Transactions, SMiRT-24
BEXCO, Busan, Korea - August 20-25, 2017
Division VII

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

Hirokazu Tsuji[1], Minoru Kanechika[2], Yoshinori Mihara[3], and Kenshiro Ishiki[4]

[1] Senior Associate Adviser, Japan Nuclear Safety Institute, Japan
[2] Technical General Manager, Kajima Corporation, Japan
[3] Deputy Senior Manager, Kajima Corporation, Japan
[4] Structural Engineer, Kajima Corporation, Japan

ABSTRACT

Japan Nuclear Safety Institute had recently reported the pioneering deterministic evaluation approach for nuclear power plant under seismic induced fault displacement. 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 the randomness of soil and building material properties, the uncertainly of contact parameters relating to adhesion and friction between soil and building, and also the uncertainty of fault hazards such as fault types and geometries. Their quantitative results for fragility data are shown in this paper.

INTRODUCTION

New Japanese safety regulations enacted in 2013 require that nuclear power plant facilities with important safety functions shall be established on ground that has been confirmed to have no outcrop of an capable fault, etc., to prevent risk of fault displacement or other soil movements that could damage buildings and equipment therein, and on-site fault assessment is a big issue in the regulatory process. Thus, the Japan Nuclear Safety Institute (JANSI) established an "On-site Fault Assessment Method Review Committee", which has proposed a procedure for comprehensive assessment of plant safety against fault displacement based on scientific and engineering wisdom. JANSI has been domestically and internationally reporting a pioneering deterministic approach to evaluating nuclear power plants against fault displacement.

The JANSI report does not focus only 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. The report also demonstrates preliminary reactor building responses against an assumed fault displacement of 30cm, which is based on the largest values of secondary faults from approximately 120 years of data in Japan. But the report describes the uncertainty of fault displacement based on probabilistic hazard analysis to be greater than that of other natural phenomena such as earthquake ground motions and seismic acceleration vibrations.

Furthermore, for plant-wide risk assessment against fault displacement hazards beyond the largest recorded value, it is necessary to promote a series of fundamental studies and to develop standard procedures for not only accident sequence analysis but also fragility analysis of buildings and structures as well as components and piping systems.

Thus, the objective of this paper is to obtain basic fragility data for 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 displacements are performed considering the randomness of soil and building material properties, the uncertainly of contact parameters relating to adhesion and friction between soil and building, and also the uncertainty of fault hazards such as fault types and geometries. This paper first presents quantitative results for fragility data. Then, for plant-wide risk assessment from the defence-in-depth viewpoint, it also presents a preliminary fragility evaluation of base mat slab against fault displacement beyond the largest recorded value of 30cm. Finally, it describes some technical issues in developing a building fragility evaluation procedure in the future in reference to tentative failure probability of a reactor building against fault displacement.

ANALYTICAL CONDITIONS

The analytical cases are listed in Table 1. For the study on variations of building responses against fault displacement, analytical conditions for a basic case are basically the same as those in the preliminary analysis of a BWR-type reactor building with a soil shear wave velocity Vs=500m/s in the JANSI report. Details of other cases are explained in later chapters.

Table 1: Analytical cases

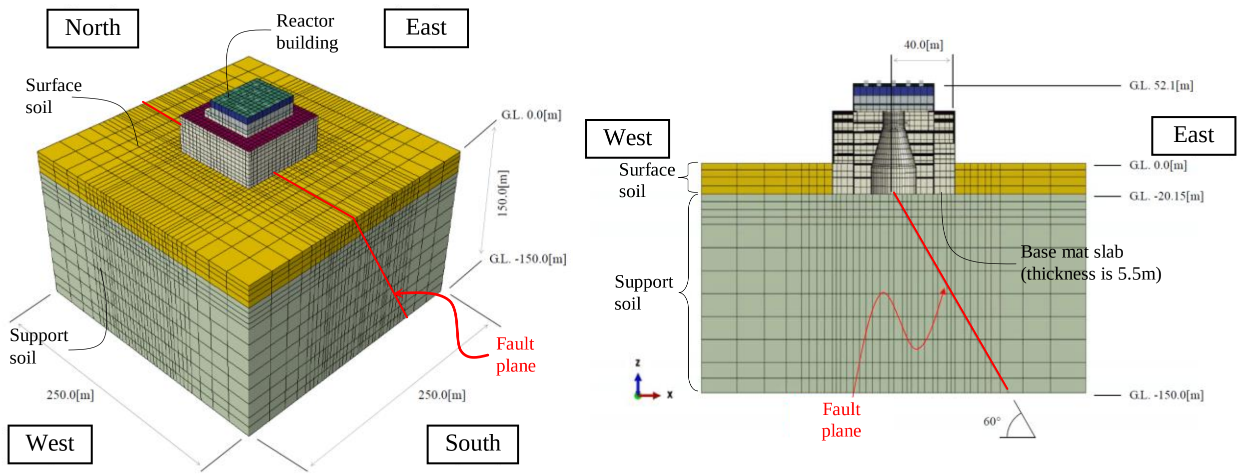
Case #	Uncertainty	Shear wave velocity (support soil)	Shear wave velocity (surface soil)	Strength of concrete	Coefficient of friction	Fault type	Fault position※	Dip angle
		m/s	m/s	MPa	-	-	-	°
0	Basic case	500	500	44.1	0	Reverse	D/2	60
1	Aleatory	459(−σ)	459(−σ)	39.7(−σ)	0	Reverse	D/2	60
2		459(−σ)	459(−σ)	51.4(+σ)	0	Reverse	D/2	60
3		562(+σ)	562(+σ)	51.4(+σ)	0	Reverse	D/2	60
4		562(+σ)	562(+σ)	39.7(−σ)	0	Reverse	D/2	60
5		500	250	44.1	0	Reverse	D/2	60
6		500	150	44.1	0	Reverse	D/2	60
7		500	500	44.1	0.8	Reverse	D/2	60
8		500	500	44.1	1.6	Reverse	D/2	60
9	Epistemic	500	500	44.1	0	Normal	D/2	60
10		500	500	44.1	0	Reverse	D/4	60
11		500	500	44.1	0	Reverse	D/2	30

※Positon of dip-slip fault immediately below base mat slab. (D: width of base mat slab)
Note: The red characters are the main variation parameter.

The soil-structure interaction finite element model used for analyses is shown in Figure 1. The building model is 80m square, the base mat slab is 5.5m thick and the lower two stories are embedded in soil. The building is modeled by laminated shell elements with 11 integration points in thickness and by beam elements. The soil model is 250m square and 150m deep. The fault plane in the basic case is assumed to be a reverse fault with a 60 degree dip angle. The soil is modeled by solid elements.

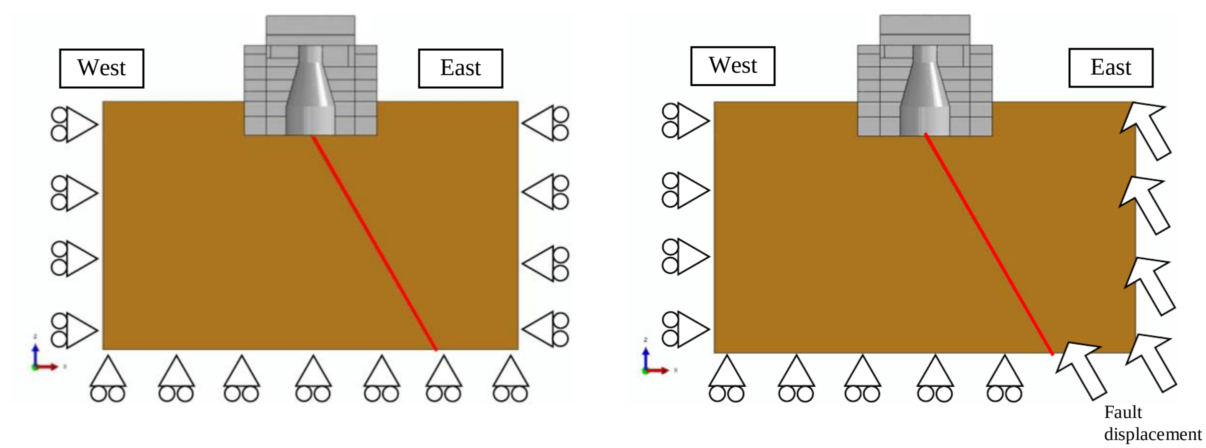
Material properties of concrete, rebar and soil are the same as those in the JANSI report. Concrete is assumed to be actual strength, and the nonlinear property of concrete is based on the isotropic plastic damage model. The nonlinear property of the rebars is based on isotropic hardening with the von Mises yield surface. The nonlinear property of the soil is based on the Mohr-Coulomb model.

Soil-structure interaction finite element analyses against fault displacement are performed through the two analytical steps shown in Figure 2. In the dead load step, linear elastic analysis is performed for soil and building dead loads. The side soil is assumed to be horizontally fixed and vertically free. The soil bottom is assumed to be vertically fixed and horizontally free. Contact interaction between each fault plane is also assumed to be firmly fixed. In the fault displacement step, after the stresses at the fault plane in the dead load step are completely released, nonlinear elasto-plastic analysis is performed for fault displacement. The coefficient of friction is assumed to be zero along the fault plane.



(a) Isometric view (b) East-west section

Figure 1. Soil-structure interaction finite element model



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

Figure 2. Analytical procedure for fault displacement

Contact interaction between soil and building is considered to be only simple contact without friction or adhesion, except in cases 7 and 8 because of their waterproof layer.

Abaqus Standard Ver.6 is used for the above soil-structure finite element analyses for fault displacement.

ANALYTICAL RESULTS FOR BASIC CASE (CASE 0)

The analytical results are shown in Table 2. For plant-wide risk assessment from the defence-in-depth viewpoint, this paper shows analytical results for case 0 up to fault displacement 60cm, which is twice of the largest recorded value of 30cm.

The average out-of-plane shear stress of the base mat slab contour plot at fault displacement 60cm is shown in Figure 3. For average out-of-plane shear stress of the base mat slab, it becomes significant beyond fault displacements of 0cm to 40cm where uplift of base mat slab seems to be dominant. Since the maximum value is about 2.38 MPa immediately above the fault plane, it is lower than out-of-plane shear capacity 2.79 MPa based on the previous experimental study even at fault displacement 60cm.

On the other hand, for average out-of-plane shear stress of building outer walls, the maximum value is about 4.94 MPa where they touch the front and back soil. Also, all concrete and rebars of the base mat slab and the building outer walls are within the elastic limit.

A building deformation plot at fault displacement 60cm is shown in Figure 4 and the contact pressure of the base mat slab contour plot at fault displacement 60cm is shown in Figure 5(a). For building deformation, there is no significant uplift of base mat slab at fault displacement 10cm. But about half of it is uplifted at fault displacements of 20cm to 30cm, and finally the building is supported only near the fault plane at fault displacement 60cm. The building deforms almost rigidly and its deformation angle is 1/151.

Table 2: Analytical results at fault displacement 60cm

Case #	Base mat slab				Outer walls	Uplift deformation angle
	Concrete		Rebar		Concrete	
	Out-of-plane shear stress	Compressive strain	Tensile strain	Compressive strain	Out-of-plane shear stress	
	MPa	μ	μ	μ	MPa	-
0	2.380	964.1	489.7	804.2	4.941	1/151
5	2.365	874.4	637.5	705.0	2.586	1/129
6	2.434	853.7	818.9	665.7	1.399	1/126
7	1.766	791.1	280.2	680.0	4.063	1/278
8	2.641	884.8	300.4	799.6	4.572	1/269
9	2.843	851.0	1825	548.6	0.5463	1/97
10	2.524	584.2	167.0	520.1	4.781	1/147
11	2.023	778.3	308.4	665.2	3.764	1/211

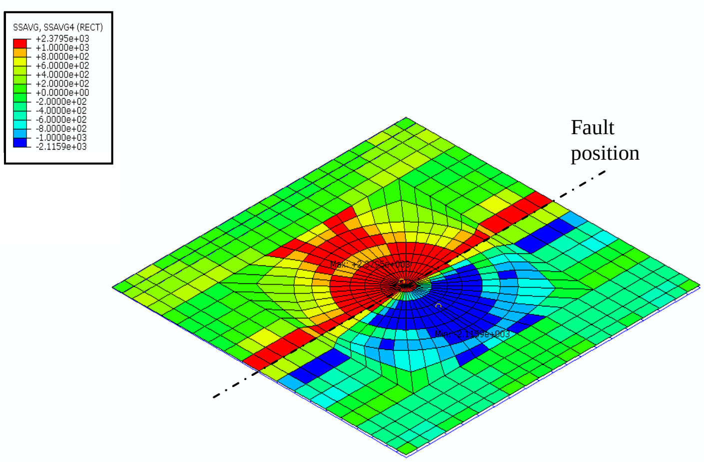


Figure 3. Average out-of-plane shear stress normal to fault

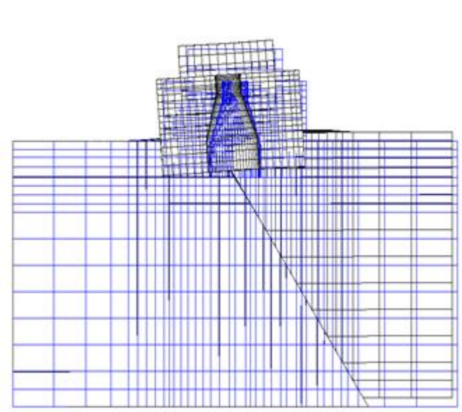
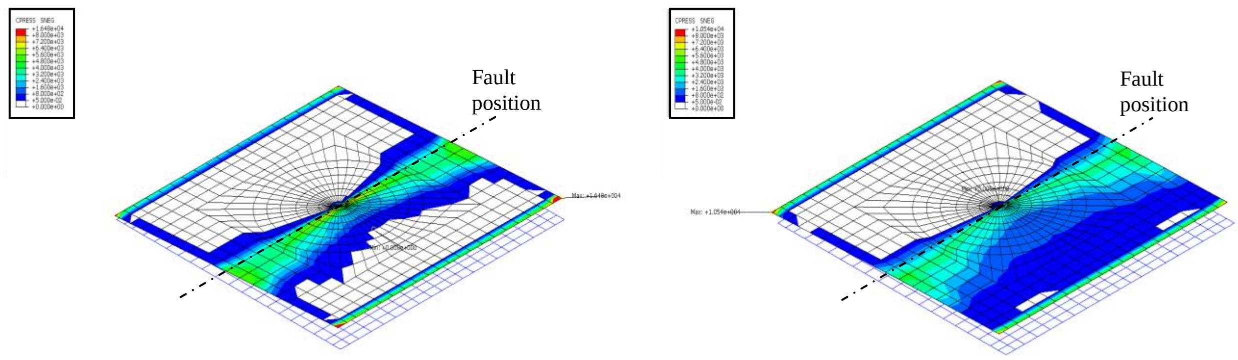


Figure 4. Building deformation plot



(a) Case 0 (coefficient of friction 0.0) (b) Case 7 (coefficient of friction 0.8)

Figure 5. Contact pressure

STUDY ON ALEATORY UNCERTAINTIES

Variability for structural responses

According to the seismic PRA standard in Japan, independent variables to evaluate the variability of building responses against fault displacement are concrete compressive strength and soil shear wave velocity. Their medians and coefficients of variance are also given. The two-point estimation method shown in Table 1 for cases 1 to 4 is applied as a sampling method to calculate the variability of building responses. Other dependent parameters are assumed to be perfectly correlated with the above independent variables.

Based on the two-point estimation method, taking into account randomness of soil and building materials, the median and logarithmic standard deviation of concrete compressive strain, calculated values of rebar strain and average out-of-plane shear stress in the base mat slab are shown for fault displacements of 5cm to 30cm in Table 3. For average out-of-plane shear stress in the base mat slab, comparing medians evaluated from cases 1 to 4 and the result of median model case 0 shown in Table 4, the error is about 10%. Therefore, for statistical accuracy, the two-point estimation method is sufficient without using a detailed method such as the Monte Carlo method. Since the overall trend of the analytical results in cases 1 to 4 was almost the same as that in case 0, explanation will be omitted.

Table 3: Variability in base mat slab (cases 1 to 4)

Fault displacement	Concrete compressive strain		Rebar tensile strain		Average out-of-plane shear stress	
	Median	Logarithmic standard deviation	Median	Logarithmic standard deviation	Median	Logarithmic standard deviation
cm	μ	μ	μ	μ	MPa	MPa
5	82.7	0.17	34.6	0.10	0.471	0.02
10	177	0.19	70.5	0.23	0.673	0.20
15	284	0.20	120	0.27	0.995	0.17
20	409	0.20	187	0.29	1.26	0.15
25	551	0.20	254	0.24	1.43	0.10
30	705	0.18	307	0.14	1.54	0.02

The logarithmic standard deviations of maximum concrete compressive strain and maximum rebar tensile strain in the base mat slab are almost 0.20 at fault displacement 30cm, but it could be larger after material yields. The logarithmic standard deviation of maximum average out-of-plane shear stress in the base mat slab is about 0.10 for fault displacements of 0cm to 30cm, which is about one half that of concrete compressive strain and rebar tensile strain.

The seismic PRA standard in Japan indicates that the logarithmic standard deviation is about 0.20 for maximum shear strain in shear walls and about 0.10 for maximum acceleration in each floor under earthquake motions. As for the quantitative value under the earthquake motions mentioned above, this variability study up to fault displacement 30cm shows that the logarithmic standard deviations of strain are about 0.20 and that of stress and deformation angle are about 0.10. But it is noted that while the response variability under earthquake motions is derived from a simple model as one element for one story, the response variability against fault displacement is based on a detailed model as two to three elements for one story.

Variability for shear wave velocity of surface soil and coefficient of friction

Analyses are performed for cases 5 to 8 with shear wave velocity of the surface soil and coefficient of friction between soil and building as variables. In these analyses, the shear wave velocities of the surface soil for cases 5 and 6 are 250m/s and 150m/s, and coefficients of friction for cases 7 and 8 are 0.8 and 1.6. In addition, the coefficients of friction are set with reference to past experimental results.

Analytical results for cases 5 to 8 are shown in Table 2. Comparing cases 0, 5 and 6, although uplift of base mat slab increased due to weakening of constraining effect of the front and back soil, there is no significant difference for average out-of-plane shear stress in the base mat slab. On the other hand, the average out-of-plane shear stress of the building's outer walls decreases as the stiffness of the surface soil decreases.

Comparing cases 0, 7 and 8, for the average out-of-plane shear stress in the base mat slab, case 7, with coefficient of friction 0.8, is the smallest. From the contact pressure of the base mat slab contour plot shown in Figure 5(b), it is thought that uplift of base mat slab is suppressed by the frictional resistance between side soil and building, but the reason why the average out-of-plane shear stress in the base mat slab for case 8 with coefficient of friction 1.6 is larger than that for case 0 is unknown.

Based on the results in this section, the targeted failure mode is assumed to be out-of-plane shear failure of the base mat slab. The variability of the average out-of-plane shear stress in the base mat slab is shown in Table 4 and Table 5. Assuming a lognormal distribution, the logarithmic standard deviation is about 0.05 for shear wave velocity of the surface soil and about 0.15 for coefficient of friction.

Table 4: Variability of average out-of-plane shear stress in base mat slab (cases 5 to 6)

Case #	average out-of-plane shear stress in base mat slab (MPa)					
	10cm	20cm	30cm	40cm	50cm	60cm
0 (Vs of surface soil 500m/s)	0.6114	1.012	1.468	1.852	2.154	2.380
5 (Vs of surface soil 250m/s)	0.7295	1.094	1.528	1.917	2.187	2.365
6 (Vs of surface soil 150m/s)	0.8030	1.134	1.588	1.983	2.256	2.434
Logarithmic standard deviation	0.075	0.051	0.043	0.039	0.029	0.022

Table 5: Variability of average out-of-plane shear stress in base mat slab (cases 7 to 8)

Case #	average out-of-plane shear stress in base mat slab (MPa)					
	10cm	20cm	30cm	40cm	50cm	60cm
0 (coefficient of friction 0.0)	0.6114	1.012	1.468	1.852	2.154	2.380
7 (coefficient of friction 0.8)	0.5654	0.9565	1.240	1.462	1.601	1.766
8 (coefficient of friction 1.6)	0.5629	1.238	1.668	1.942	2.277	2.641
Logarithmic standard deviation	0.081	0.115	0.121	0.116	0.143	0.160

According to the results in this chapter, considering variability of structural response (βr=0.10), variability of shear wave velocity of surface soil (βr=0.05) and variability of coefficient of friction (βr=0.15), the logarithmic standard deviation βr of out-of-plane shear stress is assumed to be 0.20 from the square root of the sum of squares.

STUDY ON EPISTEMIC UNCERTAINTIES

Uncertainty relating to fault displacement hazard defined as almost directly beneath building foundations is possibly classified as 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 presumably correspond to the epistemic one. Based on this 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 to fault displacement. Schematic images of analytical cases with epistemic uncertainty against dip-slip fault displacement are shown in Figure 6. In these analyses, the fault type of case 9 is a normal fault, fault location of case 10 is one quarter of the width of the base mat slab, and dip angle of case 11 is 30 degrees. Uncertainty regarding fault location and dip angle are determined by reference to very few past experimental and analytical studies.

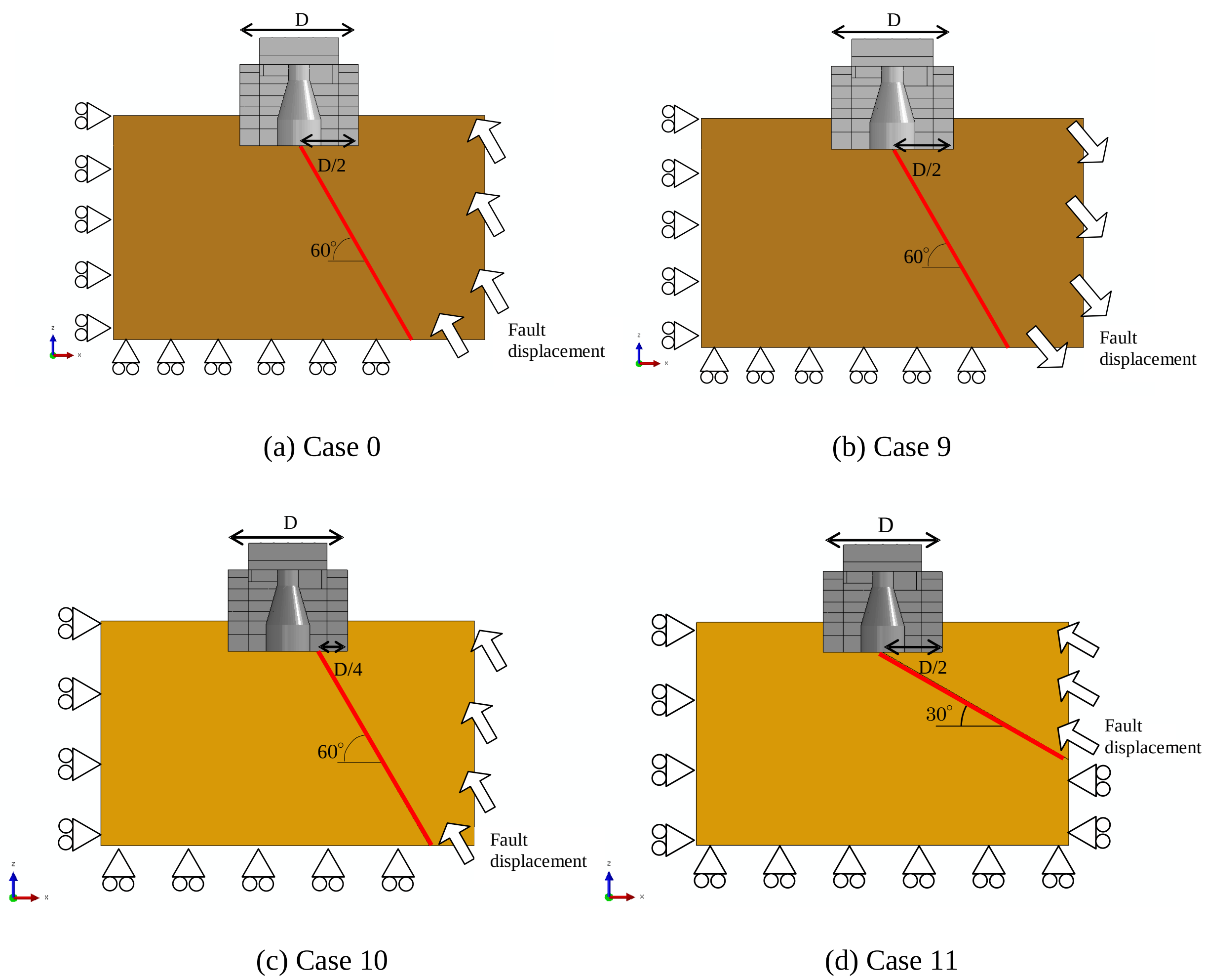


Figure 6. Schematic image of analytical cases with epistemic uncertainty

Analytical results for cases 9 to 11 are shown in Table 2. Comparing cases 0 and 9, although the maximum concrete compressive strain and the maximum rebar compressive strain in the base mat slab decrease, some rebars in the base mat slab yield in tension. This is because a normal fault occurs in a tensile stress field. Also, the average out-of-plane shear stress of building outer walls is very small, because the front and back soil move away from the building. However, due to weakening of the constraining effect of the soil against uplift of base mat slab, the average out-of-plane shear stress in the base mat slab increases.

Comparing cases 0 and 10, average out-of-plane shear stress in the base mat slab for case 10 is slightly larger than that for case 0. This is because uplift of base mat slab is increased by shifting the fault position to the hanging wall.

Comparing cases 0 and 11, the average out-of-plane shear stress in the base mat slab for case 11 is slightly smaller than that for case 0. From this result, it can be seen that the larger the angle formed with the fault plane, the greater the average out-of-plane shear stress in the base mat slab. Also, average out-of-plane shear stress in building outer walls is small, because the plasticity of soil around the building proceeds faster than for case 0 and the stress begins to decrease after the fault displacement exceeds 30cm.

Based on the results in this chapter, the variability of average out-of-plane shear stress in the base mat slab is shown in Table 6. Assuming a lognormal distribution, logarithmic standard deviation βu of the base mat slab responses relating to epistemic uncertainty is assumed to be about 0.20 on average for fault displacements of 30cm to 60cm.

Table 6: Variability of average out-of-plane shear stress in base mat slab (cases 9 to 11)

Case #	average out-of-plane shear stress in base mat slab (MPa)					
	10cm	20cm	30cm	40cm	50cm	60cm
0 (reverse fault, fault position D/2, dip angle 60°)	0.6114	1.012	1.468	1.852	2.154	2.380
9 (normal fault)	1.522	2.175	2.476	2.614	2.739	2.843
10 (fault position D/4)	0.9557	1.707	2.076	2.309	2.45	2.524
11 (dip angle 30°)	0.7469	0.9354	1.323	1.653	1.882	2.023
Logarithmic standard deviation	0.351	0.341	0.249	0.178	0.138	0.120

FRAGILITY EVALUATION OF BASE MAT SLAB

To determine the influence on core damage, a preliminary fragility evaluation of the base mat slab for case 0 is performed based on the analytical responses for fault displacement 60cm. Also, a logarithmic standard deviation of out-of-plane shear stress is assumed to be 0.20 based on the variability study on aleatory uncertainties, and median of out-of-plane shear stress is directly derived from the analytical results up to fault displacement 60cm. Logarithmic standard deviation of average out-of-plane shear stress and also conditional failure probability of base mat slab are shown in Table 7. The conditional failure probability at fault displacement 60cm is determined to be about 21%.

Table 7: Variability of out-of-plane shear stress and conditional failure probability of base mat slab

Fault displacement	Median	Logarithmic standard deviation	Conditional failure probability
cm	MPa	MPa	%
10	0.6114	0.20	0.000
20	1.012	0.20	0.000
30	1.468	0.20	0.065
40	1.852	0.20	2.003
50	2.154	0.20	9.706
60	2.380	0.20	21.153

Next, a 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, a reliable fragility curve is evaluated with epistemic uncertainty such as logarithmic standard deviation βu. Logarithmic standard deviation βu is determined to be 0.20 from the results in a previous chapter and 0.15 from a previous seismic PRA study.

A preliminary fragility curve of base mat slab against dip-slip fault displacement is shown in Figure 7. As a result, the median fragility of base mat slab to fault displacement, that is, 50% failure probability, is 79cm and a high confidence low probability of failure (HCLPF) value of base mat slab to fault displacement is 32cm.

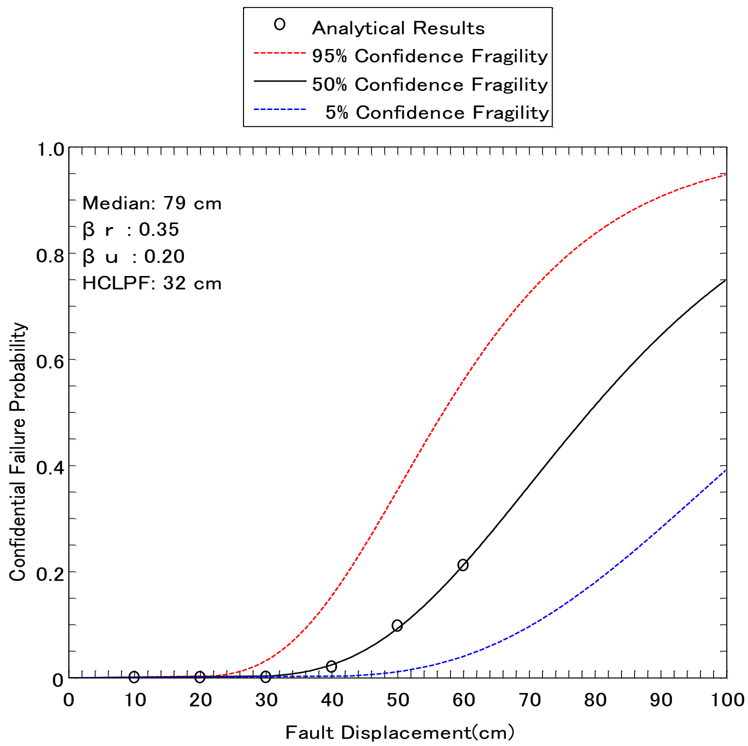


Figure 7. Preliminary fragility curve of base mat slab against dip-slip fault displacement

CONCLUSIONS AND FUTURE ISUUES

This paper has focused on obtaining basic fragility data for 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 were performed taking into account the randomness of soil and building material properties, the uncertainly of contact parameters relating to adhesion and friction between soil and building, and also the uncertainty of fault hazards such as fault types and geometries.

As a result, the logarithmic standard deviation of maximum average out-of-plane shear stress in the base mat slab was assumed to be 0.20 based on the variability study on aleatory uncertainties.

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 the largest recorded value of 30cm and was performed not only considering the above variabilities as aleatory uncertainty but also the 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 epistemic uncertainties, the logarithmic standard deviation βu of base mat slab responses relating to epistemic uncertainty was assumed to be about 0.20 on average under these conditions against dip-slip fault displacement.

As a result, the median fragility of base mat slab to fault displacement, that is, 50% failure probability, was 79cm, and the HCLPF value of base mat slab to fault displacement was 32cm.

However, these preliminary fragility results were obtained from very limited analytical conditions such as dip-slip fault, specific soil material properties and an assumed boundary conditions 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 properties, especially for a hard rock site

REFERENCES

Atomic Energy Society of Japan (2007). *A Standard for Procedure of Seismic Probabilistic Safety Assessment for Nuclear Power Plants: 2007, A Standard of the Atomic Energy Society of Japan*, AESJ-SC-P006:2007 (in Japanese).

Atomic Energy Society of Japan (2015). *Report of Research Committee on Fault Activity and Engineering Risk Assessment*, http://www.aesj.net/sp_committee/com_dansou (in Japanese).

Kumagai, H., Nukui, Y., Imamura, A., Terayama, T., Hagiwara, T. and Kojima, I. (2011). “Out-of-plane Ultimate Shear Strength of RC Mat-slab Foundations,” *Journal of structural and construction Engineering, Architectural Institute of Japan*, vol.76, no.659, p.131-140 (in Japanese).

Lee, J., and Fenves, G. L. (1998). “A Plastic-Damage Concrete Model for Earthquake Analysis of Dams,” *Earthquake Engineering and Structural Dynamics*, vol.27, p.937-956.

Mihara, Y., Fushimi, M., Miyazaki, S. and Sugita, H. (2007). “Study on Epistemic Uncertainties in Fragility Evaluation of NPP Buildings: Part 3”, *Summaries of technical papers of annual meeting Architectural Institute of Japan*, p.1083-1084 (in Japanese).

Nuclear Civil Engineering Committee of the JSCE (2015). *Research Report of the Subcommittee on Fault Displacement Evaluation* (in Japanese).

On-site Fault Assessment Method Review Committee in Japan Nuclear Safety Institute (2013). *Assessment Methods for Nuclear Power Plant against Fault Displacement*, JANSI-FDE-03 rev.1, http://www.genanshin.jp/archive/sitefault.

Shimada, T., Suzuki, Y., Takei, K., Yano, T., Sato, H., Furuno, Y. and Eguchi, M. (2015). “Experimental assessment of shear transmitting mechanism between underground outer wall of embedded nuclear power plants and lateral soil: Part 1 and Part 2,” *Summaries of technical papers of annual meeting Architectural Institute of Japan*, p.1091-1094 (in Japanese).

Solhmirzaei, R., Soroush, A. and Mortazav Zanjani, M. (2012). “Fault Rupture Propagation through Level Ground and Sloping Sand Layers,“ 4148, 15WCEE, Lisbon, Portugal.