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

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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

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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

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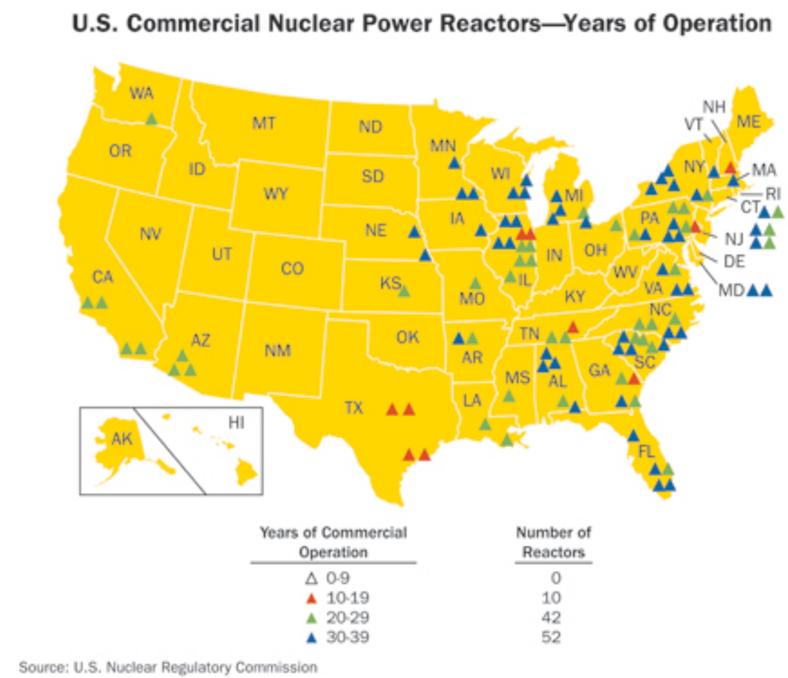
Nuclear Power Plant Background

- 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)

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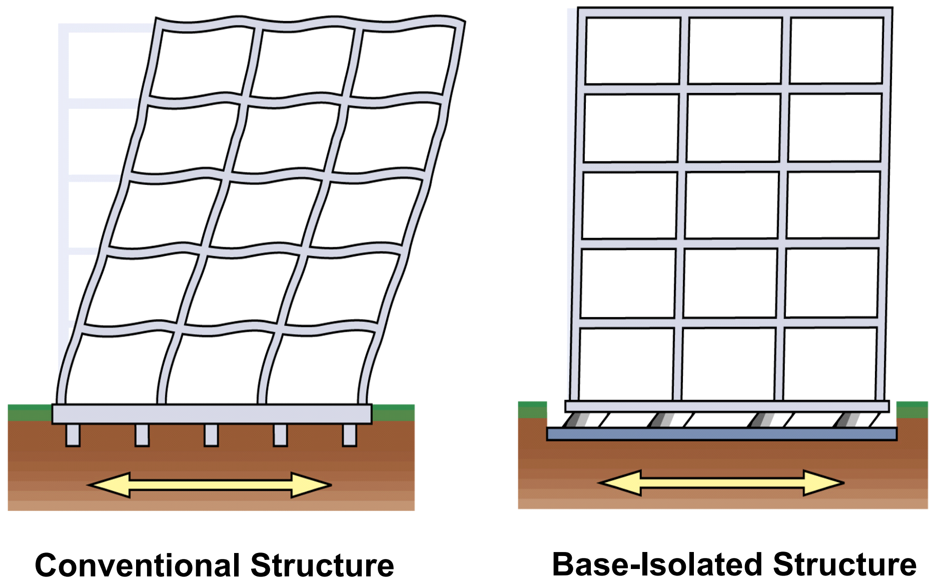
Base Isolation Background

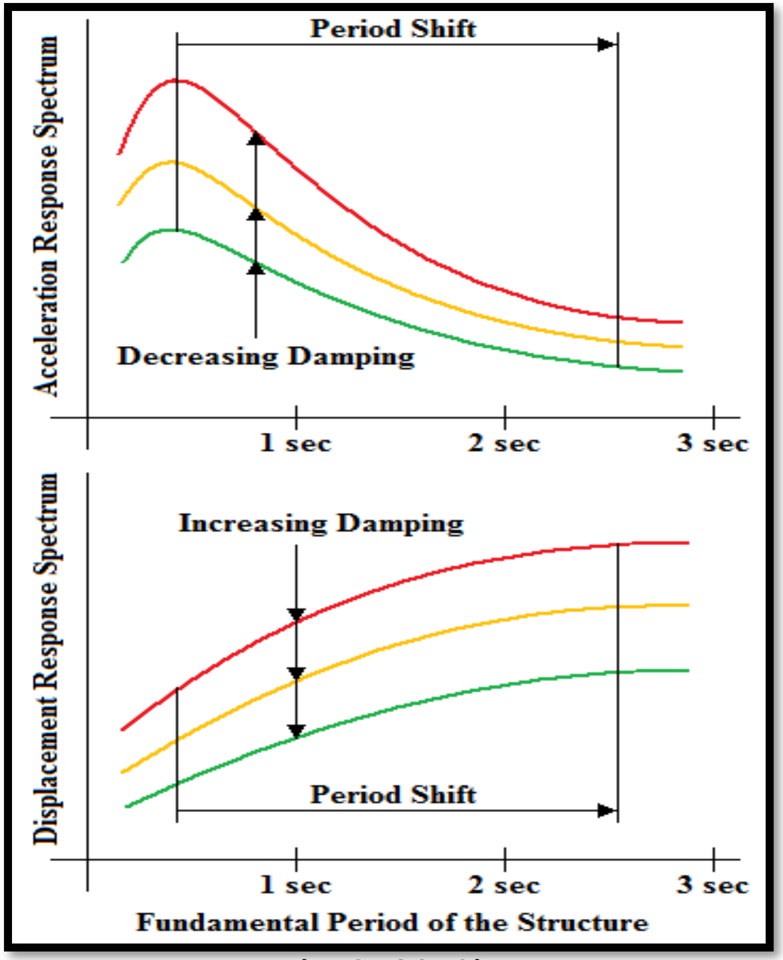


(Symans)

- 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)

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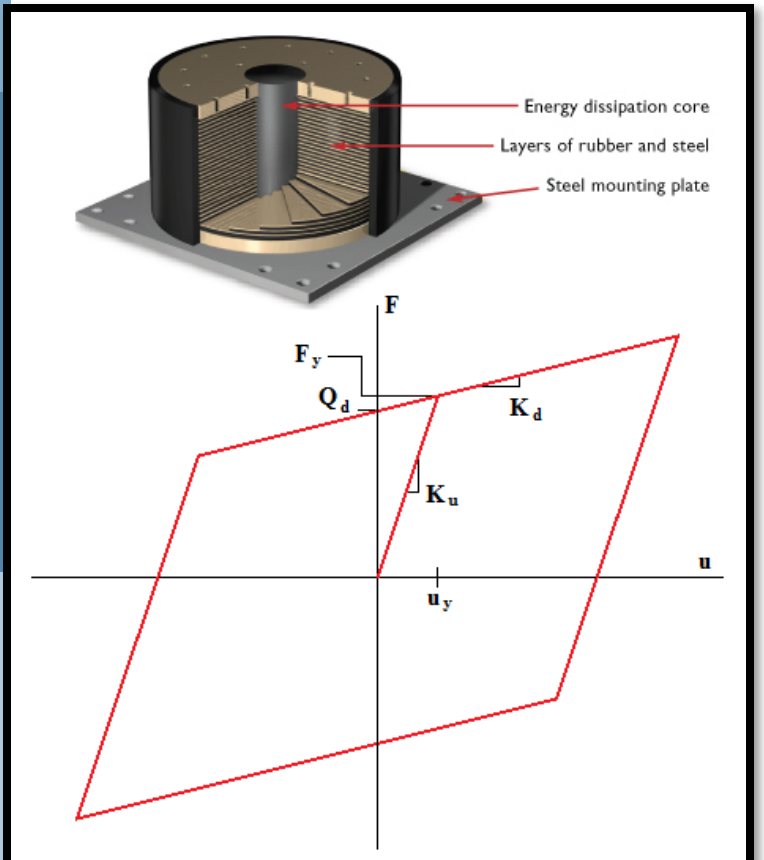
Elastomeric Bearings



(DIS, 2010)

- 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)

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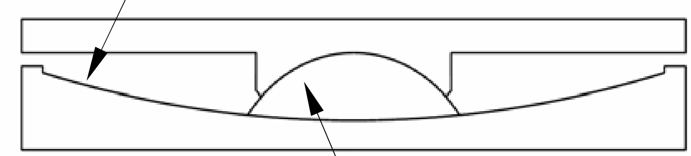
Friction Bearings

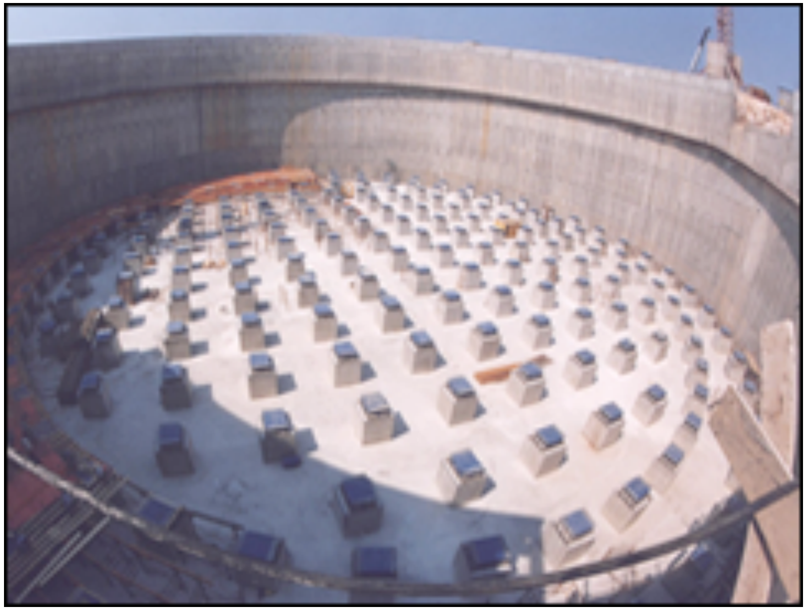
- Pendulum-like restoring force
- Lining materials with friction coefficients from 1% to more than 20%
- Period independent of structure's weight: $T = 2\pi(R/g)^{1/2}$
- Types
  - Single, Double and Triple Pendulum Friction Bearings



(Morgan, 2011)

Isolation Applications

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



(Earthquake Protection)

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NPP Isolation - Koeberg

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

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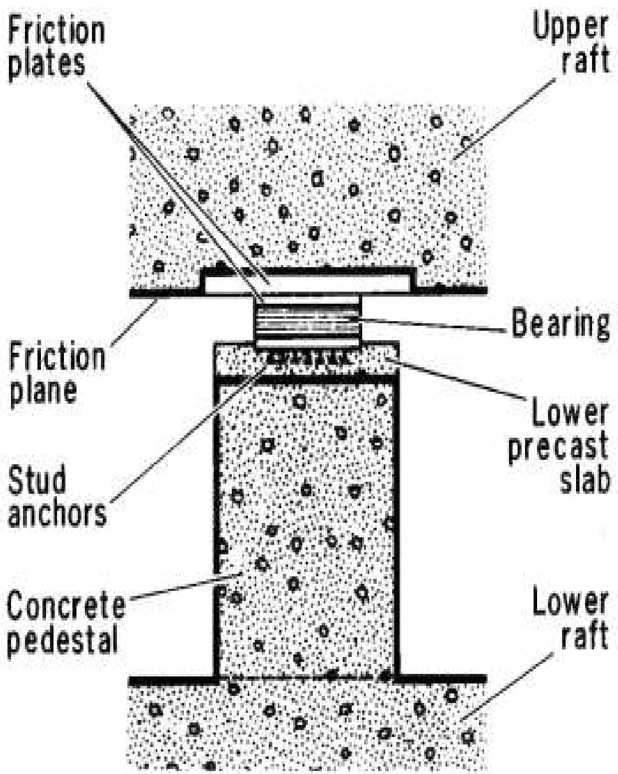
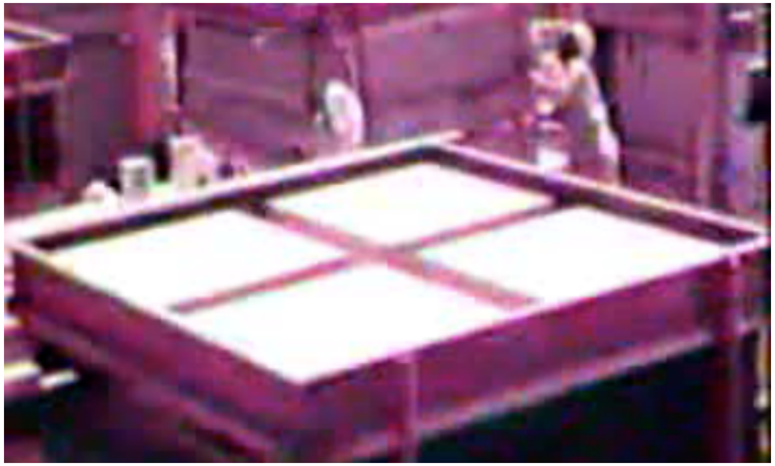
Koeberg

- 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
  - μ = 0.18



(Labbe)

Koeberg - Construction



(Spie Batignolles)

- 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

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NPP Isolation - Cruas

- Site Conditions
  - PGA = 0.3g
- Bearing Details
  - 900 Isolators per Reactor
  - Neoprene Pads
  - 5% Critical Damping

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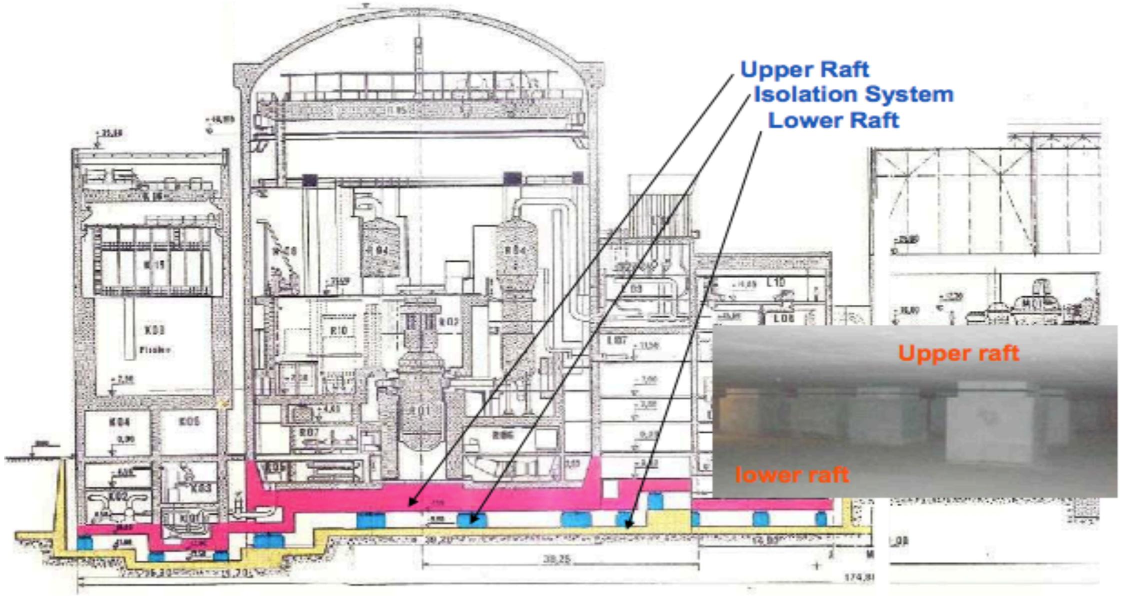
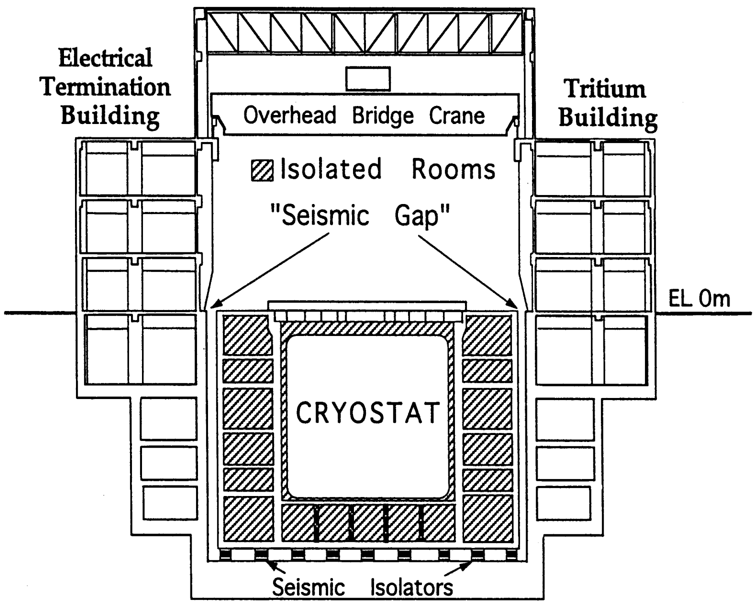
Cruas

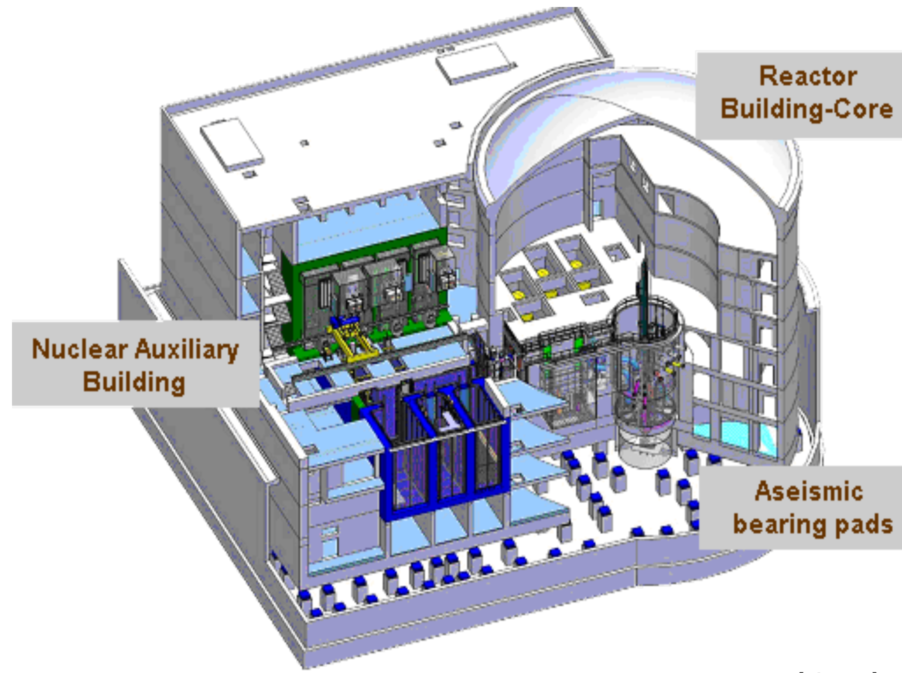

Upper Raft
Isolation System
Lower Raft
Upper raft
lower raft

(Labbe)

Other Isolated Nuclear Facilities



(Hashimoto)



(CEA)

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

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

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Table 8-1. Performance and design expectations for seismically isolated nuclear power plants[1]

	Isolation system				
Ground motion levels	**Isolation unit and system design and performance criteria**	**Approach to demonstrating acceptable performance of isolator unit**	**Superstructure design and performance**	**Umbilical line design and performance**	**Moat or hard stop design and performance**
GMRS+[2] The envelope of the RG1.208 GMRS and the minimum foundation input motion[3] for each spectral frequency	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.	Production testing must be performed on each isolator for the mean system displacement under the GMRS+ loading level and corresponding axial force.	The superstructure design and performance must conform to NUREG-0800 under GMRS+ loading.	Umbilical line design and performance must conform to NUREG-0800 under GMRS+ loading.	The moat is sized such that there is less than 1% probability of the superstructure contacting the moat or hard stop under GMRS+ loading.
EDB[4] **GMRS** The envelope of the ground motion amplitude with a mean annual frequency of exceedance of 1×10^{-5} and 167% of the GMRS+ spectral amplitude	90% confidence of each isolator and the isolation system surviving without loss of gravity-load capacity at the mean displacement under EDB loading.	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.	There should be less than a 10% probability of the superstructure contacting the moat or hard stop under EDB loading.	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.[6]	CHS displacement must be equal to or greater than the 90th percentile isolation system displacement under EDB loading. Moat or hard stop designed to survive impact forces associated with 95th percentile EDB isolation system displacement.[7] Limited damage to the moat or hard stop is acceptable but the moat or hard stop must perform its intended function.

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)

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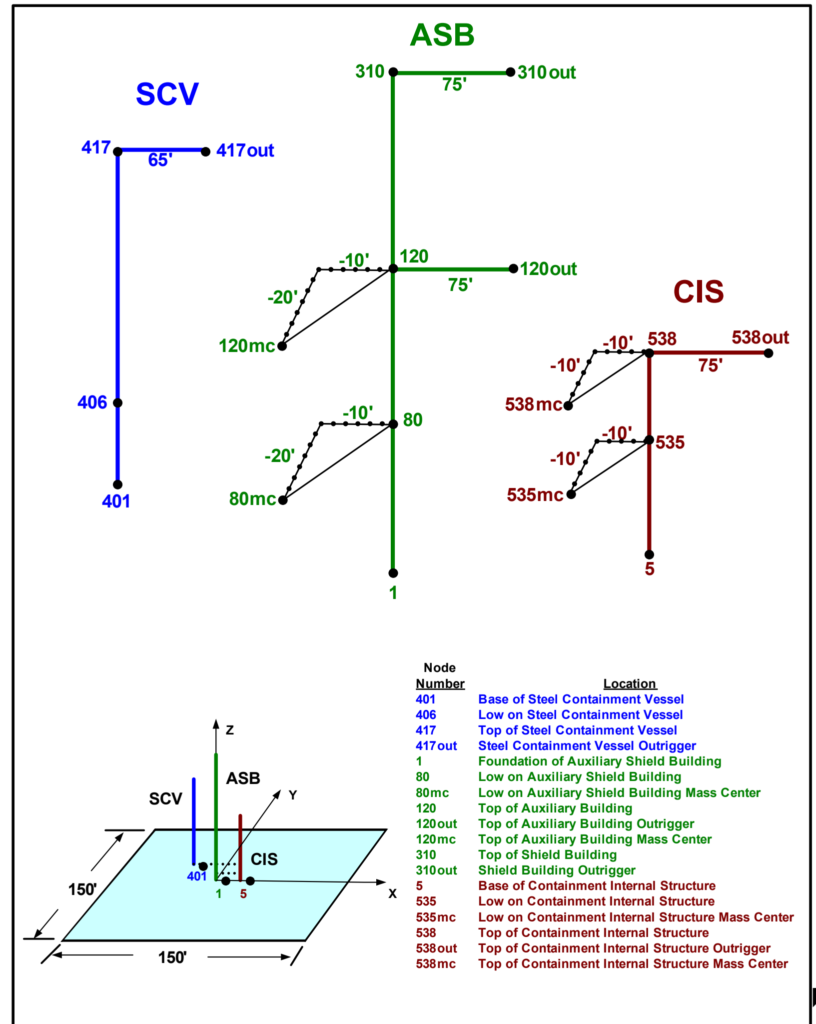
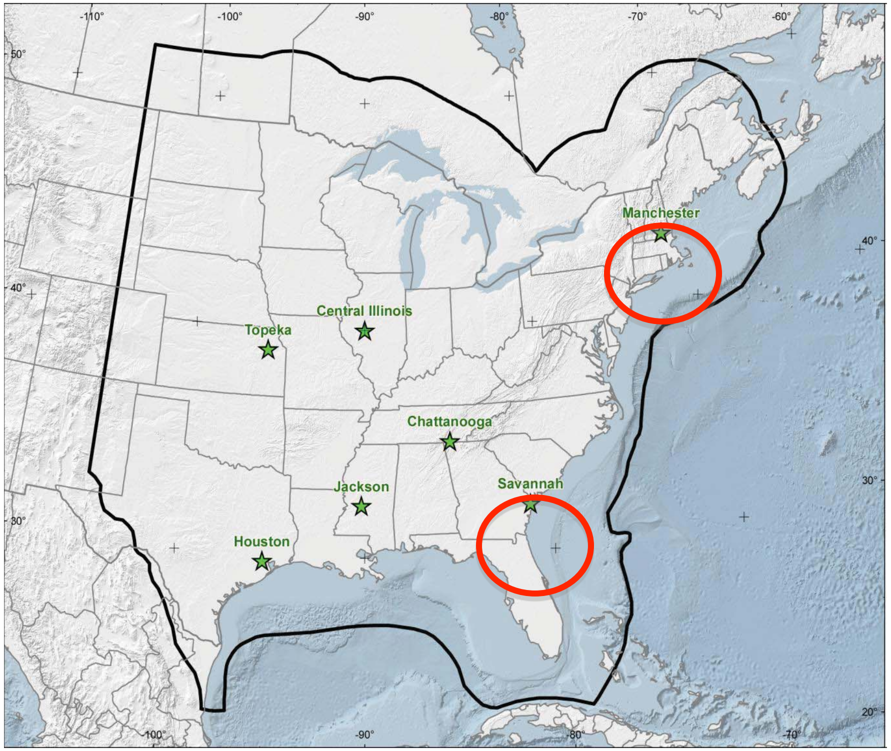
Simplified Numerical Stick Model

- 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

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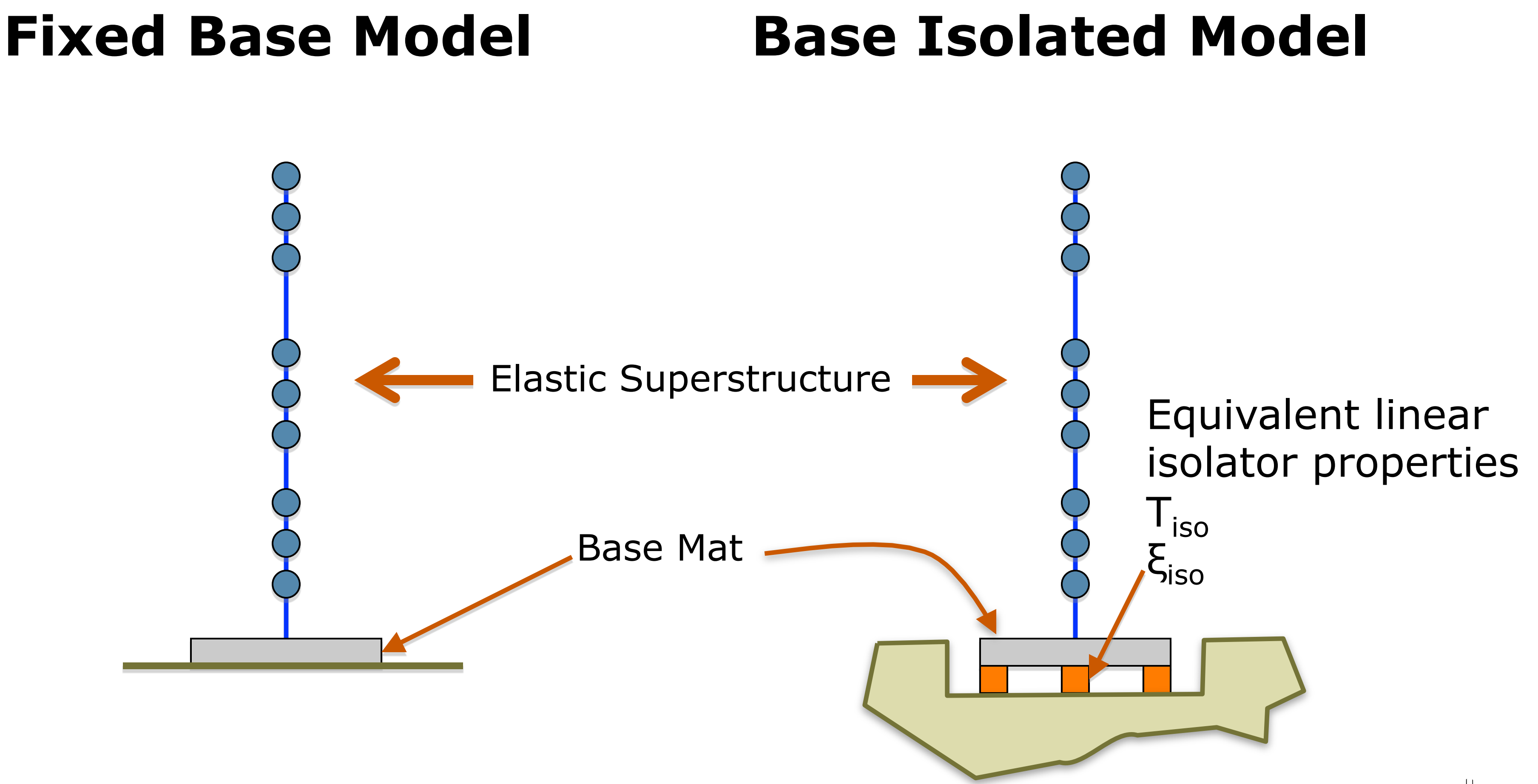
Comparison of models



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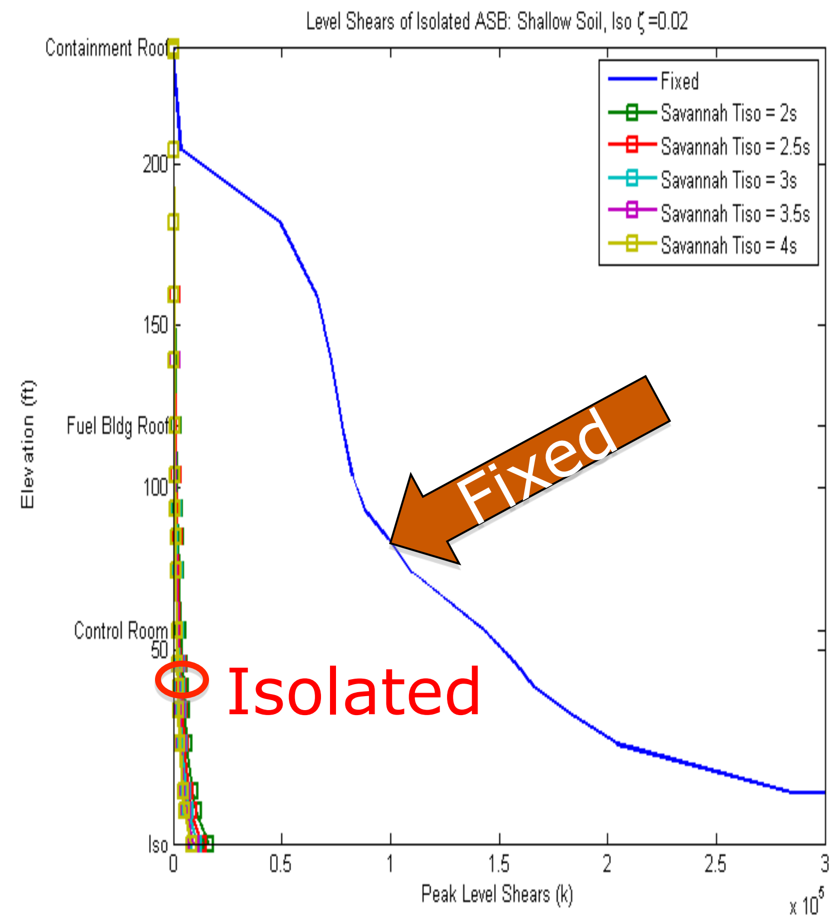
Response Spectrum Analysis

- 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

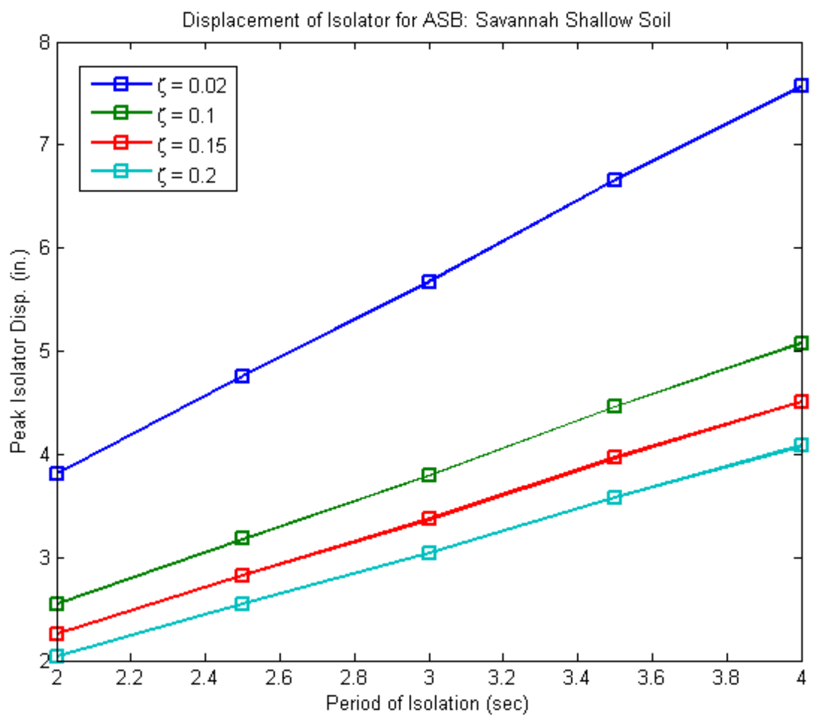
- Results shown here for $4x10^{-4}$ probability of exceedence on soft clay
- Shears at levels in isolated structure are about 1/7 of those for fixed base case
- Other hazard levels and soils exhibit similar trends

Story Shears for Fixed and Isolated Cases

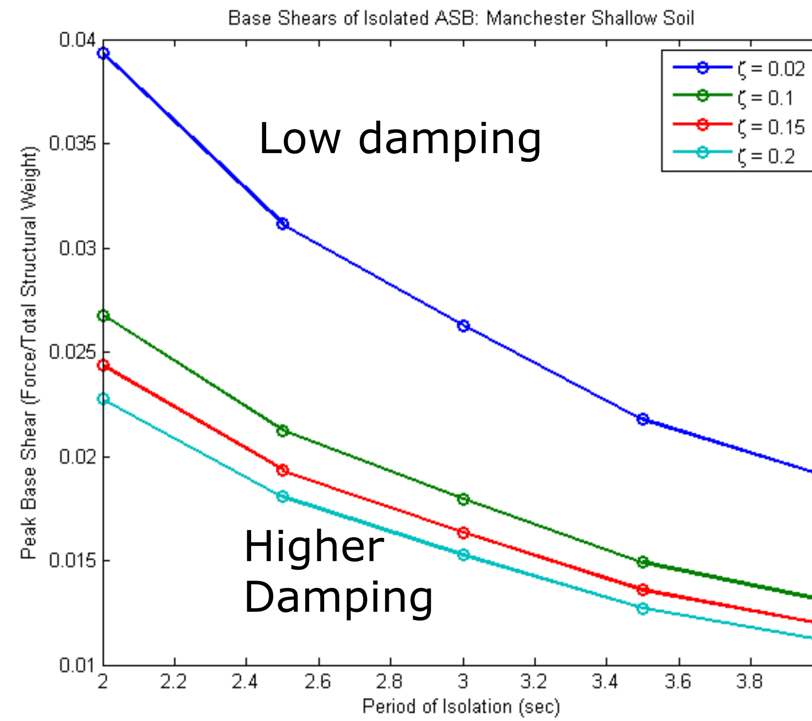


Effect of Isolator Period and Damping on Base Shear and Isolator Displacement

Isolator Displacement Demand



Base Shear Demand



All demands decrease with increased damping of isolators

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

(Savannah: 4×10^{-4} Hazard on Soft Clay)

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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)

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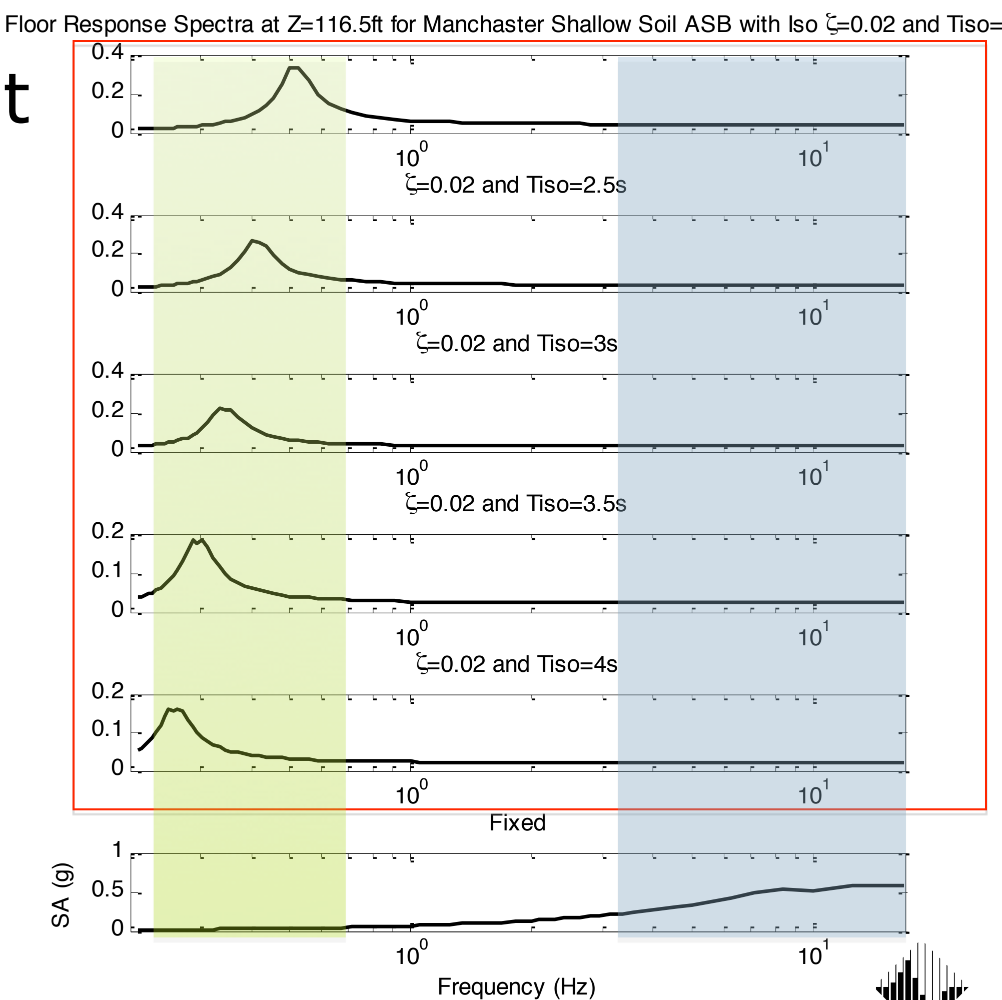
Dependence of Floor Spectra On Different Isolator Periods

- 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

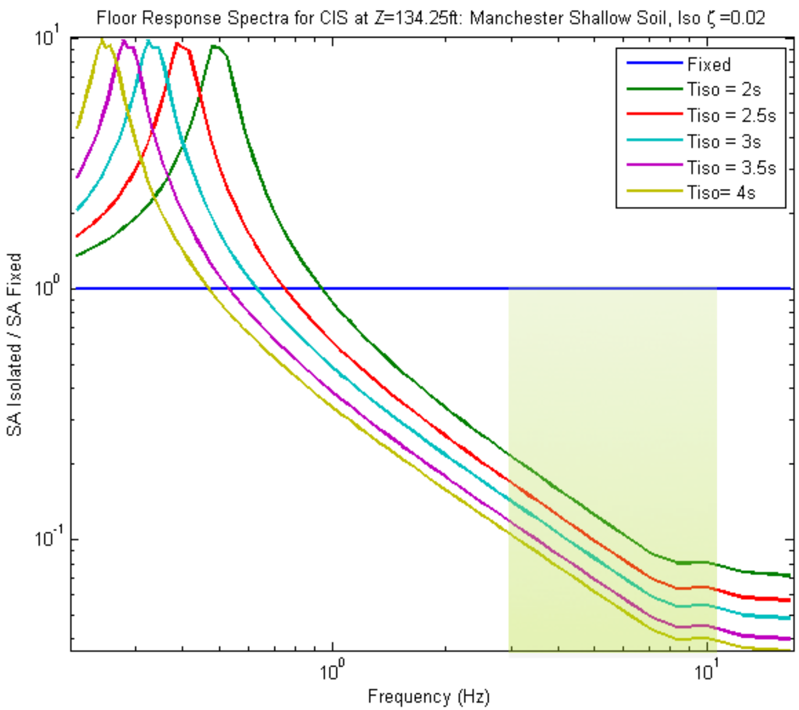
In high frequency range,

- 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.

Sa(Isolated)/Sa(Fixed Base)



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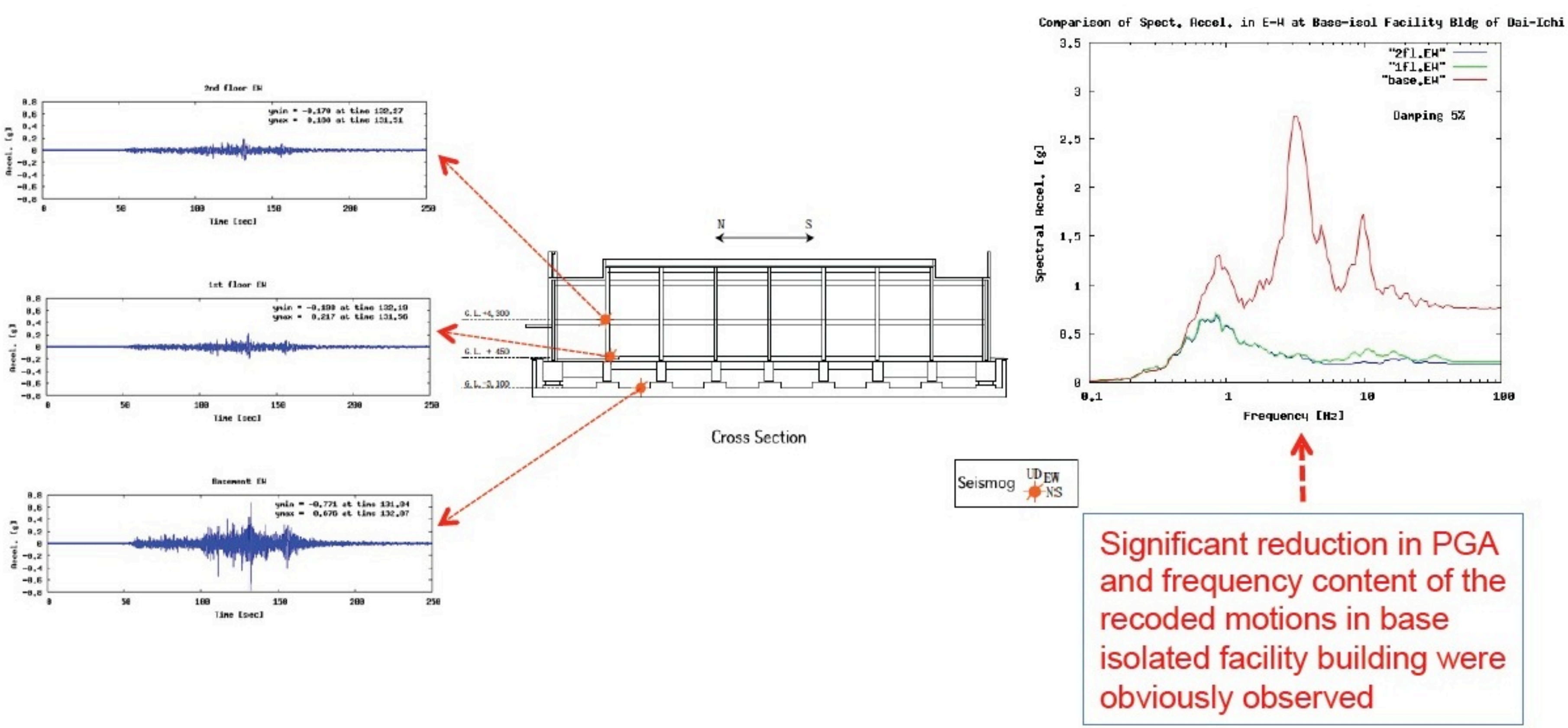
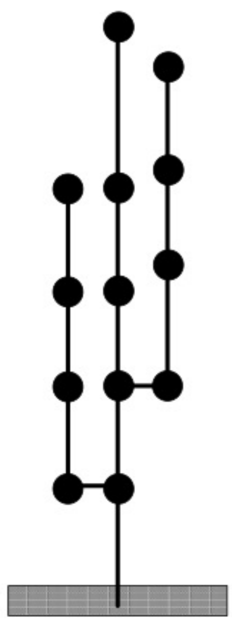
Realistic Floor Spectra – Evidence from Earthquake Records

Fukushima Daiichi Emergency Operations Facility

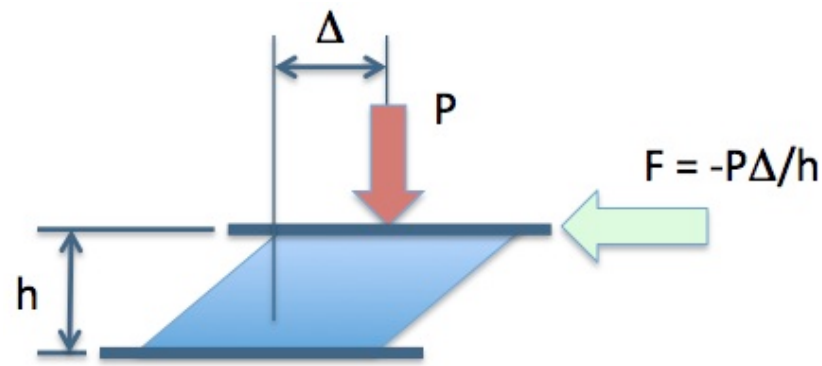
Base Isolated Facility Building: E-W component



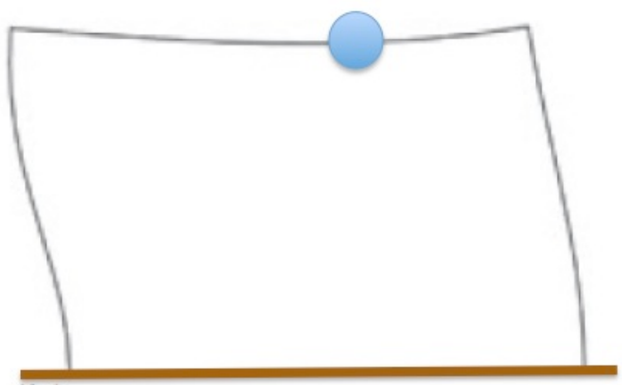
But spectra may be sensitive to modeling of structure and isolators



Simple lumped mass stick models will not capture vertical response effects

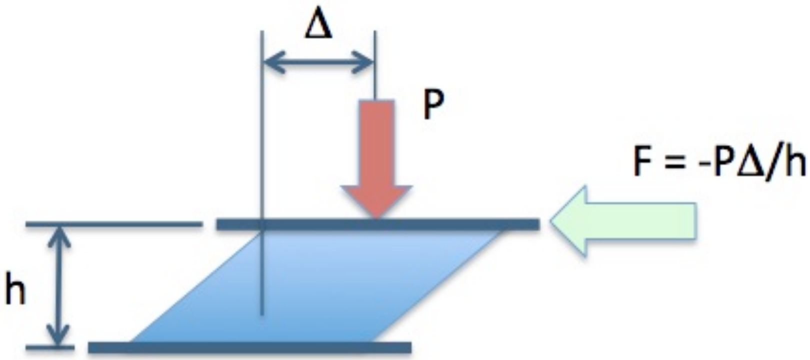


P–Δ effects in bearings

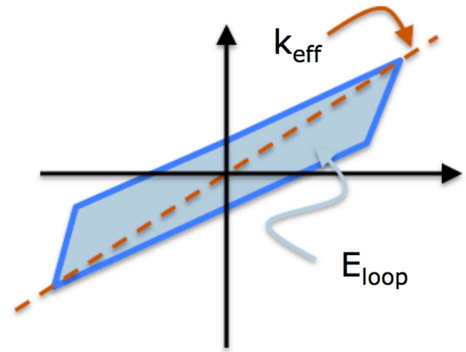


Coupled Vertical-Lateral Mode Shapes in Asymmetric Structures

Floor spectra in high frequency range is sensitive bearing properties



P−Δ effects in bearings



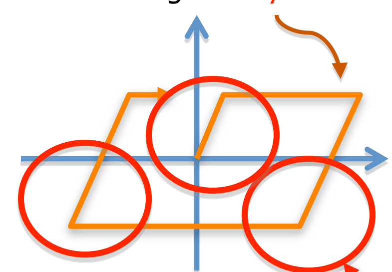
Strongly nonlinear systems trigger high frequency vibrations

Vertical ground excitations will trigger horizontal vibrations in superstructure

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

Responds at effective period of isolator

Impact like loading triggers response at natural frequencies of supported structure



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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

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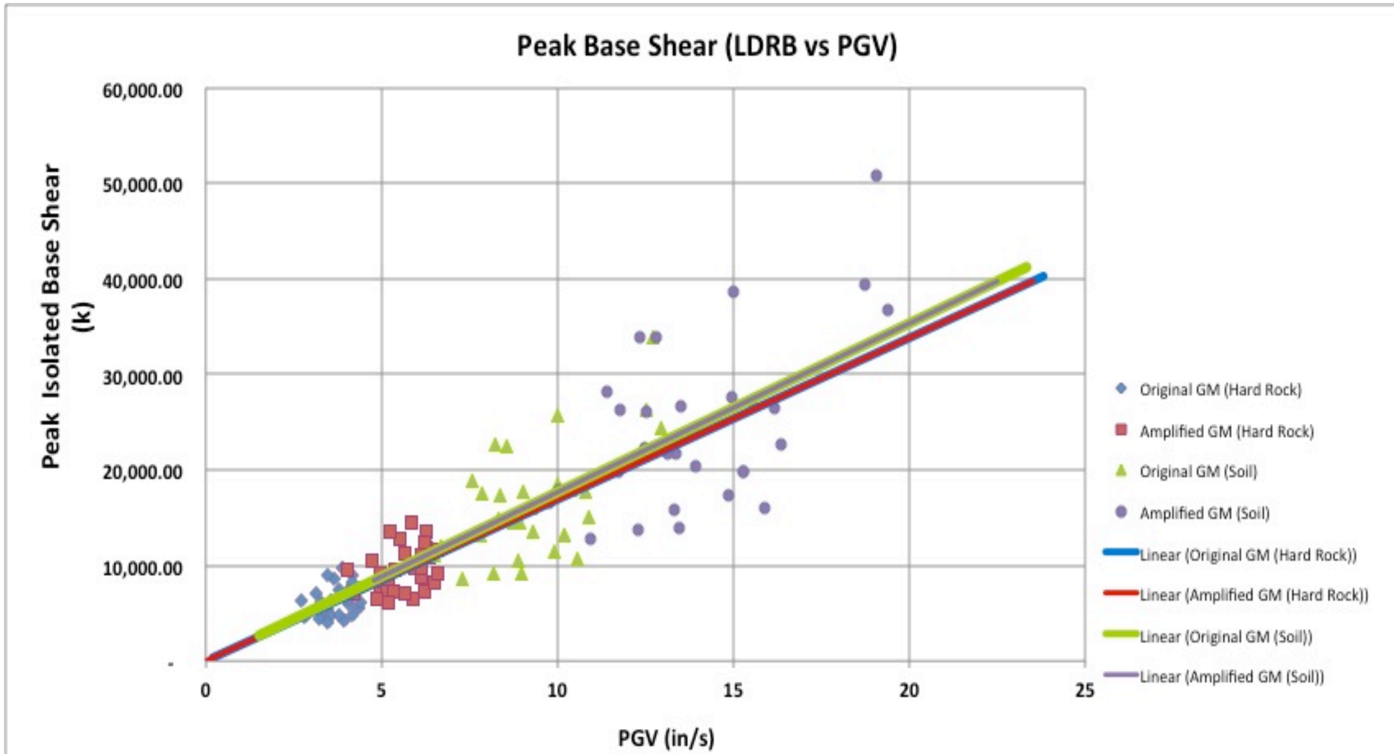
Time History Analysis – Results (LDRB)



- Similar response between the amplified and original ground motions

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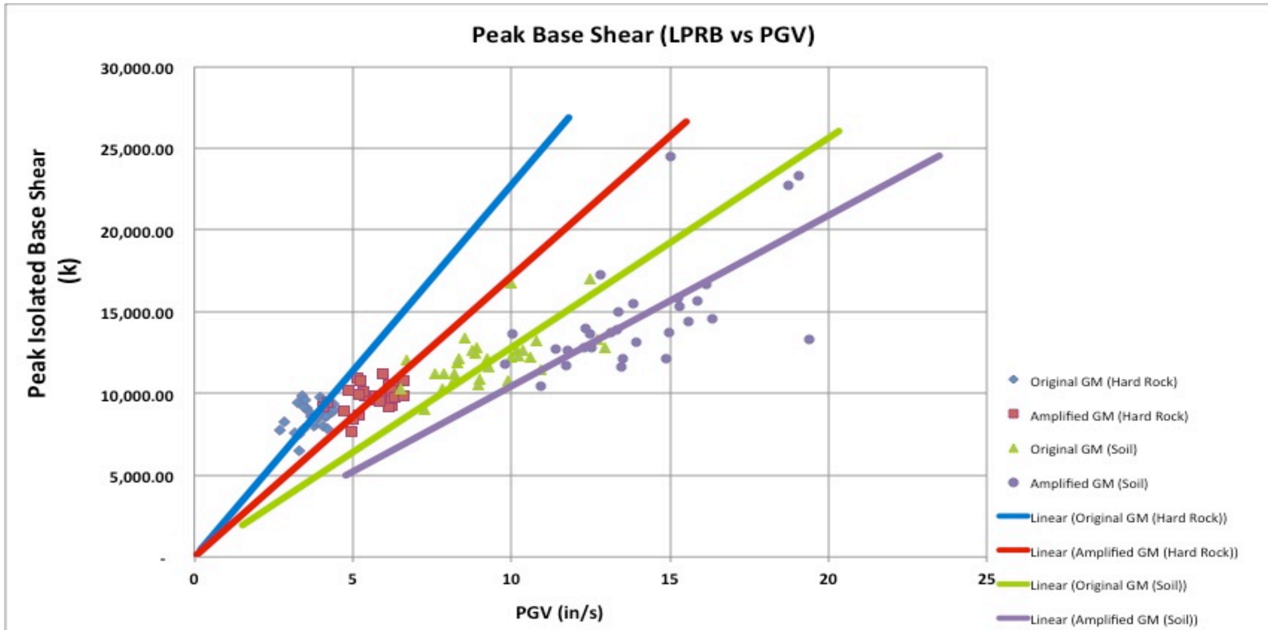
Time History Analysis – Results (LPRB)



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

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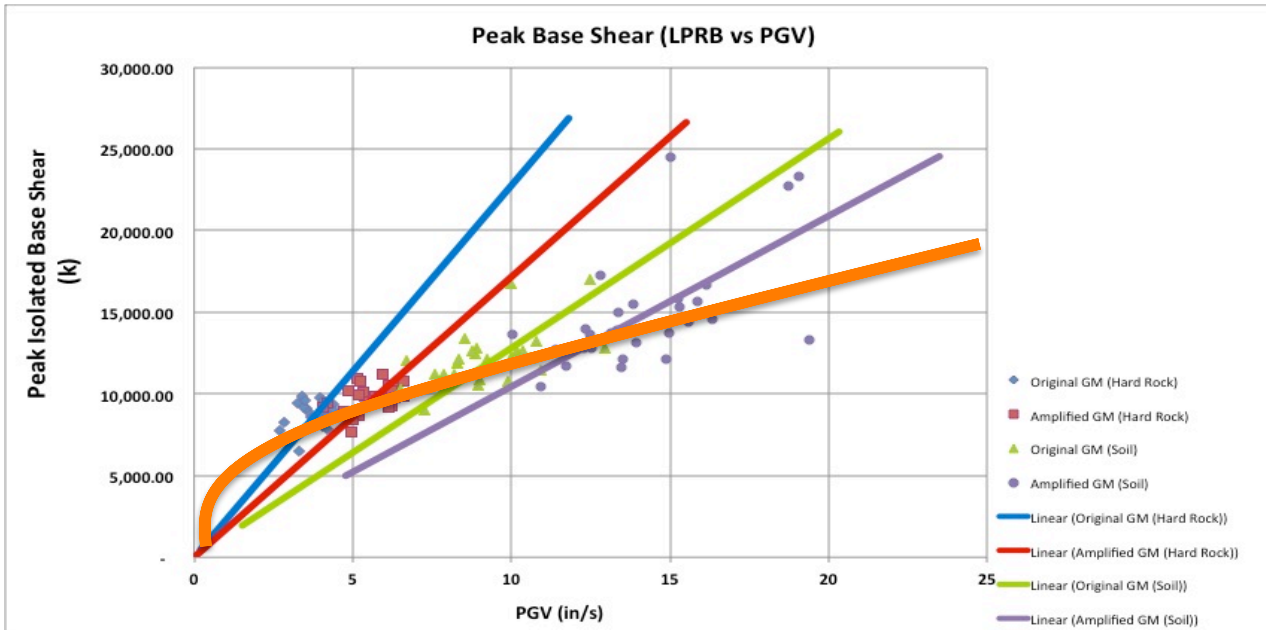
Time History Analysis – Results (LPRB)



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

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Future Work

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

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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

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Thanks!