

Keywords: Fault Displacement, Fragility Analysis, Nuclear Power Plant Building, Aleatory Uncertainty, Epistemic Uncertainty

1. Introduction

New Japanese safety regulation enforced in 2013 requires that NPP facilities with important safety functions shall be established on the ground that has been confirmed to have no outcrop of a capable fault, etc. preventing a risk of fault displacement or other movements damaging the buildings and equipment therein. Therefore, on-site fault assessment is one of the big issues in Japanese regulatory process. Based on the above background, Japan Nuclear Safety Institute (JANSI) had established "On-site Fault Assessment Method Review Committee" that showed the procedure to comprehensive assessment of plant safety against fault displacement putting together scientific and engineering wisdom. As the result of that, JANSI has been domestically and internationally reporting the pioneering deterministic approach for nuclear power plant against fault displacement [1].

JANSI report [1] does not focus just on whether an on-site fault may be an active fault. Rather, it is intended to show a scientific and engineering framework to examine “whether it has a significant impact on the safety functions of important nuclear power plant facilities” when there is ground deformation due to fault movement in the ground on which they are sited. Also the report demonstrates the preliminary reactor building responses against assumed fault displacement 30cm that is based on the largest values of secondary faults with approximately 120 years of data in Japan. But the uncertainty of fault displacement based on probabilistic hazard analysis is considered to be greater than that of other natural phenomena e.g. earthquake ground motions or seismic acceleration vibration in the report. Furthermore, for plant-wide risk assessment against fault displacement hazards beyond the largest recorded value, it is seriously necessary to promote a series of fundamental studies and develop the standard procedures regarding not only accident sequence analysis but also fragility analysis of buildings and structures as well as components and piping systems.

Based on the above background, the objective of this paper is focusing to obtain basic fragility data for the aleatory and epistemic uncertainties of structural responses for nuclear power plant buildings against fault displacement. A number of nonlinear soli-structure finite element analyses against relatively large fault displacement are performed with not only the randomness of soil and building materials but also the uncertainty of fault hazards such as fault types and geometries. Their quantitative results for fragility data are first shown in this paper. For plant-wide risk assessment from the defense-in-depth viewpoint, the preliminary fragility evaluation of base mat slab against fault displacement beyond the largest recorded value 30cm is also shown in this paper. Finally, some technical issues to develop building fragility evaluation procedure in the future are shown in reference to tentative failure probability of a reactor building against fault displacement.

2. 2. Variability of Responses for NPP Building against Fault Displacement

2.1 Analytical conditions

Analytical conditions are basically the same as those in the preliminary analysis of BWR-type reactor building for shear wave velocity of the soil Vs=500m/s shown in JANSI report [1] unless soil and building material properties are varied. The details are shown in the following.

2.1.1 Analytical cases

According to seismic PRA standard in Japan [2], independent variables to evaluate the variability of building responses against fault displacement are concrete compressive strength Fc and shear wave velocity of the soil Vs. Their medians and coefficient of variances are also given based on seismic PRA standard in Japan [2].

Two point estimate method shown in Table 1 is applied as a sampling method to calculate the variability of building responses. Other dependent parameters are assumed to be perfectly correlated with independent variables.

Table 1 – Analytical cases for two point estimate method

Case #	Fc	Vs
#1	-σ	-σ
#2	+σ	-σ
#3	+σ	+σ
#4	-σ	+σ

2.1.2 Analytical model

Soli-structure finite element model is used for BWR-type reactor building. The dimension of building model is 80m x 80m square. Thickness of base mat slab is 5.5m and the lower two stories are embedded in soil. The dimension of soil model is 250m x 250m square and 150m depth. Fault plane is assumed to be reverse fault with 60 degree dip angle. Soli-structure finite element model is shown in Fig.1.

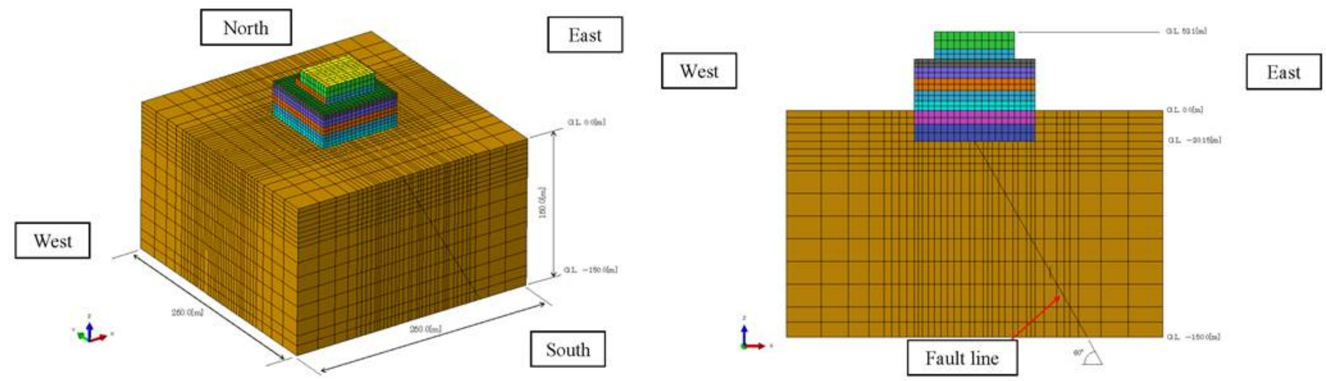


Fig. 1 – Soli-structure finite element model (Left: Birds-eye View, Right: East-west Section)

2.1.3 Material property

Material properties of concrete, rebar and soil is the same as those in JANSI report [1]. Nonlinear property of concrete is based on the plastic damage model [3] and nonlinear property of rebar is based on the isotropic hardening with von Mises yield surface. Although soil is assumed to be elastic, there are no big differences in base mat slab responses comparing to elasto-plastic behavior based on Mohr-Coulomb model.

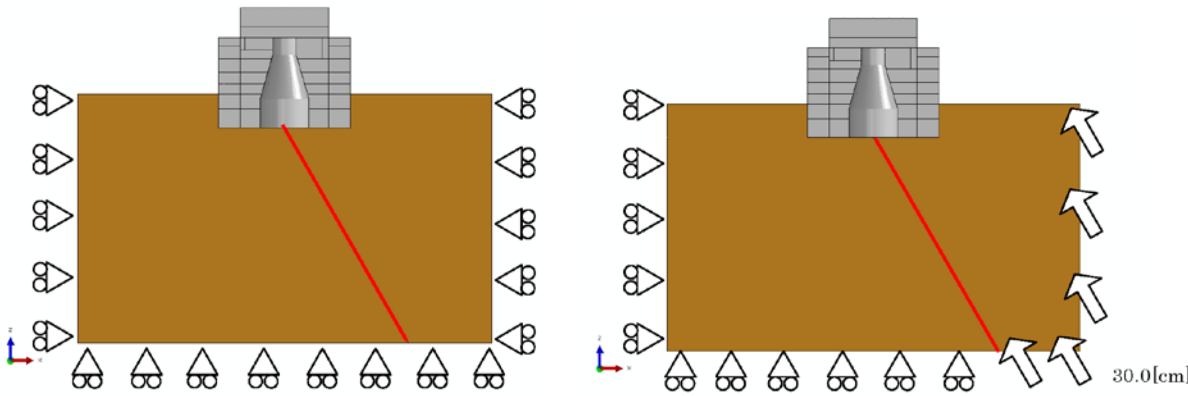
2.1.4 Analytical procedures

Soli-structure finite element analyses against fault displacement are performed through two analytical steps shown in Fig.2.

In dead load step, linear elastic analysis is performed acting dead loads of soil and building. Boundary condition of the side of soil is assumed to be horizontally fixed and vertically free. Boundary condition of the bottom of soil is assumed to be vertically fixed and horizontally free. Contact interaction between each fault plane is also assumed to be firmly fixed.

In fault displacement step, after the stresses at the fault plane in dead load step are completely released, nonlinear elasto-plastic analysis is performed acting reverse fault displacement 30cm with 60 degree dip angle. Coefficient of friction is assumed to be zero along fault plane. Contact interaction between soil and building is considered only simple contact without friction and adhesion because of waterproof layer.

Abaqus Standard Ver6.12-3 is used for the above soli-structure finite element analyses against fault displacement.



(a) Dead load step (b) Fault displacement step

Fig. 2 – Analytical procedure for fault displacement

2.2 Analytical results

Comparisons of the maximum response values of base mat slab and building outer walls are shown in Table 2 and Table 3 for all analytical cases at fault displacement 30cm. Focusing case #4 that shows relatively large building responses, building deformation plot is shown in Fig.3, average out-of-plane shear stress of base mat slab contour plot is shown in Fig.4 and minimum principal strain of building outer walls contour plot is shown in Fig.5. Based on the analytical results including the above figures, overall tendency of building responses is the following.

First, regarding building deformation, uplift of base mat slab does not significantly occur at fault displacement 10cm. But about one third of base mat slab is uplifted at fault displacement 15cm and finally about half of it is uplifted at fault displacement 30cm.

Second, regarding average out-of-plane shear stress of base mat slab, it becomes drastically large beyond fault displacement 10cm to 15cm where uplift of base mat slab seems to be dominant. Since the maximum value is about 1.6 N/mm^2 directly on fault plane, no out-of-plane shear failure occurs even at fault displacement 30cm based on the previous experimental study [4]. Also, all rebar of base mat slab are fully elastic.

Third, regarding minimum principal strain of building outer walls, the minimum value occurs at the corner of the lowest outer walls and is below the concrete compressive strength level even at fault displacement 30cm. Also, all rebar of building outer walls are fully elastic.

Forth, regarding deformation angle at each floor, although the upper floors are slightly larger than the lower floors, the building almost deforms rigidly.

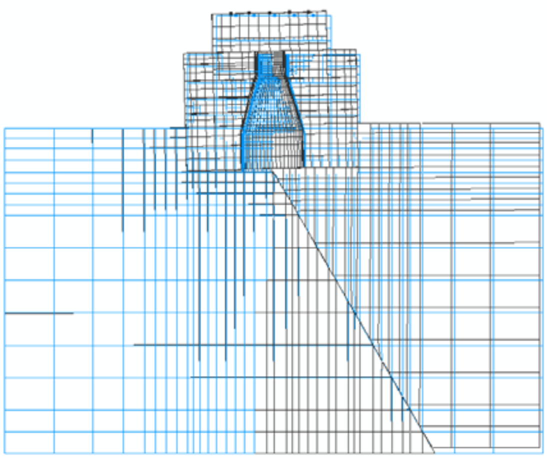
Finally, according to the comparisons of every analytical cases which vary soil and building material properties, while concrete compressive strength has a significant impact on building stresses, soil stiffness has a high impact on building compressive strain and deformation angle.

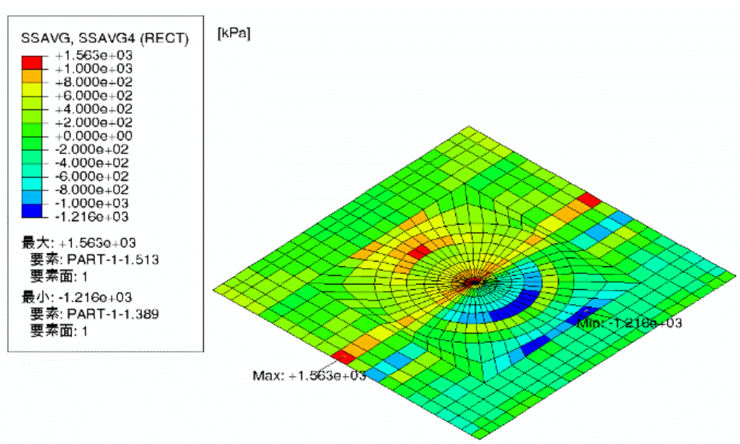
Table 2 – Comparisons of the maximum response values of base mat slab (Fault displacement 30cm)

Case #	Concrete		Rebar	
	Average out-of-plane shear stress	Minimum principal strain	Compressive strain	Tensile strain
#1	1.6 MPa	-580 μ	-620 μ	310 μ
#2	1.6 MPa	-510 μ	-550 μ	310 μ
#3	1.6 MPa	-640 μ	-790 μ	340 μ
#4	1.6 MPa	-740 μ	-880 μ	380 μ

Table 3 – Comparisons of the maximum response values of building outer walls (Fault displacement 30cm)

Case #	Concrete		Deformation angle (4^{th} floor)
	Maximum principal strain	Minimum principal strain	
#1	1400 μ	-1200 μ	1/360
#2	1300 μ	-1000 μ	1/360
#3	1790 μ	-1410 μ	1/460
#4	1950 μ	-1560 μ	1/440





(Case#4, Fault displacement 30cm)

Fig. 3 – Building deformation plot

Fig. 4 – Average out-of-plane shear stress normal to fault

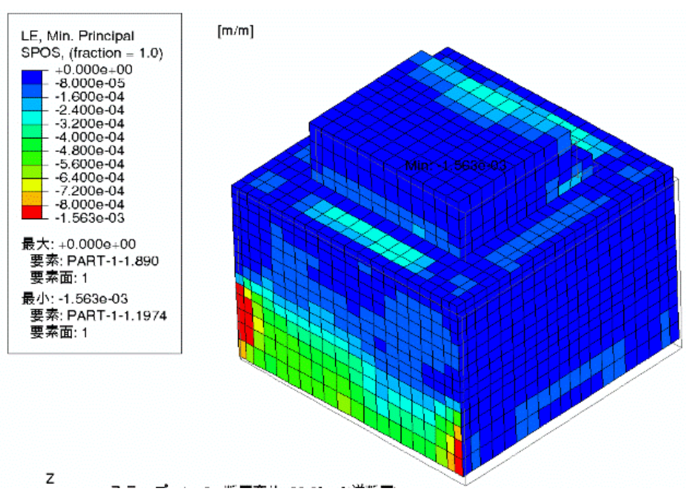


Fig. 5 – Minimum principal strain of building outer walls (Case#4, Fault displacement 30cm)

2.3 Variability of structural responses

Based on two point estimate method with the randomness of soil and building materials, median and l logarithmic standard deviation of concrete compressive strain, rebar strain and average out-of-plane shear stress in base mat slab are calculated against fault displacement 5cm to 30cm shown in Table 4 to Table 6. As reference, median and l logarithmic standard deviation of concrete compressive strain in building outer walls are also shown in Table 7.

Logarithmic standard deviation of maximum concrete compressive strain in base mat slab and building outer walls is almost 0.2 at fault displacement 30cm. Logarithmic standard deviation of maximum rebar tensile strain in base mat slab is also about 0.2 at fault displacement 30cm but it could be larger after rebar yields. Logarithmic standard deviation of maximum average out-of-plane shear stress in base mat slab is about 0.1 against fault displacement 25cm to 30cm which is about one half of that of concrete compressive strain.

Seismic PRA standard in Japan [2] indicates that logarithmic standard deviation is about 0.2 for maximum shear strain in shear walls and is about 0.1 for maximum acceleration in each floor under earthquake motions. Similar to the quantitative value under the earthquake motions mentioned above, this variability study up to fault displacement 30cm shows that logarithmic standard deviation of strain measures are about 0.2 and that of stress measures and deformation angle are about 0.1. But it is noted that while the response variability under earthquake motions is derived from simple model as one element for one story, the response variability against fault displacement is based on detailed model as two to three elements for one story.

Assuming median and l logarithmic standard deviation of response and capacity, conditional failure probability of the reactor building up to fault displacement 30cm is 0.00%. Capacity values for concrete compressive strain and rebar tensile strain are based on the lower limit shown in Japanese design standard [5]. Also, capacity value for out-of-plane shear strength is based on the lower limit shown in previous experimental study [4].

Table 4 – Variability of concrete compressive strain in base mat slab

Fault displacement	Median	Logarithmic standard deviation	Conditional failure probability
5cm	83μ	0.17	0.00%
10cm	177μ	0.19	0.00%
15cm	284μ	0.20	0.00%
20cm	409μ	0.20	0.00%
25cm	551μ	0.20	0.00%
30cm	705μ	0.18	0.00%

Table 5 – Variability of rebar tensile strain in base mat slab

Fault displacement	Median	Logarithmic standard deviation	Conditional failure probability
5cm	35μ	0.10	0.00%
10cm	71μ	0.23	0.00%
15cm	120μ	0.27	0.00%
20cm	187μ	0.29	0.00%
25cm	254μ	0.24	0.00%
30cm	307μ	0.14	0.00%

Table 6 – Variability of average out-of-plane shear stress in base mat slab

Fault displacement	Median	Logarithmic standard deviation	Conditional failure probability
5cm	0.47MPa	0.02	0.00%
10cm	0.67MPa	0.20	0.00%
15cm	1.00MPa	0.17	0.00%
20cm	1.26MPa	0.15	0.00%
25cm	1.43MPa	0.10	0.00%
30cm	1.54MPa	0.02	0.00%

Table 7 – Variability of concrete compressive strain in building outer walls

Fault displacement	Median	Logarithmic standard deviation	Conditional failure probability
5cm	103μ	0.23	0.00%
10cm	279μ	0.25	0.00%
15cm	493μ	0.24	0.00%
20cm	742μ	0.24	0.00%
25cm	1000μ	0.20	0.00%
30cm	1250μ	0.16	0.00%

3. Preliminary Building Fragility Evaluation

For plant-wide risk assessment from the defense-in-depth viewpoint, the preliminary fragility evaluation of base mat slab up to fault displacement 60cm that is twice of the largest recorded value 30cm is shown in this chapter.

3.1 Median fragility evaluation with aleatory uncertainty

3.1.1 Analytical conditions

Analytical conditions are basically the same in chapter 2 unless only median values for soil and building material properties are used. In fault displacement step, nonlinear elasto-plastic analysis is performed by applying reverse fault displacement 60cm with 60 degree dip angle. In this analysis, nonlinear property of soil is based on the Mohr-Coulomb model since it seems to be seriously plastic.

3.1.2 Analytical results

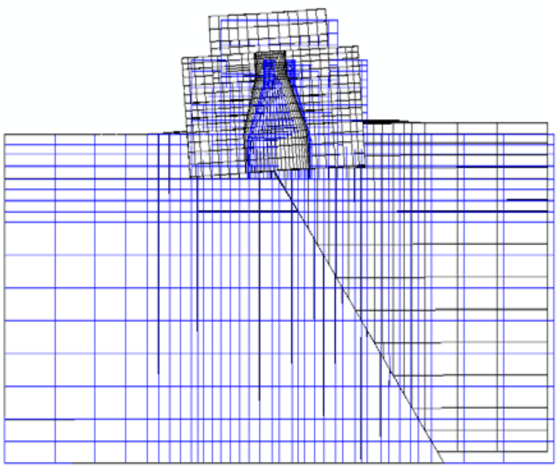
Comparisons of the maximum response values of base mat slab etc. are shown in Table 8 at fault displacement 60cm. Also, building deformation plot is shown in Fig.6, average out-of-plane shear stress of base mat slab contour plot is shown in Fig.7 and minimum principal strain of building outer walls contour plot is shown in Fig.8.

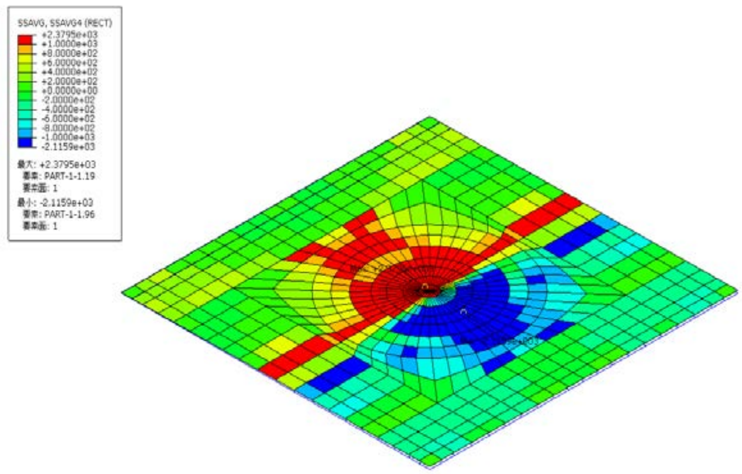
Regarding average out-of-plane shear stress of base mat slab, the maximum value is about 2.4 N/mm^2 directly on fault plane. Therefore, no out-of-plane shear failure occurs even at fault displacement 60cm based on the previous experimental study [4]. Also, all rebar of base mat slab are fully elastic.

Regarding minimum principal strain of building outer walls, the minimum value is smaller than the result at fault displacement 30cm in chapter 2. That is because plastic damage of the surrounding soil is relatively dominant comparing to that of building outer walls. Therefore, responses of building outer walls are conservatively obtained if the surrounding soil is assumed to be elastic.

Table 8 – Comparisons of the maximum response values of Base Mat Slab etc. (Fault displacement 60cm)

Base mat slab concrete		Base mat slab rebar		Deformation angle (4^{th} floor)
Average out-of-plane shear stress	Minimum principal strain	Compressive strain	Tensile strain	
2.4 MPa	-960 μ	-800 μ	490 μ	1/150





(Fault displacement 60cm)

Fig. 6 – Building deformation plot

Fig. 7 – Average out-of-plane shear stress normal to fault

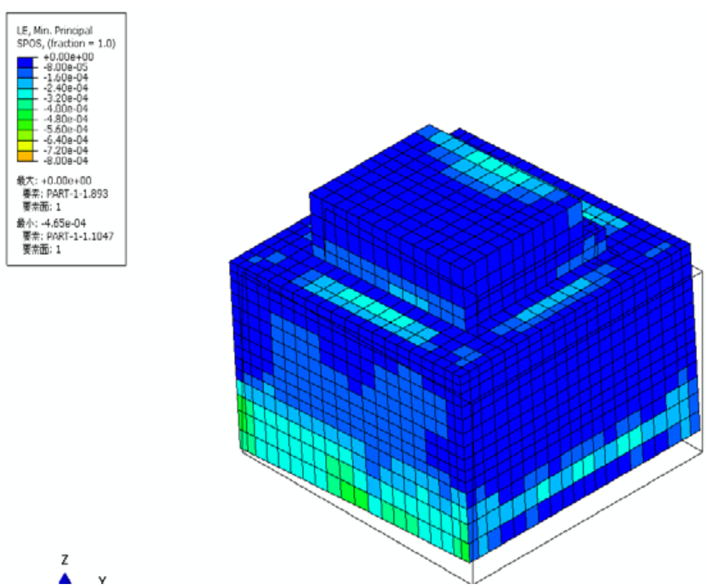


Fig. 8 – Minimum principal strain of building outer walls (Fault displacement 60cm)

3.1.3 Median fragility evaluation of base mat slab

From the viewpoint of the influence on core damage, preliminary fragility evaluation of base mat slab is performed with the analytical responses at fault displacement 60cm. According to the results in chapter 2, the targeted failure mode is supposed to be out-of-plane shear failure of base mat slab. Also, logarithmic standard deviation of out-of-plane shear stress is assumed to be 0.10 based on the variability study in chapter 2 and median of out-of-plane shear stress is directly derived from the results of section 3.1.2 up to fault displacement 60cm. Based on the above assumption, median and logarithmic standard deviation of average out-of-plane shear stress and also conditional failure probability of base mat slab are shown in Table 9. Capacity value is the same as that in chapter 2.

Table 9 – Variability of average out-of-plane shear stress and conditional failure probability of base mat slab

Fault displacement	Median	Logarithmic standard deviation*	Conditional failure probability
30cm	1.5MPa	0.10	0.00%
40cm	1.9MPa	0.10	0.00%
50cm	2.2MPa	0.10	0.44%
60cm	2.4MPa	0.10	5.48%

*) Logarithmic standard deviation of out-of-plane shear stress is assumed to be 0.10 based on the variability study in chapter 2.

3.2 Fragility evaluation with epistemic uncertainty

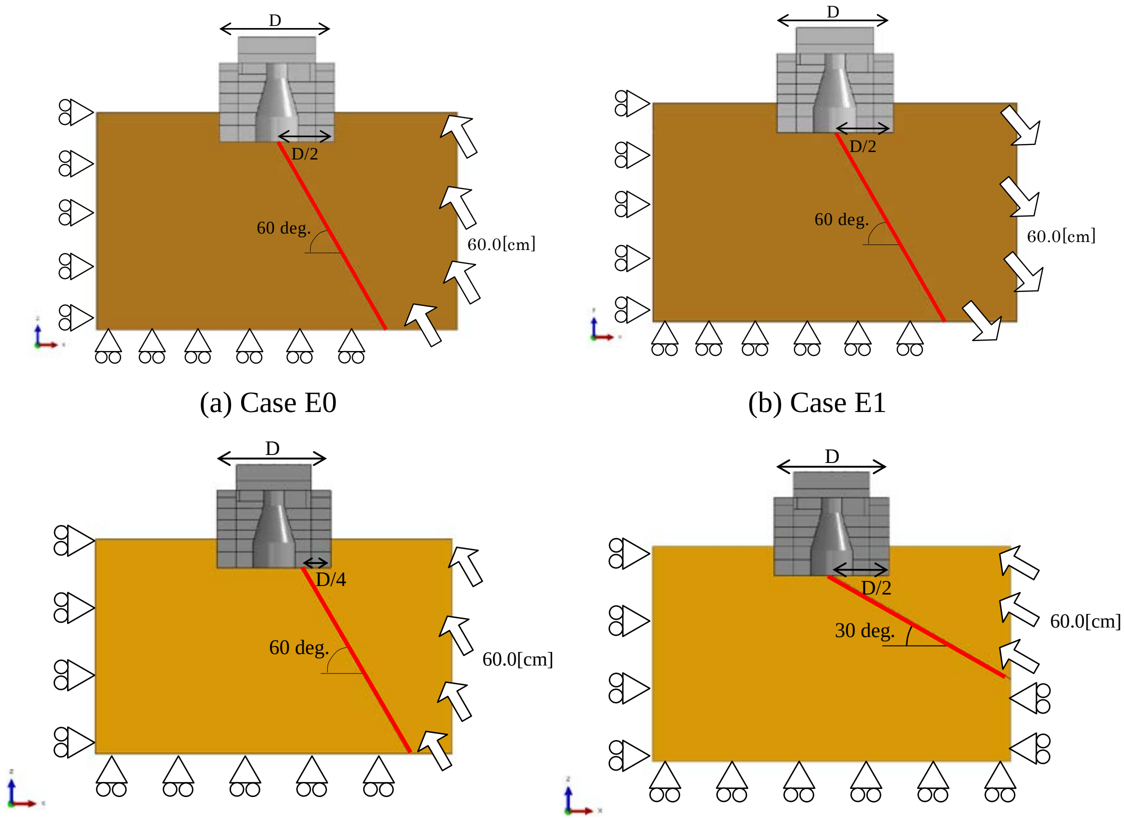
3.2.1 Analytical cases

Uncertainty such as variabilities studied in chapter 2 is generally classified in aleatory uncertainty. On the other hand, uncertainty relating to fault displacement hazard defined nearly beneath building foundations is possibly classified in epistemic uncertainty because of lack of relevant knowledge including experimental and analytical data under present circumstances. For example, uncertainties relating to fault types and fault geometries such as location, dip angle and slip direction are presumably corresponding to epistemic one. Based on such a current situation, some nonlinear soli-structure finite element analyses focusing on the above parameters are performed to obtain quantitative data relating to epistemic uncertainty of building responses against fault displacement. All analytical cases with epistemic uncertainty against dip-slip fault displacement in addition to the case in section 3.1 are shown in Table 10. Nonlinear elasto-plastic analyses are performed by applying fault displacement 60cm with such fault parameters, using the same analytical conditions as those described in section 3.1.

Table 10 – Analytical cases with epistemic uncertainty against dip-slip fault displacement

Case #	Fault type	Fault location*	Dip angle	Remarks
E0 (Sec. 3.1)	Reverse dip-slip fault	D/2	60 degree	Fig.9 (a)
E1	Normal dip-slip fault	D/2	60 degree	Fig.9 (b)
E2	Reverse dip-slip fault	D/4	60 degree	Fig.9 (c)
E3	Reverse dip-slip fault	D/2	30 degree	Fig.9 (d)

*) As a fault location, initial contact length between soil and base mat slab with dip-slip fault displacement is shown in this table. Here D is width of base mat slab.



(a) Case E0 (b) Case E1

(c) Case E2 (d) Case E3

Fig. 9 – Schematic image of analytical cases with epistemic uncertainty against dip-slip fault displacement

3.2.2 Epistemic uncertainty of base mat slab responses

Average out-of-plane shear stress of base mat slab for all analytical cases is shown in Table 11. Assuming lognormal distribution for them, the median and logarithmic standard deviation is calculated in this table. Therefore, logarithmic standard deviation βu of base mat slab responses relating to epistemic uncertainty is supposed to be about 0.2 on average under these conditions against dip-slip fault displacement.

Table 11 – Comparison of average out-of-plane shear stress of base mat slab

Fault displacement	Case E0	Case E1	Case E2	Case E3	Median	Logarithmic standard deviation
30cm	1.5MPa	2.5MPa	2.1MPa	1.3MPa	1.8MPa	0.25
40cm	1.9MPa	2.6MPa	2.3MPa	1.7MPa	2.1MPa	0.18
50cm	2.2MPa	2.7MPa	2.5MPa	1.9MPa	2.3MPa	0.14
60cm	2.4MPa	2.8MPa	2.5MPa	2.0MPa	2.4MPa	0.12

3.2.3 Fragility evaluation of base mat slab

Based on the results in section 3.1.3, median fragility curve with the aleatory uncertainty such as logarithmic standard deviation βr is obtained by the method of least squares to interpolate the conditional failure probabilities. Furthermore, reliable fragility curve is evaluated with the epistemic uncertainty such as logarithmic standard deviation βu. Logarithmic standard deviation βu is determined to be 0.20 by reference to the results in previous section 3.2.2 and also the value 0.15 in previous seismic PRA study [6]. Preliminary fragility curve of base mat slab against dip-slip fault displacement is shown in Fig.10. As the result, median fragility value of base mat slab to fault displacement, that is 50% failure probability, is 80cm and high confidence low probability of failure (HCLPF) value of base mat slab to fault displacement is 43cm.

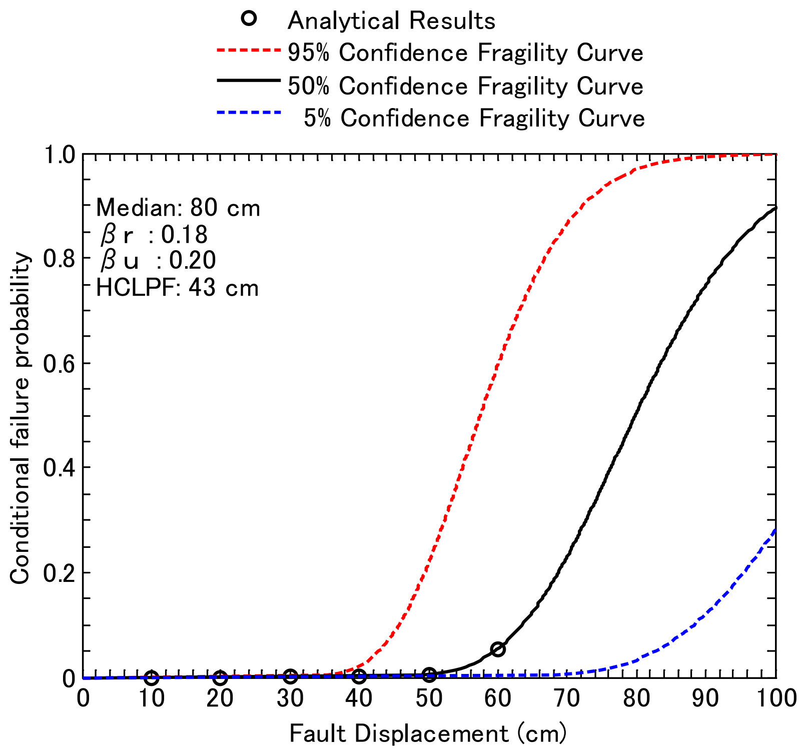


Fig. 10 – Preliminary fragility curve of base mat slab against dip-slip fault displacement

4. Conclusions and Future Issues

This paper is focusing to obtain basic fragility data for the aleatory and epistemic uncertainties of structural responses for nuclear power plant buildings against fault displacement. A number of nonlinear soli-structure finite element analyses against relatively large fault displacement are performed with not only the randomness of soil and building materials but also the uncertainty of fault hazards such as fault types and geometries.

As the results, logarithmic standard deviation of maximum concrete compressive strain and maximum rebar tensile strain in base mat slab and building outer walls is almost 0.2. Also, logarithmic standard deviation of maximum average out-of-plane shear stress in base mat slab is about 0.1.

Furthermore, for plant-wide risk assessment from the defense-in-depth viewpoint, the preliminary fragility evaluation of base mat slab up to fault displacement 60cm that is twice of the largest recorded value 30cm is performed not only considering the above variabilities as aleatory uncertainty but also with epistemic one relating to fault types and fault geometries such as location, dip angle and slip direction. From the results of the analytical parametric study on the epistemic uncertainties, logarithmic standard deviation βu of base mat slab responses relating to epistemic uncertainty is supposed to be about 0.2 on average under these conditions against dip-slip fault displacement.

As the above results, median fragility value of base mat slab to fault displacement, that is 50% failure probability, is 80cm and high confidence low probability of failure (HCLPF) value of base mat slab to fault displacement is 43cm.

However, this preliminary fragility results are obtained from the very limited analytical conditions such as dip-slip fault, specific soil material property and an assumed boundary condition between soil and building. Therefore, to obtain more generic and standard data for fragility evaluation against fault displacement, the following uncertainty issues should be investigated and discussed in the future.

- Uncertainty of fault type such as strike-slip fault
- Uncertainty of soil material property, especially applicability to hard rock site
- Uncertainly of contact parameters relating to adhesion and friction between soil and building

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