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

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Background

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
## Analysis Cases

### Analysis cases to study on aleatory and epistemic uncertainty

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

### Analysis cases to compare soft rock site with hard rock site

<table>
<thead>
<tr>
<th>Items</th>
<th>Case0</th>
<th>Case6</th>
<th>Case9</th>
<th>Case12</th>
<th>Case13</th>
<th>Case14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support soil Vs</td>
<td>500m/s</td>
<td>500m/s</td>
<td>500m/s</td>
<td>1500m/s</td>
<td>1500m/s</td>
<td>1500m/s</td>
</tr>
<tr>
<td>Surface soil Vs</td>
<td>500m/s</td>
<td>150m/s</td>
<td>500m/s</td>
<td>1500m/s</td>
<td>150m/s</td>
<td>1500m/s</td>
</tr>
<tr>
<td>Fault type</td>
<td>Reverse</td>
<td>Reverse</td>
<td>Normal</td>
<td>Reverse</td>
<td>Reverse</td>
<td>Normal</td>
</tr>
</tbody>
</table>

soft rock site (basic case)  
hard rock site
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**

<table>
<thead>
<tr>
<th>Fault type</th>
<th>Base mat slab</th>
<th>Outer walls</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Concrete</td>
<td>Rebar</td>
</tr>
<tr>
<td></td>
<td>compressive</td>
<td>tensile</td>
</tr>
<tr>
<td>Reverse (Basic)</td>
<td>964.1μ</td>
<td>489.7μ</td>
</tr>
<tr>
<td>Normal</td>
<td>851.0μ</td>
<td>1825μ</td>
</tr>
</tbody>
</table>

- **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

<table>
<thead>
<tr>
<th>Fault position</th>
<th>Base mat slab</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2 of base mat (Basic)</td>
<td>2.380MPa</td>
</tr>
<tr>
<td>1/4 of base mat</td>
<td>2.524MPa</td>
</tr>
</tbody>
</table>

- 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

<table>
<thead>
<tr>
<th>Dip angle</th>
<th>Base mat slab</th>
</tr>
</thead>
<tbody>
<tr>
<td>60° (Basic)</td>
<td>2.380MPa</td>
</tr>
<tr>
<td>30°</td>
<td>2.023MPa</td>
</tr>
</tbody>
</table>

- 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

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

※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)

Max: 4.21 MPa
Ave: 2.30 MPa

Max: 2.54 MPa

Fault position

Inside shell

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

• Median fragility curve by method of least squares

[Inside shell]
• Median (50% failure probability): 79 cm
• HCLPF value: 32 cm
• Smaller than outside shell

Cf. HCLPF: High Confidence Low Probability of Failure
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