FRAGILITY EVALUATION WITH ALEATORY AND EPISTEMIC UNCERTAINTY AGAINST FAULT DISPLACEMENT FOR NUCLEAR POWER PLANT BUILDINGS

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Japan Nuclear Safety Institute had recently reported the pioneering deterministic evaluation approach for nuclear power plant under seismic induced fault displacement [1]. But the uncertainty of fault displacement based on probabilistic hazard analysis is described 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 soil-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.

I. 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 soil 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 issued 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 evaluation 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 described 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 soil-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.

II. VARIABILITY OF RESPONSES FOR NPP BUILDING AGAINST FAULT DISPLACEMENT

II.A. Analytical conditions

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

II.A.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 I is applied as a sampling method to calculate the variability of building responses. Other dependent parameters are assumed to be perfectly correlated with above mentioned independent variables.

TABLE I. Analytical cases for two point estimate method

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

II. A.2. Analytical model

Soil-structure interaction finite element model used for analyses is shown in Fig. 1. 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.

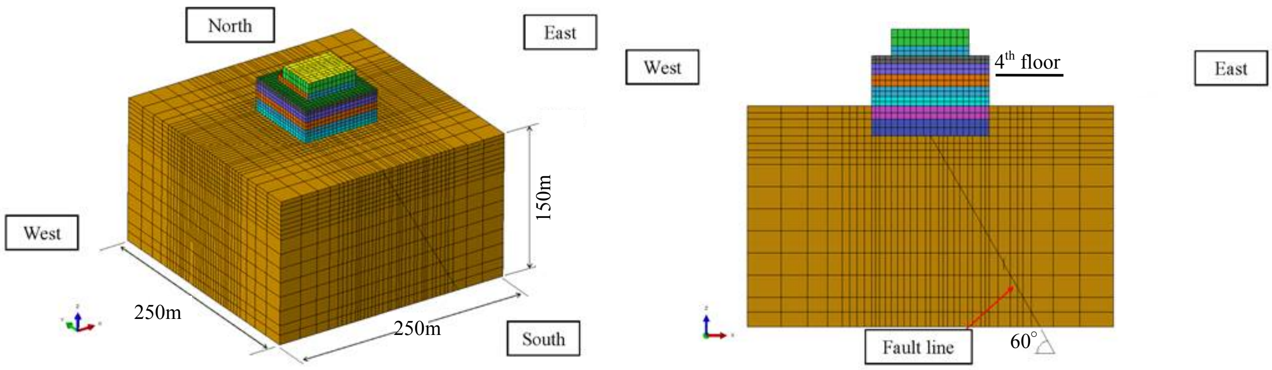


Fig. 1. Soil-structure interaction finite element model (Left: Isometric view, Right: East-west section)

II.A.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.

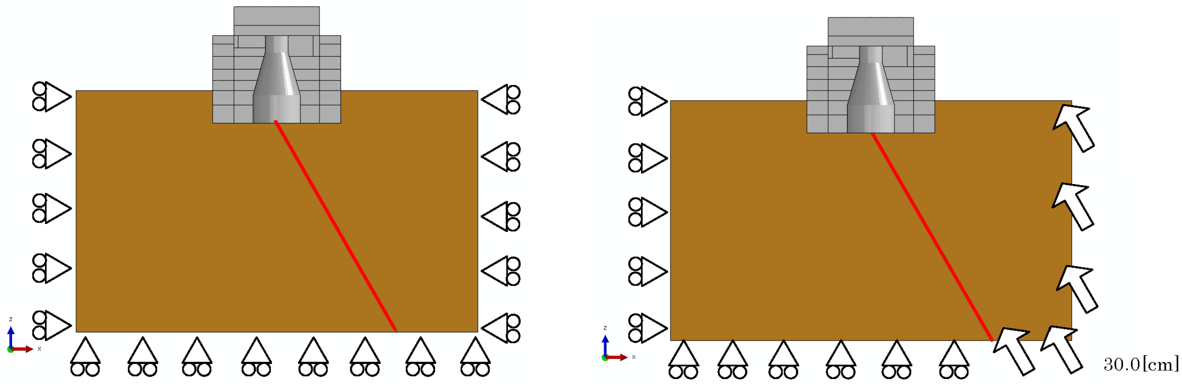
II.A.4. Analytical procedures

Soil-structure interaction 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 soil side 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 of 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 soil-structure finite element analyses against fault displacement.



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

Fig. 2. Analytical procedure for fault displacement

II.B. Analytical results

Comparisons of the maximum response values of base mat slab and building outer walls are shown in TABLE II and TABLE III for all analytical cases at fault displacement 30cm. Focusing on 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. Based on the analytical results including the above, 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 significantly 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 immediately just above fault plane, no out-of-plane shear failure occurs even at fault displacement of 30cm based on the previous experimental study [4]. Also, all rebar of base mat slab are within 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 of 30cm. Also, all rebar of building outer walls are within elastic.

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

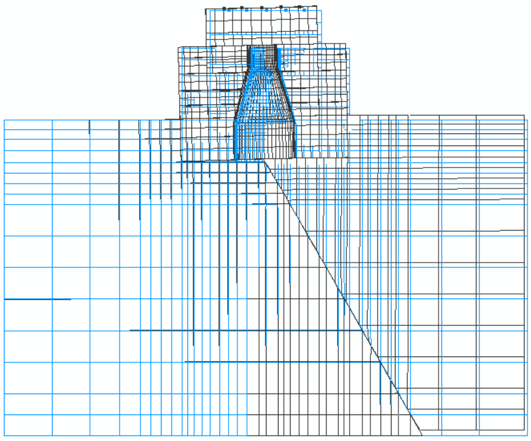
Finally, according to the comparisons of every analytical cases which vary soil and building material properties, while concrete compressive strength has a relatively small impact on building strain, soil stiffness has a significant impact on building compressive strain and deformation angle.

TABLE II. 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	-640μ	-620 μ	310 μ
#2	1.6 MPa	-560μ	-550 μ	310 μ
#3	1.6 MPa	-810μ	-790 μ	340 μ
#4	1.6 MPa	-900μ	-880 μ	380 μ

TABLE III. Comparisons of the maximum response values of building outer walls (Fault displacement 30cm)

Case #	Concrete		Deformation angle (4^{th} floor in Fig. 1)
	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

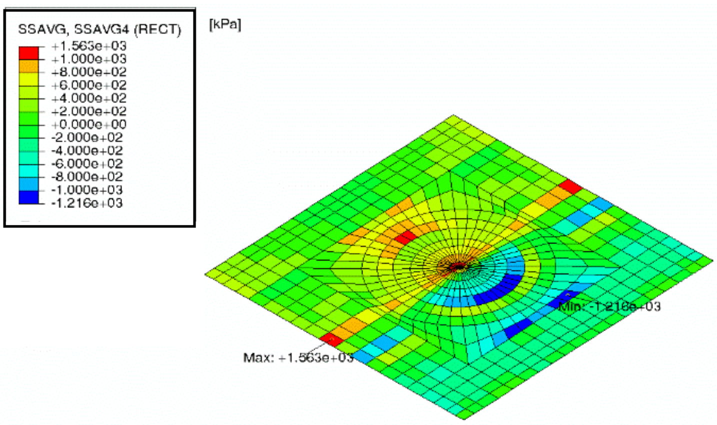


Fig. 4. Average out-of-plane shear stress normal to fault

II.C. Variability of structural responses

Based on two point estimate method with the randomness of soil and building materials, median and 1 logarithmic standard deviation of concrete compressive strain, rebar strain and out-of-plane shear stress in base mat slab are calculated against fault displacement 10cm to 30cm shown in TABLE IV to TABLE VI.

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 for 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 investigated in the past experimental study [4].

TABLE IV. Variability of concrete compressive strain in base mat slab

Fault displacement	Median	Logarithmic standard deviation	Conditional failure probability
10cm	177μ	0.19	0.00%
20cm	409μ	0.20	0.00%
30cm	705μ	0.18	0.00%

TABLE V. Variability of rebar tensile strain in base mat slab

Fault displacement	Median	Logarithmic standard deviation	Conditional failure probability
10cm	71μ	0.23	0.00%
20cm	187μ	0.29	0.00%
30cm	307μ	0.14	0.00%

TABLE VI. Variability of out-of-plane shear stress in base mat slab

Fault displacement	Median	Logarithmic standard deviation	Conditional failure probability
10cm	0.67MPa	0.20	0.00%
20cm	1.26MPa	0.15	0.00%
30cm	1.54MPa	0.02	0.00%

III. 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 of 30cm is shown in this chapter.

III.A. Median fragility evaluation with aleatory uncertainty

III.A.1. Analytical conditions

Analytical conditions are basically the same in chapter II except 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.

III.A.2. Analytical results

Comparisons of the maximum response values of base mat slab etc. are shown in TABLE VII at fault displacement 60cm.

Regarding average out-of-plane shear stress of base mat slab, the maximum value is about 2.4 N/mm^2 just above 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 principal strain of building outer walls, the minimum value is smaller than the result at fault displacement 30cm in chapter II. 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 VII. Comparisons of the maximum response values of Base Mat Slab etc. (Fault displacement 60cm)

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

III.A.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 II, 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 II and median of out-of-plane shear stress is directly derived from the results of section III.A.2 up to fault displacement 60cm. Based on the above assumption, relationship between response and capacity regarding out-of-plane shear stress of base mat slab median is shown in Fig. 5 and logarithmic standard deviation of average out-of-plane shear stress and also conditional failure probability of base mat slab are shown in TABLE VIII. Capacity value is the same as that in chapter II.

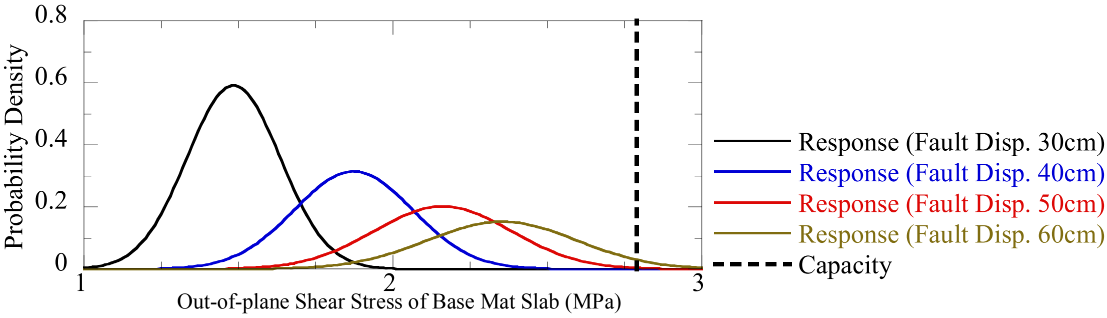


Fig. 5. Relationship between response and capacity regarding out-of-plane shear stress of base mat slab

TABLE VIII. Variability of 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 II.

III.B. Fragility evaluation with epistemic uncertainty

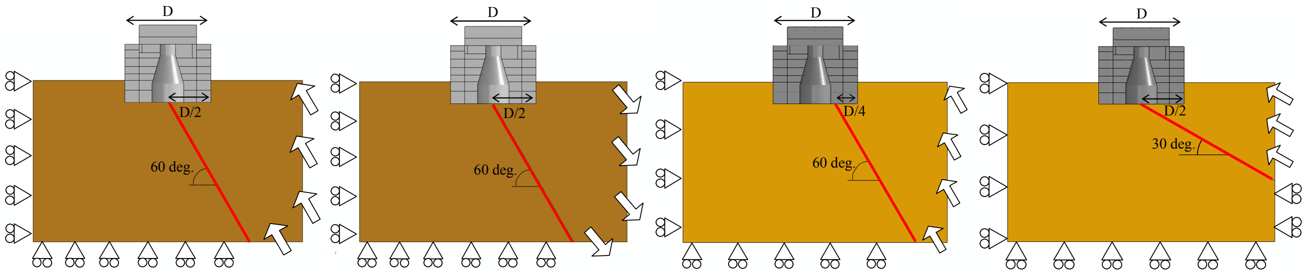
III.B.1. Analytical cases

Uncertainty such as variabilities studied in chapter II 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 soil-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 III.A are shown in TABLE IX. Uncertainty regarding fault location and dip angle are determined by reference to very few past experimental and analytical studies[6]. 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 III.A.

TABLE IX. Analytical cases with epistemic uncertainty against dip-slip fault displacement

Case #	Fault type	Fault location*	Dip angle	Remarks
E0 (Sec. III.A.)	Reverse dip-slip fault	D/2	60 degree	Fig. 6 (a)
E1	Normal dip-slip fault	D/2	60 degree	Fig. 6 (b)
E2	Reverse dip-slip fault	D/4	60 degree	Fig. 6 (c)
E3	Reverse dip-slip fault	D/2	30 degree	Fig. 6 (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. 6. Schematic image of analytical cases with epistemic uncertainty against dip-slip fault displacement

III.B.2. Epistemic uncertainty of base mat slab responses

Out-of-plane shear stress of base mat slab for all analytical cases is shown in TABLE X. Assuming lognormal distribution for them, the median and logarithmic standard deviation is calculated in this table. Then, 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 X. Comparison of 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

III.B.3. Fragility evaluation of base mat slab

Based on the results in section III.A.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 III.B.2 and also the value 0.15 in previous seismic PRA study [7]. Preliminary fragility curve of base mat slab against dip-slip fault displacement is shown in Fig. 7. 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. Based on the composite uncertainty including aleatory and epistemic uncertainties, mean fragility curve is also shown by blue thick line.

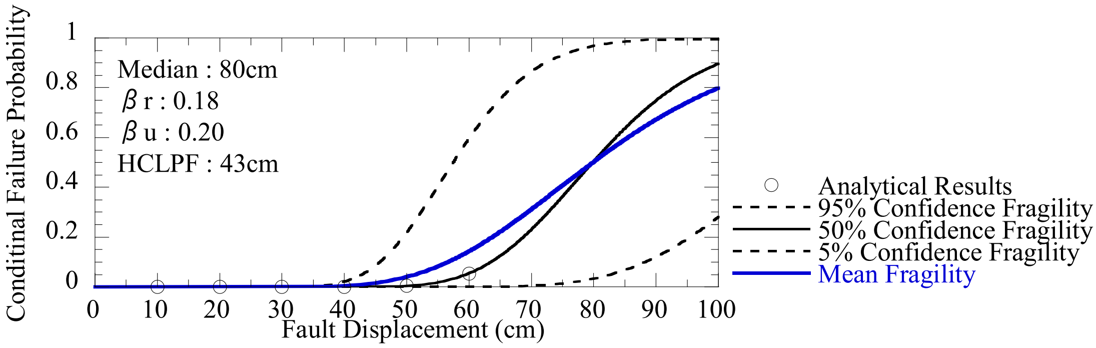


Fig. 7. Preliminary fragility curve of base mat slab against dip-slip fault displacement

IV. 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 soil-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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