Seismic Behavior of APR1400 Nuclear Power Plant with Base Isolation System

Han, Seung-Ryong
KEPCO-E&C
Contents

I. Introduction of APR1400 with Base Isolation System

II. Rev. A model (Conceptual Design of Base-Isolated APR1400)

III. Rev. B model (Practical Design of Base-Isolated APR1400)

IV. Results

V. Conclusions
I. Introduction of APR1400 with Base Isolation System
I. Introduction of APR1400 with Base Isolation System

Seismic Isolation Scope: Nuclear Island

Bearing Type: LRB or FB(EQS)

Target SSE:
- Horizontal EQ: 0.5g
- Vertical EQ: 2/3 ~ 1 of Horizontal EQ
I. Introduction of APR1400 with Base Isolation System (cont’d)

### Title
Development and Application of Seismic Isolation System for Nuclear Power Plant Export

### Purpose
- Development of essential analysis and design technologies
- Development of structural design criteria and seismic performance assessment
- Development of Domestic Seismic Isolators for NPPs

### Duration
`5 years (Stage 1: 3 years, Stage 2: 2 years)`

### Subprojects

<table>
<thead>
<tr>
<th>Subproject</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subproject 1</td>
<td>Development of essential analysis and design technologies</td>
</tr>
<tr>
<td>Subproject 2</td>
<td>Development of Structural Design Criteria</td>
</tr>
<tr>
<td>Subproject 3</td>
<td>Development of Seismic Performance Assessment</td>
</tr>
<tr>
<td>Subproject 4</td>
<td>Development of Seismic Isolators for NPPs</td>
</tr>
</tbody>
</table>

### Main Project Institute
- Main Project: KEPCO-ENC
- Subproject 1: KEPCO-ENC / Subproject 2: KHNP
- Subproject 3: KAERI / Subproject 4: KHNP
II. Rev. A model (Conceptual Design of Base-Isolated APR1400)
II. Rev. A model

NI Mat
- Element: Solid
- Material: Conc

Moat & Bearing
- Element: Solid & beam
- Material: Conc

RCB
- Element: Beam
- Nodal Add Mass

AUX BD
- Element: Beam
- Nodal Add Mass
II. Rev. A model (cont’d)

Lead Rubber Bearing (LRB)
- Element: Beam
- Material: Conc. equivalent to LRB
- Height: 0.4 m

Pedetral
- Element: Beam
- Material: Conc.
- Size: 6' × 6' × 6'
II. Rev. A model (cont’d)

Numeric Properties of Base Isolation System

1. Use Effective Stiffness($K_{eff}$), Vertical Stiffness($K_v$) provided by Vendor(Unison Co.)

2. Calculate Equivalent Beam Properties for Bearings ($I_{33}, I_{22}, I_{11}, A, A_s$)

3. Estimate Eccentricity of Weight(Calculation of weight of each region)

4. Re-Calculate Vertical Loading Capacity per Regions & determine Multiple Parameter($\alpha$)


6. Modal Analysis(Target period)
II. Rev. A model (cont’d)

1. Use Effective ($K_{eff}$), Vertical Stiffness($K_v$) provided by Vendor

- **LRB Properties** -

<table>
<thead>
<tr>
<th>LRB Design (Bridge)</th>
<th>$D$</th>
<th>$F_c$</th>
<th>$W_1$</th>
<th>$K_{uu}$</th>
<th>$K_d$</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>$K_{eff}$</th>
<th>$\xi_{eq}$</th>
<th>$\text{Damping Gain} (%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP630-L-P-10</td>
<td>280</td>
<td>1,350</td>
<td>50</td>
<td>0.025</td>
<td>0.05</td>
<td>1.00</td>
<td>0.01</td>
<td>1.00</td>
<td>0.05</td>
<td>3.00</td>
</tr>
<tr>
<td>LP630-L-P-15</td>
<td>280</td>
<td>1,350</td>
<td>50</td>
<td>0.025</td>
<td>0.05</td>
<td>1.00</td>
<td>0.01</td>
<td>1.00</td>
<td>0.05</td>
<td>3.00</td>
</tr>
<tr>
<td>LP630-L-P-20</td>
<td>280</td>
<td>1,350</td>
<td>50</td>
<td>0.025</td>
<td>0.05</td>
<td>1.00</td>
<td>0.01</td>
<td>1.00</td>
<td>0.05</td>
<td>3.00</td>
</tr>
</tbody>
</table>

**SILER International Workshop (2013. 06. 18 ~ 19)**

1. Use Effective ($K_{eff}$), Vertical Stiffness($K_v$) provided by Vendor

- **LRB Properties** -

<table>
<thead>
<tr>
<th>LRB Design (Bridge)</th>
<th>$D$</th>
<th>$F_c$</th>
<th>$W_1$</th>
<th>$K_{uu}$</th>
<th>$K_d$</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>$K_{eff}$</th>
<th>$\xi_{eq}$</th>
<th>$\text{Damping Gain} (%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP630-L-P-10</td>
<td>280</td>
<td>1,350</td>
<td>50</td>
<td>0.025</td>
<td>0.05</td>
<td>1.00</td>
<td>0.01</td>
<td>1.00</td>
<td>0.05</td>
<td>3.00</td>
</tr>
<tr>
<td>LP630-L-P-15</td>
<td>280</td>
<td>1,350</td>
<td>50</td>
<td>0.025</td>
<td>0.05</td>
<td>1.00</td>
<td>0.01</td>
<td>1.00</td>
<td>0.05</td>
<td>3.00</td>
</tr>
<tr>
<td>LP630-L-P-20</td>
<td>280</td>
<td>1,350</td>
<td>50</td>
<td>0.025</td>
<td>0.05</td>
<td>1.00</td>
<td>0.01</td>
<td>1.00</td>
<td>0.05</td>
<td>3.00</td>
</tr>
</tbody>
</table>

**SILER International Workshop (2013. 06. 18 ~ 19)**
II. Rev. A model (cont’d)

2. Calculate Equivalent Beam Properties for Bearings (I_{33}, I_{22}, I_{11}, A, A_s)

- Circular Beam Section Properties (2\text{nd} Moments, Torsional moment)

\[
K_{\text{eff}} = \frac{12EI}{l^3} \Rightarrow I_{33} = I_{22} = \frac{K_{\text{eff}} \times l^3}{12E} (J \approx 2I)
\]

- Area, Shear area

\[
K_v = \frac{EA}{l} \Rightarrow A = \frac{K_v \times l}{E} (A_s \approx 0.9A)
\]
II. Rev. A model (cont’d)

3. Estimate Eccentricity of Weight (Cal. of weight of each region)
4. Re-Calculate Vertical Loading Capacity per Regions & determine Multiple Parameter (alpha)

<table>
<thead>
<tr>
<th>Region name</th>
<th>Weight Ratio</th>
<th>No. real bearing</th>
<th>No. numerical bearing</th>
<th>alpha</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>0.257</td>
<td>115</td>
<td>69</td>
<td>1.669</td>
</tr>
<tr>
<td>R2</td>
<td>0.159</td>
<td>71</td>
<td>34</td>
<td>2.085</td>
</tr>
<tr>
<td>R3</td>
<td>0.197</td>
<td>88</td>
<td>42</td>
<td>2.085</td>
</tr>
<tr>
<td>R4-1</td>
<td>0.089</td>
<td>40</td>
<td>12</td>
<td>3.325</td>
</tr>
<tr>
<td>R4-2</td>
<td>0.040</td>
<td>18</td>
<td>7</td>
<td>2.6</td>
</tr>
<tr>
<td>R4-3</td>
<td>0.043</td>
<td>19</td>
<td>11</td>
<td>1.75</td>
</tr>
<tr>
<td>R4-4</td>
<td>0.054</td>
<td>24</td>
<td>9</td>
<td>2.7</td>
</tr>
<tr>
<td>R5</td>
<td>0.161</td>
<td>72</td>
<td>35</td>
<td>2.066</td>
</tr>
<tr>
<td>1</td>
<td>447</td>
<td>219</td>
<td></td>
<td>2.0411</td>
</tr>
</tbody>
</table>
II. Rev. A model (cont’d)

6. Modal Analysis & Target Period

<table>
<thead>
<tr>
<th></th>
<th>Freq.(Hz)</th>
<th>Period(sec)</th>
<th>Modal Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.515</td>
<td>1.939</td>
<td>EW Dir</td>
</tr>
<tr>
<td>2</td>
<td>0.515</td>
<td>1.940</td>
<td>NS Dir</td>
</tr>
<tr>
<td>3</td>
<td>0.555</td>
<td>1.802</td>
<td>Torsional mode</td>
</tr>
</tbody>
</table>
II. Rev. A model (cont’d)

6. Modal Analysis & Target Period

<table>
<thead>
<tr>
<th></th>
<th>Freq.(Hz)</th>
<th>Period(sec)</th>
<th>Modal Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.515</td>
<td>1.939</td>
<td>EW Dir</td>
</tr>
<tr>
<td>2</td>
<td>0.515</td>
<td>1.940</td>
<td>NS Dir</td>
</tr>
<tr>
<td>3</td>
<td>0.555</td>
<td>1.802</td>
<td>Torsional mode</td>
</tr>
</tbody>
</table>
III. Rev. B model (Practical Design of Base-Isolated APR1400)
III. Rev. B model

1. Identify Shape of Rigid Beam (55ft) on Beam Stick Model

Concentration of axial loads around beam elements
III. Rev. B model (cont’d)

2. Re-Composition of Rigid Beam using 3D APR1400 FE model(55~68ft Shear wall)
III. Rev. B model (cont’d)

3. Re-Composition of Rigid Beam of Beam Stick Model
III. Rev. B model (cont’d)

4. Figure of Distribution of Axial Loads (Old & New Model)

Old Beam Stick Model (Rev.A)  New Beam Stick Model (Rev.B)
III. Rev. B model (cont’d)

5. Comparison of Axial Loads for Each Model

Standard Deviation

- Old BS Model → 262.5 kips
- New BS Model → 101.8 kips
- 3D FE Model → 104.6 kips

O.K.
III. Rev. B model (cont'd)

6. Final Axial Load Distribution and Layout of Isolators

Weight of APR1400 for Each Region

<table>
<thead>
<tr>
<th>Region</th>
<th>Weight (tonf)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>122,360</td>
<td>0.26</td>
</tr>
<tr>
<td>R1</td>
<td>83,796</td>
<td>0.18</td>
</tr>
<tr>
<td>R2</td>
<td>93,902</td>
<td>0.20</td>
</tr>
<tr>
<td>R3</td>
<td>86,302</td>
<td>0.19</td>
</tr>
<tr>
<td>R4</td>
<td>79,094</td>
<td>0.17</td>
</tr>
<tr>
<td>Sum.</td>
<td>465,455</td>
<td>1.0</td>
</tr>
</tbody>
</table>
III. Rev. B model (cont’d)

7. Design Flow of Base Isolation System

1st Step: Identification of Design Condition for an Objective NPP

2nd Step: Target Design Performance

3rd Step: Assumption of Type of Bearing & Properties & Isolated Area, etc

4th Step: Design of Bearing (Rubber or Friction Types)

5th Step: Expected Target Period & Max. Displacement & Eccentricity etc

6th Step: Check Safety of Base Isolation System

7th Step: Seismic Analysis of Str. With Base Isolation

8th Step: Check Allowable Limits of Design Response

Nuclear Safety First, Last and Always
III. Rev. B model (cont’d)

8. LRB Design

- **Structural Information**
  - Object: APR1400 (SKN34 Nuclear Island)
  - Total weight: 465400 tonf
  - Plant dimension: 104m * 84m
  - Model type: Beam Stick elements for super structure + Solid elements for NI & Moat foundation
  - 6456 Nodes, 2781 Frames, 3628 Solids
  - Target period: 2.30 second

- **Device Information**
  - Type of base isolation: Lead Rubber Bearing (LRB)
  - Diameter of device: 1500 mm
  - Diameter of lead bar: 250 mm
  - Number of device: 454 ea
  - Average face stress: 70 kgf/cm²
  - Thickness of rubber: 11 cm
  - Shear modulus of rubber: 5 kgf/cm²
  - 1st shape factor: 28.0
  - 2nd shape factor: 13.6
  - Height of pedestal: 1800 mm
  - Diameter of pedestal: 3000 mm
  - Damping ratio of device: 0.256
  - Element for device: Equivalent beam
IV. Results
IV. Results


1. Seismic Input motion: reinforced RG1.60 DRS, 0.5g ZPA
2. Surface analysis & Rigid Soil on Fixed base (\(V_s=1e+6\) ft/s, \(V_p=2e+6\) ft/s)
3. SAP2000 model results with Frame Element isolators (no damping) and Rubber isolators (25.6% damping)
4. SASSI2000 model results with Frame Element isolators (25.6% damping)

Design Response Spectra and Time Histories

Horizontal Spectral Acceleration on the top of RCB
IV. Results (cont’d)

Verification of the Rev. B model using SAP 2000 & SASSI2000 (cont’d)

1. Seismic Input motion: reinforced RG1.60 DRS, 0.5g ZPA
2. Surface Analysis & Rigid Soil on Fixed base (\(V_s=1e+6\) ft/s, \(V_p=2e+6\) ft/s)
3. SAP2000 model results with Frame Element isolators (no damping) and Rubber isolators (25.6% damping)
4. SASSI2000 model results with Frame Element isolators (25.6% damping)

Vertical Spectral Acceleration on the top of RCB
IV. Results (cont’d)

Preliminary Seismic Analysis Results
1. Seismic Input motion: reinforced RG1.60 DRS, 0.5g ZPA
2. Generic soil profiles (Nine layered profiles and one fixed base condition)
3. SASSI2000 model results with Frame Element isolators (25.6% damping)
4. FRS generation with 1.2 times scaling, 15% widening, 5% damping

Floor Response Spectra on Containment Shell
IV. Results (cont’d)

Preliminary Seismic Analysis Results (cont’d)
1. Seismic Input motion: reinforced RG1.60 DRS, 0.5g ZPA
2. Generic soil profiles (Nine layered profiles and one fixed base condition)
3. SASSI2000 model results with Frame Element isolators (25.6% damping)
4. FRS generation with 1.2 times scaling, 15% widening, 5% damping

Floor Response Spectra on Primary Shield Wall & Secondary Shield Wall

Generic Soil Profiles for the APR1400 Standard Design
IV. Results (cont’d)

Preliminary Seismic Analysis Results (cont’d)
1. Seismic Input motion: reinforced RG1.60 DRS, 0.5g ZPA
2. Generic soil profiles (Nine layered profiles and one fixed base condition)
3. SASSI2000 model results with Frame Element isolators (25.6% damping)
4. FRS generation with 1.2 times scaling, 15% widening, 5% damping

Floor Response Spectra on Auxiliary Building
IV. Results (cont’d)

Nonlinear Fixed Base Seismic Analysis of the Rev. B model
1. Seismic Input motion: reinforced RG1.60 DRS, 0.5g ZPA
2. Fixed base and Nonlinear analysis
3. SAP2000 model results with Rubber Isolators (Double linear)

Design Response Spectra and Time Histories

Horizontal Spectral Acceleration on the top of RCB
IV. Results (cont’d)

Nonlinear Fixed Base Seismic Analysis of the Rev. B model (cont’d)

1. Seismic Input motion: reinforced RG1.60 DRS, 0.5g ZPA
2. Fixed base and Nonlinear analysis
3. SAP2000 model results with Rubber Isolators (Double linear)

Vertical Spectral Acceleration on the top of RCB

Design Response Spectra and Time Histories
IV. Results (cont’d)

Nonlinear Hybrid Domain SSI Analysis

1. Direct Hybrid Domain Method (Time-consuming and cumbersome iteration procedure is not needed)
2. Use real time interaction force of the interface nodes between super-structure basemat and soil (KISSIE)
3. DHFTD(Direct-Hybrid-Frequency-Time-Domain method Procedure

1) Step 1 : Calculation of transfer function on attached nodes (Linear SSI Analysis of Isolated NPP in FD)

\[
\begin{bmatrix}
S^*_s(\omega) & S^*_a(\omega) & 0 & 0 \\
S_{as}(\omega) & S^*_a(\omega) & S_{ab}(\omega) & 0 \\
0 & S_{ba}(\omega) & S^*_b(\omega) & S_{be}(\omega) \\
0 & 0 & S_{eb}(\omega) & S_{ee}(\omega) + \bar{S}_{ee}(\omega)
\end{bmatrix}
\begin{bmatrix}
U^*_s(\omega) \\
U_a(\omega) \\
U_b(\omega) \\
U_e(\omega)
\end{bmatrix} =
\begin{bmatrix}
0 \\
0 \\
0 \\
F_{eq}(\omega)
\end{bmatrix}
\]

\[
S(\omega) = (1 + i2\beta_d)K - \omega^2M, \quad \bar{S}(\omega) = (1 + i2\beta_d)\bar{K}(\omega) - \omega^2\bar{M}(\omega)
\]

2) Separation of super-structure system from SSI system

\[
M_s\ddot{u}_s(t) + C_{ss}\dot{u}_s(t) + K_{ss}u_s(t) = -f_a(t)
\]

\[
\{f_a(t)\} = \mathcal{F}^{-1}\{\mathcal{F}(f_a)\} = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_{ma}(\omega)U_a(\omega)\tilde{X}_g(\omega)e^{i\omega t}d\omega
\]

\[
S_{ma}(\omega) = (1 + i2\beta_d)K_{ma} - \omega^2M_{ma}
\]

3) Solving a nonlinear problem at the fixed base condition (Nonlinear Seismic Analysis of Isolated NPP in TD)

\[
\begin{bmatrix}
\mathbf{m}_{ss} & \mathbf{m}_{sl} & 0 \\
\mathbf{m}_{ls} & \mathbf{m}_{ll} & \mathbf{m}_{sa} \\
0 & \mathbf{m}_{la} & \mathbf{m}_{aa}
\end{bmatrix}
\begin{bmatrix}
\ddot{\mathbf{u}}_s(t) \\
\ddot{\mathbf{u}}_l(t) \\
\ddot{\mathbf{u}}_a(t)
\end{bmatrix}
+ \begin{bmatrix}
\mathbf{c}_{ss} & \mathbf{c}_{sl} & 0 \\
\mathbf{c}_{ls} & \mathbf{c}_{ll} & \mathbf{c}_{sa} \\
0 & \mathbf{c}_{la} & \mathbf{c}_{aa}
\end{bmatrix}
\begin{bmatrix}
\dot{\mathbf{u}}_s(t) \\
\dot{\mathbf{u}}_l(t) \\
\dot{\mathbf{u}}_a(t)
\end{bmatrix}
+ \begin{bmatrix}
f_{sa}(t) \\
f_{la}(t) \\
f_{aa}(t)
\end{bmatrix} = \begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix}
\]

(a) FRS of top of inner str. with base isolated
(b) Hysteretic loop of the base isolation
IV. Results (cont’d)

Hybrid Simulation Test Plan
1. Provide a direct mechanism to examine the effect of full scale bearing behavior on system response
2. Real Time Hybrid Simulation Test + Full Scale Test
3. Cowork with UC Berkeley and UC San Diego
4. Simulation Program : OpenSees, OpenFresco
5. Modify UCSD SRMD to carry out hybrid simulations
6. Use relatively complex 3D beam stick model of superstructure
7. Model isolators as various combinations of real and numerically simulated bearings
V. Conclusion
V. Conclusion

1. By developing the detailed finite element model (Rev. B) with improved arrangement of bearings, more accurate seismic analyses could be performed and more reliable responses could be obtained.

2. The results of the seismic analyses show that the response of the APR1400 NPP with a base isolation system is significantly reduced horizontally.

3. Seismic response of nonlinear models for the base-isolated APR1400 is affected by the 1st stiffness of bearings rather than the effective stiffness of bearings.

4. Nonlinear SSI analyses considering nonlinearity of base isolation systems are being performed by the nonlinear hybrid domain SSI method proposed by KEPCO-E&C.

5. The 3D finite element model for the superstructure of the APR1400 is being considered for the SSI analysis and full scale tests such as Real-Time Hybrid Simulation Tests with UCB and UCSD are being planned.
Thank You