Overview of Seismic Isolation of Nuclear Power Plants

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Outline

- Motivation
- Nuclear Power Plant (NPP) Background
- Seismic Isolation Background
- Analysis
- Conclusions and Future Research
Motivation

- US Energy Sector
  - Increased Energy Demand and Environmental Concerns
- Potential for Nuclear Power Renaissance
- Policy Perspective: Goal is to ensure the safety and security of nuclear power plants (NPPs)
- Engineers: Improve design to address concerns likely to be raised in the licensing process
- Seismic Isolation can be reliable means of improving seismic safety
Motivation – PEER Project

- Long-term project sponsored by:
  - Electric Power Research Institute (EPRI)
  - Korean Electric Power Corporation (KEPCO)

- Goal
  - To understand the viability of seismic isolation in NPPs using Performance Based Design methodologies

- Pilot Studies
  - Background Information
  - Preliminary Analysis
Nuclear Power Plant Background

- February 2012: 1st Nuclear Reactor Construction Permit in 35 Years
- Changes in licensing and development of NPPs since the 1970s
- 114 reactors in use today

(NRC, 2011)
Base Isolation Background

- Introduction of laterally flexible layer between structure and foundation
- Structure moves as a rigid body supported by bearings
Base Isolation Background

- **Period Shift:**
  \[ T = 2\pi(M/K)^{1/2} \]

- **Balance between SA and SD (design of isolation gap)**

- **Higher mode contributions are nearly zero for ideal case**

(DIS, 2010)
Elastomeric Bearings

- Laminated rubber layers and steel shims
- Damping: 2-20%
- Can achieve shear strains above 200%
- Types
  - Low Damping Rubber Bearings (LDRB)
  - Lead Plug Rubber Bearings (LPRB)
  - High Damping Rubber Bearings (HDRB)

(DIS, 2010)
Friction Bearings

- Pendulum-like restoring force
- Lining materials with friction coefficients from 1% to more than 20%
- Period independent of structure’s weight: 
  \[ T = 2\pi(R/g)^{1/2} \]

- Types
  - Single, Double and Triple Pendulum Friction Bearings

(Morgan, 2011)
Isolation Applications

- Structures
- Bridges
- Off-shore Oil Platforms
- LNG Tanks
- Port Cranes
- NPPs

(Earthquake Protection)
NPP Isolation - Koeberg

- Design by Framatome
- Built in 1976 in Koeberg, South Africa
- First Seismically Isolated Nuclear Power Plant
- Twin 900 MWe PWR Units
Koeberg

- Site Conditions
  - PGA = 0.6g

- Bearing Details
  - 900 Isolators per Reactor
  - Neoprene Pads and Sliders
  - 5% critical damping
  - 2 in. displacement at point of sliding
  - $\mu = 0.18$
Koeberg - Construction

- Pre-fabricated units
- Each unit weighed approximately 4 tons
- 20-60 units installed per day
- Horizontality of unit carefully checked throughout production and installation process
NPP Isolation - Cruas

- Design by Framatome
- Built in 1978 in Cruas, France
- (4) 900 MWe PWR Units
NPP Isolation - Cruas

- **Site Conditions**
  - PGA = 0.3g

- **Bearing Details**
  - 900 Isolators per Reactor
  - Neoprene Pads
  - 5% Critical Damping
Cruas

(Labbe)
Other Isolated Nuclear Facilities

- **ITER and Jules Horowitz Reactor**
  - Low Damping Elastomer Bearings
  - Under Construction in France

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Fig. 1. Partial isolated building (East–West section).

Partial seismic isolation was selected (Fig. 1). In this case the tokamak building pit, in which the tokamak machine and its ancillary systems are installed, will be supported on horizontally compliant seismic isolators which reduce the earthquake acceleration (from 0.4 to 0.2 g). However, the relative motion between the unisolated and isolated parts of the building will be relatively large, from 5 to 15 cm in any horizontal direction and from 1 to 2 cm vertically, depending on the characteristics of the isolators. Pipes, busbars, cables, HVAC ducts, mechanical rails and other services must cross the boundary from the non-isolated part of the building to the isolated structure (subsequently referred to as the seismic gap) absorbing the relative motion and withstanding the inertia force. Therefore, in order to realize this partial seismic isolation method, a feasibility of layout of these services across the seismic gap must be shown ensuring their integrity during earthquake.

In order to reduce the effect caused by the large displacement, some piping elements, such as U-type routings, longer straight pipes, coil springs and velocity proportional type oil dampers, are installed considering minimum space and cost according to the results of analyses. With the analysis method, a conventional one is used in this study considering the Ministry of International Trade and Industries (MITI) Notification No. 501 and the seismic design criteria of the Japan Electrical Association (JEAG 4601). Stresses at various points are analyzed by using the computer program SAP-V. The displacement and the acceleration are combined to the operational loading of each representative service.

For the normal busbars and the HVAC ducts, special expansion joints are investigated from the first. For the mechanical rail for remote handling transporter, a special adjusting mechanism is investigated.

Table 1 summarizes the generic items crossing the seismic gap.
NRC Regulations

- Types of Isolators
  - Low Damping Rubber Bearing
  - Lead Rubber Bearing
  - Friction Pendulum Bearing

- High Damping Rubber Bearings?
  - Problems with scragging and unpredictable changes in properties

- 90% < confidence in the survival of the isolation system

- Limited moat damage or potential for hard stop
Table 8-1. Performance and design expectations for seismically isolated nuclear power plants

<table>
<thead>
<tr>
<th>Ground motion levels</th>
<th>Isolation unit and system design and performance criteria</th>
<th>Approach to demonstrating acceptable performance of isolator unit</th>
<th>Superstructure design and performance</th>
<th>Umbilical line design and performance</th>
<th>Moat or hard stop design and performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMRS+ (^2)</td>
<td>No long-term change in mechanical properties. 100% confidence of the isolation system surviving without damage when subjected to the mean displacement of the isolator system under the GMRS+ loading.</td>
<td>Production testing must be performed on each isolator for the mean system displacement under the GMRS+ loading level and corresponding axial force.</td>
<td>The superstructure design and performance must conform to NUREG-0800 under GMRS+ loading.</td>
<td>Umbilical line design and performance must conform to NUREG-0800 under GMRS+ loading.</td>
<td>The moat is sized such that there is less than 1% probability of the superstructure contacting the moat or hard stop under GMRS+ loading.</td>
</tr>
<tr>
<td>EDB (^4)-GMRS</td>
<td>90% confidence of each isolator and the isolation system surviving without loss of gravity-load capacity at the mean displacement under EDB loading.</td>
<td>Prototype testing must be performed on a sufficient number of isolators at the CHS (^5) displacement and the corresponding axial force to demonstrate acceptable performance with 90% confidence. Limited isolator unit damage is acceptable but load-carrying capacity must be maintained.</td>
<td>There should be less than a 10% probability of the superstructure contacting the moat or hard stop under EDB loading.</td>
<td>Greater than 90% confidence that each type of safety-related umbilical line, together with its connections, remains functional for the CHS displacement. Performance can be demonstrated by testing, analysis or a combination of both.</td>
<td>CHS displacement must be equal to or greater than the 90th percentile isolation system displacement under EDB loading.</td>
</tr>
</tbody>
</table>

1. Analysis and design of safety-related components and systems should conform to NUREG-0800, as in a conventional nuclear structure.
2. 10CFR50 Appendix S requires the use of an appropriate free-field spectrum with a peak ground acceleration of no less than 0.10g at the foundation level. RG1.60 spectral shape anchored at 0.10g is often used for this purpose.
3. The analysis can be performed using a single composite spectrum or separately for the GMRS and the minimum spectrum.
4. The analysis can be performed using a single composite spectrum or separately for the \(10^{-5}\) MAFE response spectrum and 167% GMRS.
5. CHS=Clearance to the Hard Stop
6. Seismic Category 2 SSCs whose failure could impact the functionality of umbilical lines should also remain functional for the CHS displacement.
7. Impact velocity calculated at the displacement equal to the CHS assuming cyclic response of the isolation system for motions associated with the 95th percentile (or greater) EDB displacement.
How might Isolation Benefit Current NPP designs

- A simple numerical “stick” model was found in the open literature to represent an AP 1000 standard plant design (Westinghouse)
Simplified Numerical Stick Model

- From EPRI/Bechtel study of SSI modeling
- Structures Considered
  - Auxiliary/Containment Building (ASB) ($T_1 = 0.31$ sec)
  - Containment’s Internal Structure (CIS) ($T_1 = 0.08$ sec)
- 2D idealization used for pilot study
Ground Motions Used

- Simplified generalized modal analysis was done in Matlab based on response spectrum.
- Two sites from Seismic Source Characterization Study considered.
- Spectra based on NUREG 1.60 and PGA estimates.

Hazard estimates for Manchester, New Hampshire and Savannah, Georgia sites were used to generate spectra.
Comparison of models

Fixed Base Model

Base Isolated Model

Elastic Superstructure

Base Mat

Equivalent linear isolator properties

$T_{iso}$

$\xi_{iso}$
Response Spectrum Analysis

- Period of Isolation = 2, 2.5, 3, 3.5 and 4 s
- Damping Ratio of Isolator = 2, 10, 15 and 20%
- Method of Analysis: Generalized Modal Analysis
- Program: MATLAB (code courtesy of Dr. Tracy Becker)
Savannah Site with Shallow Soil Results in Largest Response

- Results shown here for $4 \times 10^{-4}$ probability of exceedence on soft clay
- Shears at levels in isolated structure are about 1/7 of those for fixed base case
- Other hazard levels and soils exhibit similar trends
Effect of Isolator Period and Damping on Base Shear and Isolator Displacement

All demands decrease with increased damping of isolators

With increasing isolator period, isolator displacement increases, but base shear decreases (tradeoff needed)

(Savannah: $4 \times 10^{-4}$ Hazard on Soft Clay)
Floor Response Spectra

- Period of Isolation = 2, 2.5, 3, 3.5 and 4 s
- Damping Ratio of Isolator = 2, 10, 15 and 20%
- 3 Key Locations
  - Control Room (ASB)
  - Fuel Building’s Roof (ASB)
  - Operating Desk (CIS)
- Method of Analysis: Generalized Modal Analysis
- Program: MATLAB (code courtesy of Dr. Tracy Becker)
Dependence of Floor Spectra On Different Isolator Periods

- Floor spectra calculated at different levels for fixed base and isolated plant
- Fixed base has high spectral values at high frequencies
- Isolated plant has high spectral values near frequency of isolation system
Comparison of Ratio of Floor Spectral Values for Isolated and Fixed Base NPP

In high frequency range,
- Spectral values decrease with increasing isolator period
- Reduction of floor spectrum by 60 to 80% in this range possible compared to fixed base case.

In low frequency range,
- Significant amplifications occur at natural frequency of isolator,
- Amplification can be by order of magnitude,
- For long period isolators, the fixed base spectral accelerations may be quite low, and a large amplification near the isolation frequency may not be important. However, this needs to be confirmed.
Realistic Floor Spectra – Evidence from Earthquake Records

Fukushima Daiichi Emergency Operations Facility

Base Isolated Facility Building: E-W component

Significant reduction in PGA and frequency content of the recorded motions in base isolated facility building were obviously observed.
But spectra may be sensitive to modeling of structure and isolators.

Simple lumped mass stick models will not capture vertical response effects.

Coupled Vertical-Lateral Mode Shapes in Asymmetric Structures.
Floor spectra in high frequency range is sensitive bearing properties

P–Δ effects in bearings

Vertical ground excitations will trigger horizontal vibrations in superstructure

Strongly nonlinear systems trigger high frequency vibrations

Ma + Cv + K_{eff}d = -ma_g - Q_y

Responds at effective period of isolator

Impact like loading triggers response at natural frequencies of supported structure
Time History Analysis

- **Ground Motion Time Histories**
  - 30 simulated time histories
  - Hard Rock and Soil
  - 43 miles from the New Madrid source
  - Magnitude 7.6 Earthquake
  - Amplification factor = 1.5 to simulate new seismic characterization

- **Model**
  - ASB with representative LDRB and LPRB bearings
  - SAP2000
Time History Analysis – Results (LDRB)

- Similar response between the amplified and original ground motions
Time History Analysis – Results (LPRB)

- Linear regressions do not fit data well outside range of peak values
- Difficult to use equivalent linear models for nonlinear bearings
Time History Analysis – Results (LPRB)

- Linear regressions do not fit data well outside range of peak values
- Difficult to use equivalent linear models for nonlinear bearings
Future Work

- Effects of Vertical Motion
- Shape of Hysteretic Loops
- Asymmetric Structures (coupled H-V response)
- Soil-Structure Interaction
- Experimental Work
Conclusions

- Isolation has shown to effectively reduce shears and drifts at various locations for both models.
- Isolation has the ability to maintain effectiveness for variations in ground motions.
- Performance Based Design can really provide an effective means of addressing seismic issues concerning isolation application.
- Future research and development offers a great opportunity for collaboration across various engineering fields.
Thanks!