Fragility Evaluation with Aleatory and Epistemic Uncertainty against Fault Displacement for Reactor Buildings

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Background

New Japanese Safety Regulation (2013)

Nuclear power plant facilities shall be on ground without outcrop of capable fault.

Big issue in regulatory process in Japan

[Japan Nuclear Safety Institute (JANSI)]

- "On-site Fault Assessment Method Review Committee"
- JANSI report (Sep. 2013)
- Preliminary reactor building responses against fault displacement 30cm

Cf. 30cm is based on the largest value of secondary faults from approximately 120 years of data in Japan.

Objective and Method

[Objective]

・To obtain basic fragility data for aleatory and epistemic uncertainties of reactor building responses against fault displacement

[Method]

1. Quantitative results by nonlinear FEA for soft rock site
   Aleatory uncertainty : the randomness of soil & building material properties
   Epistemic uncertainty : the uncertainty of fault hazards

2. Analytical results for hard rock site, comparison with soft rock site

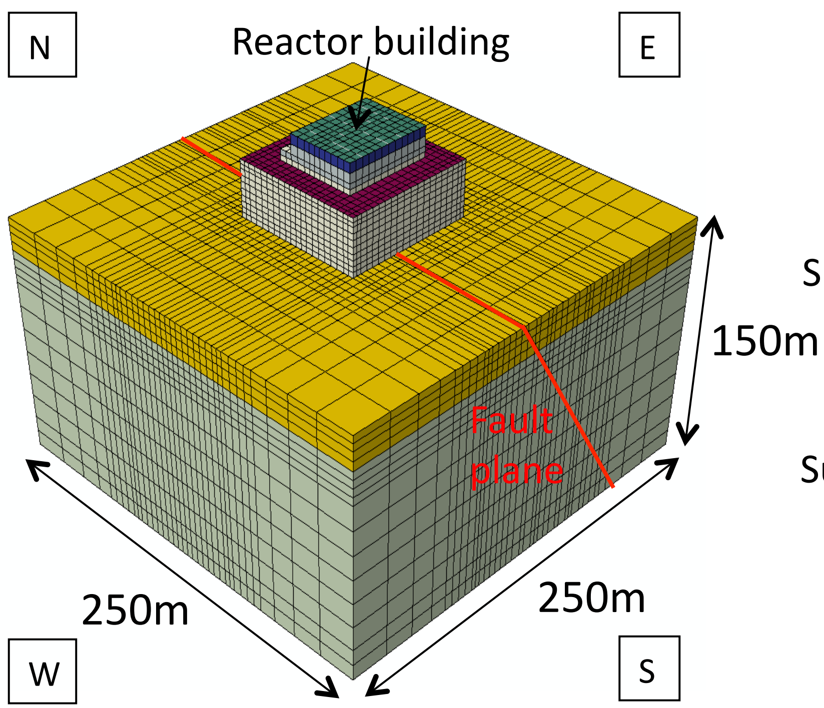
3. Preliminary fragility evaluation against fault displacement 60cm for plant-wide risk assessment

4. Some technical issues for fragility procedure in the future

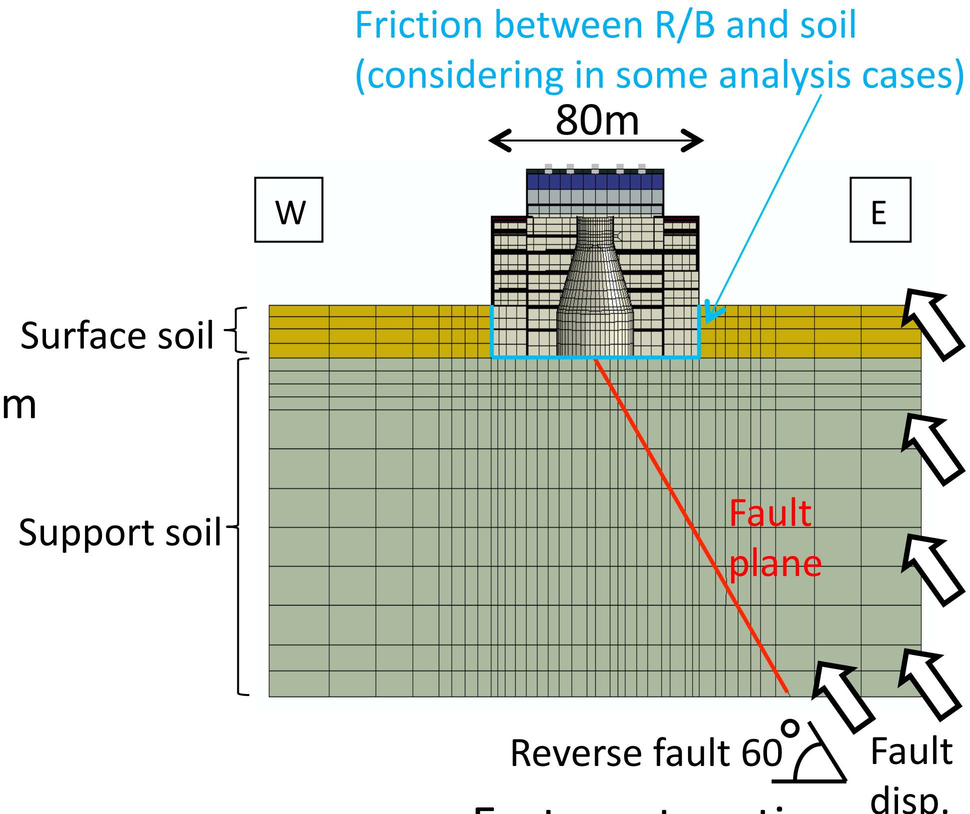
Analysis Model

[Soil-structure interaction finite element model]

- Building : BWR-type reactor building with base mat slab 5.5m thick
- Soil : soft rock site with Vs=500m/s, hard rock site with Vs=1500m/s
- Material nonlinearity, contact interaction between building and soil



Isometric view



East-west section

Analysis model of basic case

Analysis Cases

Analysis cases to study on aleatory and epistemic uncertainty

Uncertainty	Items	Basic case	Parametric study (11 cases)
Aleatory uncertainty	Randomness of Vs and Fc	Vs=500m/s Fc=44.1MPa	4 cases of ±σ combination
	Surface soil Vs	500m/s	250m/s, 150m/s
	Coefficient of friction	0.0	0.8, 1.6
Epistemic uncertainty	Fault type	Reverse	Normal
	Fault position	1/2 of base mat	1/4 of base mat
	Dip angle	60°	30°

Analysis cases to compare soft rock site with hard rock site

Items	Case0	Case6	Case9	Case12	Case13	Case14
Support soil Vs	500m/s	500m/s	500m/s	1500m/s	1500m/s	1500m/s
Surface soil Vs	500m/s	150m/s	500m/s	1500m/s	150m/s	1500m/s
Fault type	Reverse	Reverse	Normal	Reverse	Reverse	Normal

↑ soft rock site (basic case) (Case0)

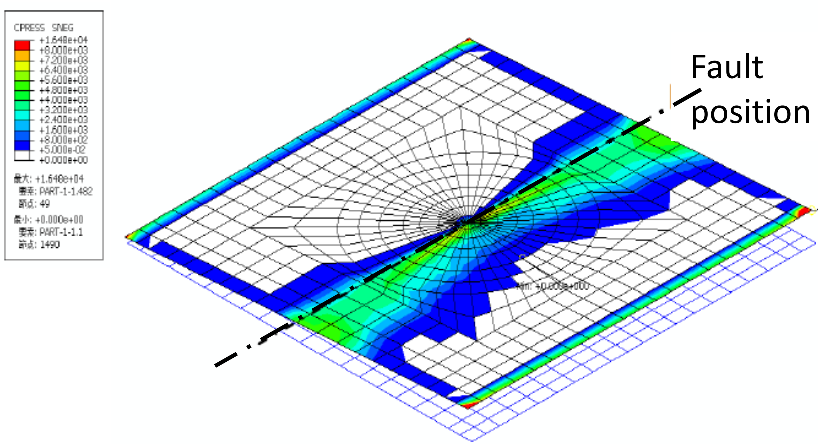
↑ hard rock site (Case12)

Analytical Results for Basic Case

- The building rotates almost rigidly.
- Supported only near the fault plane at fault displacement 60cm

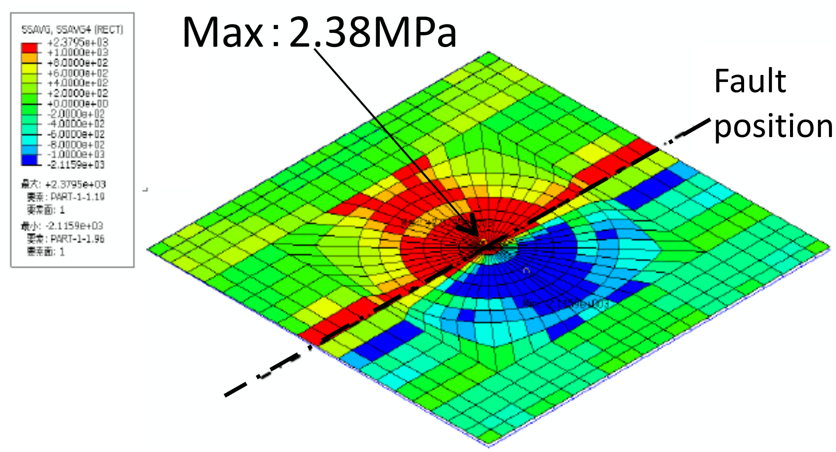
- Max. value of out-of-plane shear stress of base mat slab : immediately above the fault plane
- Significant at dominant uplift of base mat slab

- Concrete and rebar : within the elastic limit



Contact pressure

(Basic case : fault disp. 60cm)



Out-of-plane shear stress

(Basic case : fault disp. 60cm)

Study on Epistemic Uncertainty Part.1

［Analyses with fault types as variables］

Stress and strain at fault displacement 60cm

Fault type	Base mat slab			Outer walls
	Concrete compressive strain	Rebar tensile strain	Out-of-plane shear stress	Out-of-plane shear stress
Reverse (Basic)	964.1μ	489.7μ	2.380MPa	4.941MPa
Normal	851.0μ	1825μ	2.843MPa	0.5463MPa

・Reverse fault : compressive stress field

Base mat slab concrete compressive strain ： large

・Normal fault : tensile stress field

Base mat slab some rebars : yield in tensile strain

Base mat slab out-of-plane shear stress : increase

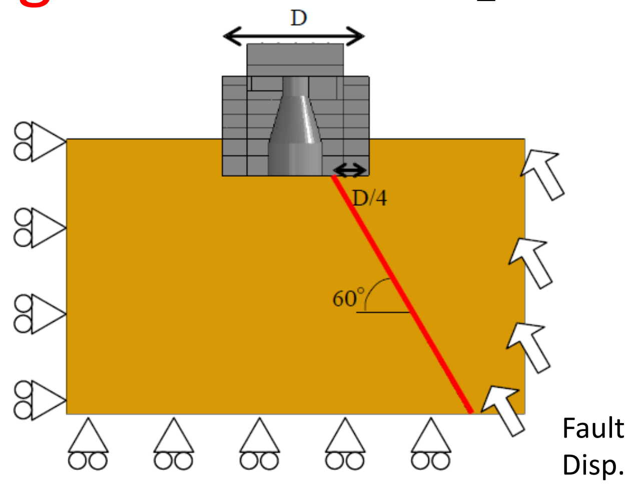
Outer walls out-of-plane shear stress : very small

Study on Epistemic Uncertainty Part.2

［Analyses with fault position and dip angle as variables］

Out-of-plane shear stress at fault displacement 60cm

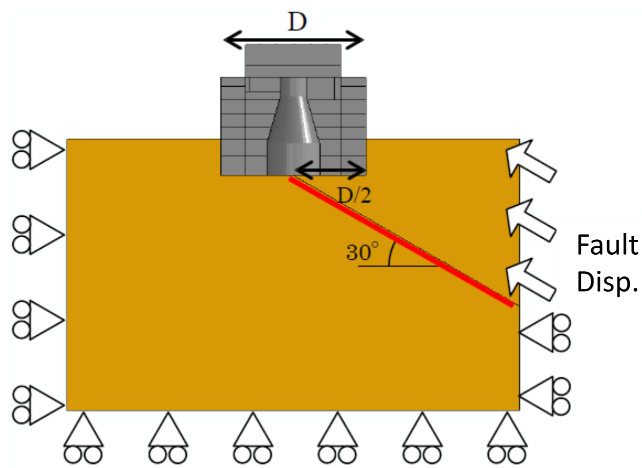
Fault position	Base mat slab
1/2 of base mat (Basic)	2.380MPa
1/4 of base mat	2.524MPa



・Fault position shifts to the hanging wall,
base mat slab out-of-plane shear stress and uplift increase.

Out-of-plane shear stress at fault displacement 60cm

Dip angle	Base mat slab
60°(Basic)	2.380MPa
30°	2.023MPa

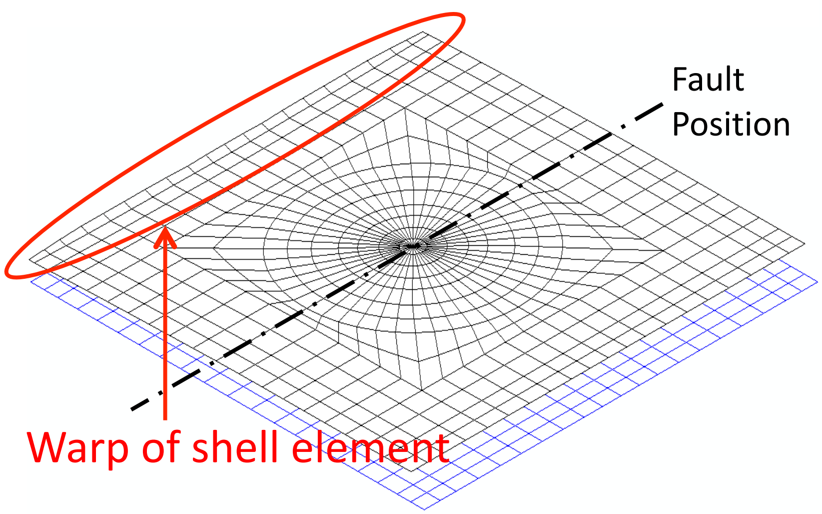


・The larger dip angle,
the greater base mat slab out-of-plane shear stress

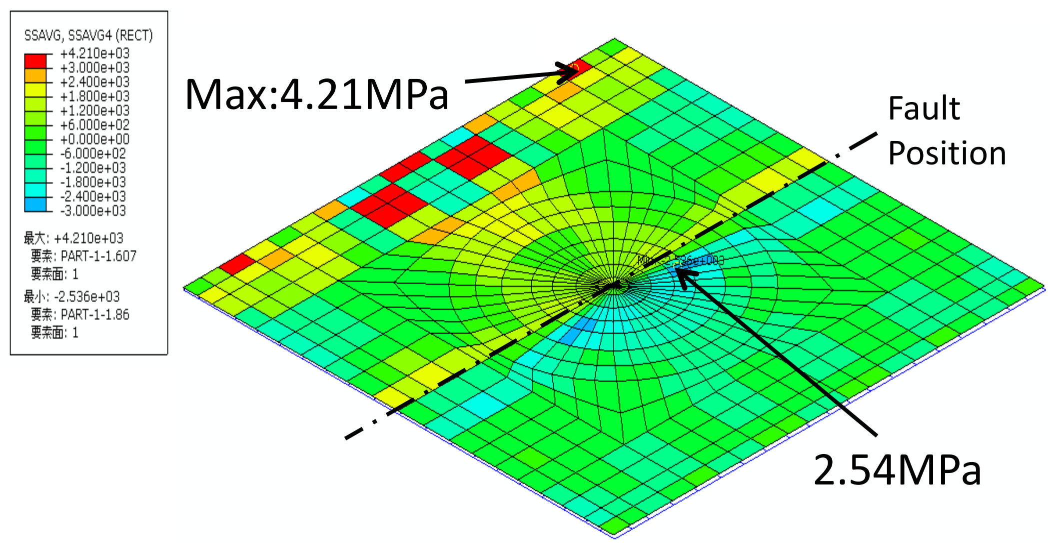
Analytical Results for Case12 (Hard Rock Site)

- Suppressed uplift of base mat slab by surface hard soil（Vs=1500m/s）
- Increase of compression force due to the reverse fault displacement

- Warp of some elements at the edge of the base mat slab
- Out-of-plane shear stress max. value : 4.21MPa at the edge
  (Cf. Max. value for soft rock site : 2.38MPa above the fault plane)



Deformation plot
(Case12 : fault disp. 60cm)

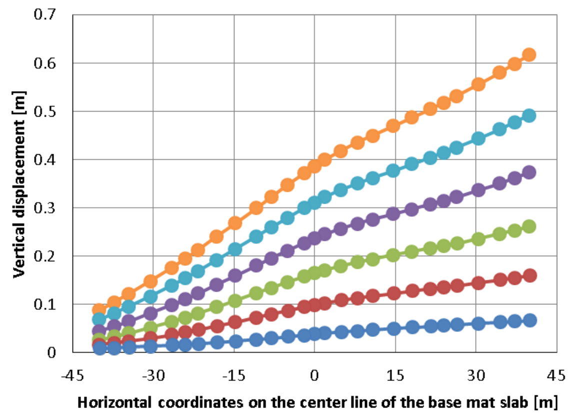


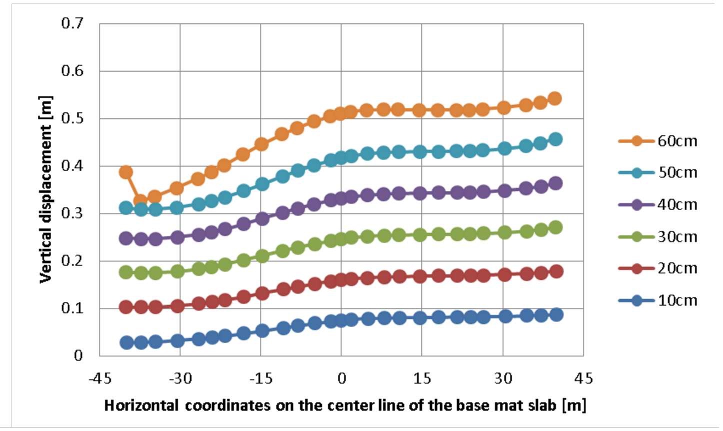
Out-of-plane shear stress
(Case12 : fault disp. 60cm)

Deformation Distribution of Base Mat Slab

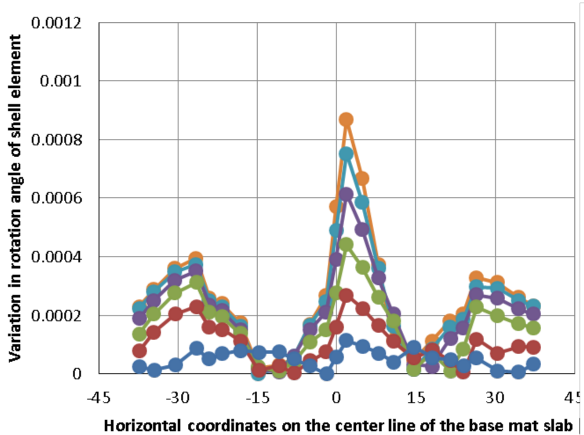
- Rigid body rotation of building
- The softer the surface soil, the clearer the uplift of base mat slab
- Local out-of-plane deformation gradual increase
- No difference between soft and hard rock site above the fault plane

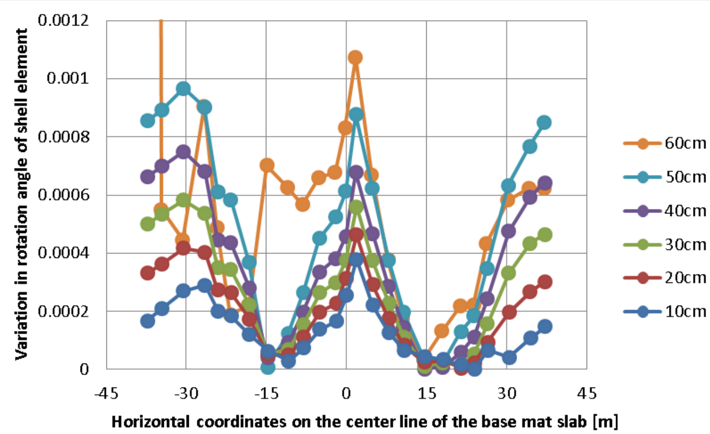
Vertical displacement
(every fault disp. 10cm)





Variation
in rotation angle
(every fault disp. 10cm)





Case0 (soft rock site)   Case12 (hard rock site)

Main Failure Mode for Fragility Evaluation

- Out-of-plane failure of building outer walls: no dominant failure mode by considering realistic surface soil
- Out-of-plane failure of base mat slab : target of fragility evaluation

Main failure mode for fault displacement

Fault type	Effect on the building	Failure mode of outer wall	Failure mode of base mat slab
Normal	Dip-slip displacement	In-plane shear failure	Out-of-plane flexural/shear failure
Reverse	Dip-slip displacement	In-plane shear failure	Out-of-plane flexural/shear failure
	Compression force in the direction orthogonal to the fault plane	Out-of-plane flexural/shear failure (underground)	—※
Strike-slip	Strike-slip displacement	Out-of-plane flexural/shear failure (underground)	—※

※Although it generates stress, it will not reach the failure level.

Policy for fragility Evaluation

[Inside the containment vessel (shell wall)]

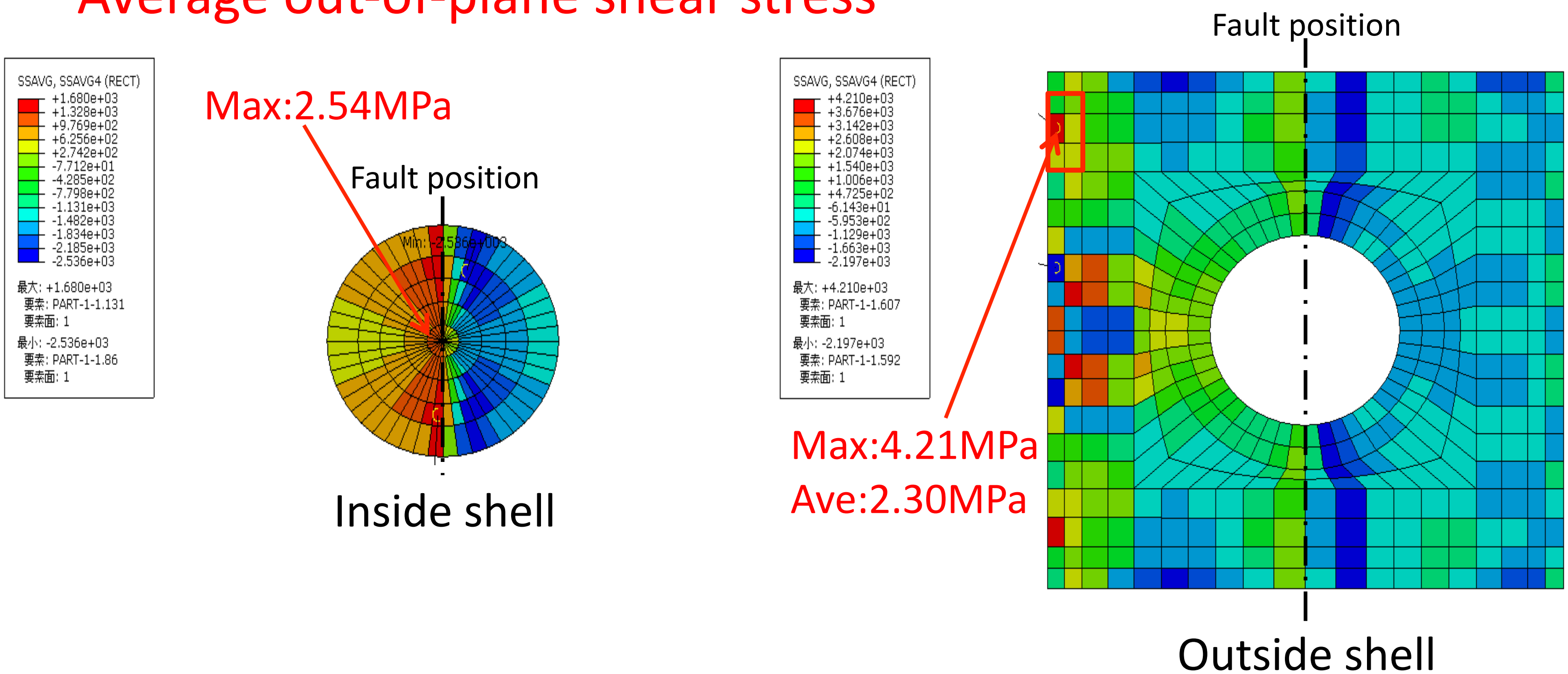
・Focusing on the support function of the containment vessel

・Maximum out-of-plane shear stress of one element

[Outside the containment vessel (shell wall)]

・Focusing on the stability of the reactor building as a whole

・Average out-of-plane shear stress



Out-of-plane shear stress (Case12 : fault disp. 60cm)

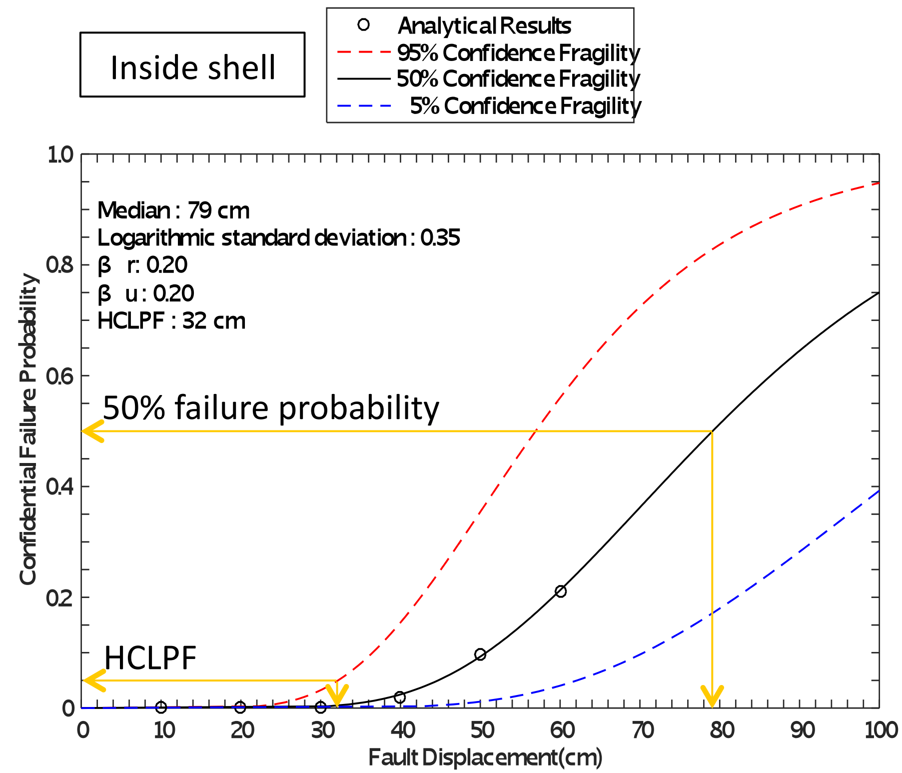
Fragility Evaluation Results for Soft Rock Site

- Preliminary fragility evaluation under the following conditions
  - >Median : The analysis results every 10cm
  - >Logarithmic standard deviation : 0.20 on both aleatory and epistemic uncertainty (from the previous study)
- Conditional failure probability at fault displacement 60cm: 21%

- Median fragility curve by method of least squares

[Inside shell]

- Median (50% failure probability) : 79cm
- HCLPF value : 32cm
- Smaller than outside shell

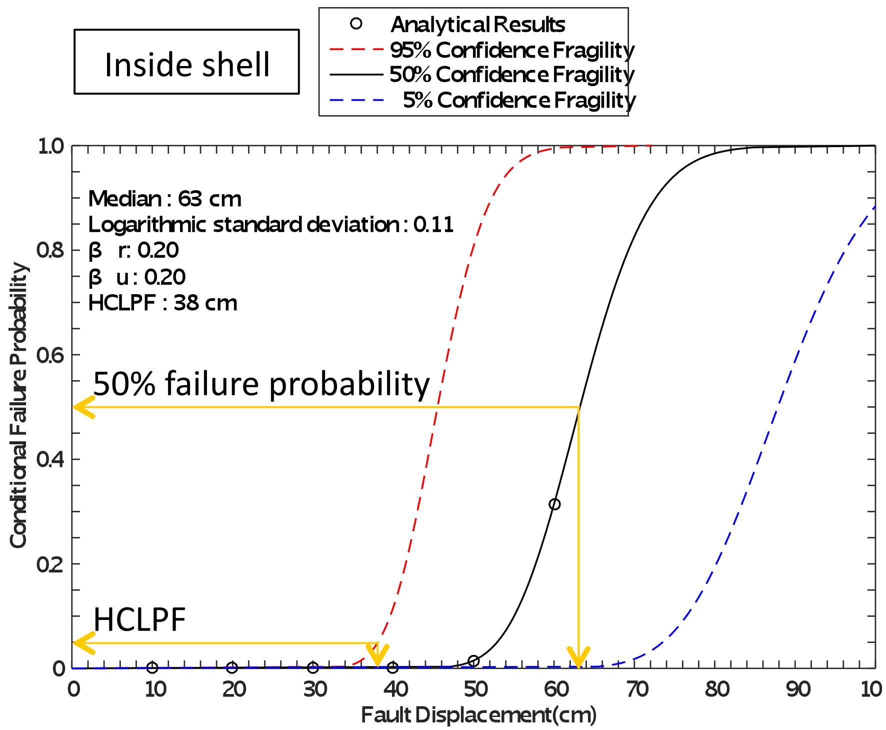


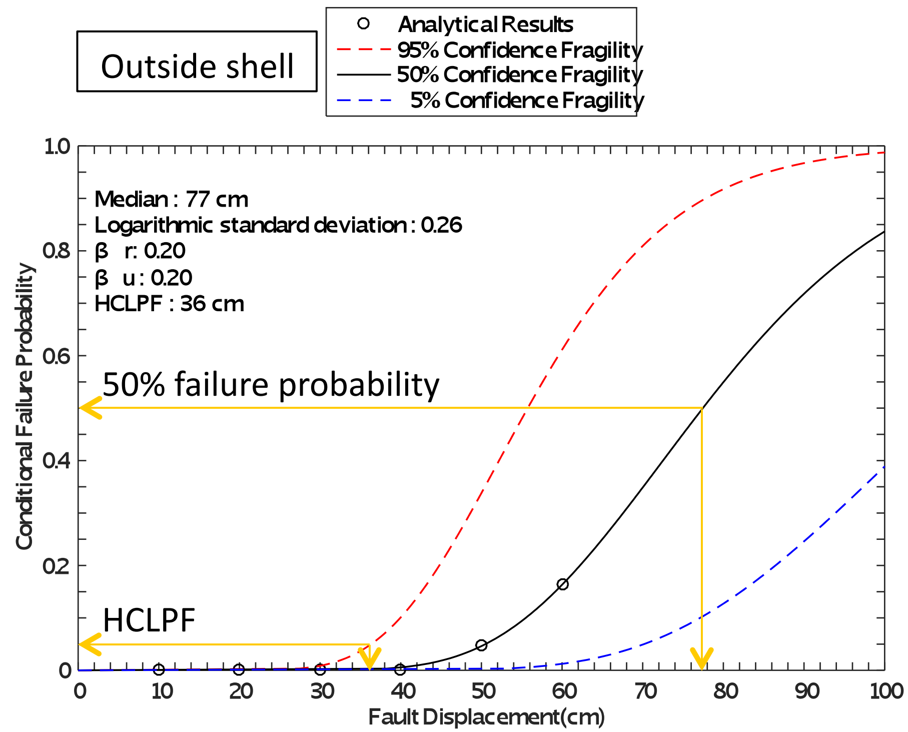
Cf. HCLPF : High Confidence Low Probability of Failure

Fragility curve

Fragility Evaluation Results for Hard Rock Site

・Median and logarithmic standard deviation same conditions as soft rock site





[Inside shell]

- Median (50% failure probability) : 63cm
- HCLPF value : 38cm
- Cliff edge at fault displacement 50cm

[Outside shell]

- Median (50% failure probability) : 77cm
- HCLPF value : 36cm

Conclusions and Future Issues

[Conclusions]

・Nonlinear soil-structure interaction finite element analyses
・Quantitative results considering uncertainty against fault displacement

・Logarithmic standard deviation：0.20 (for aleatory and epistemic uncertainty)

・Out-of-plane shear stress for hard rock site: slightly larger
・No significant difference between soft and hard rock site

・Major failure mode : out-of-plane shear failure of base mat slab
・HCLPF value for both soft and hard rock site： more than 30cm

[Future Issues]

・More generic fragility data
・Uncertainty of fault type such as strike-slip fault