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Recent Tests and Analyses of Seismically Isolated Nuclear Power Plants

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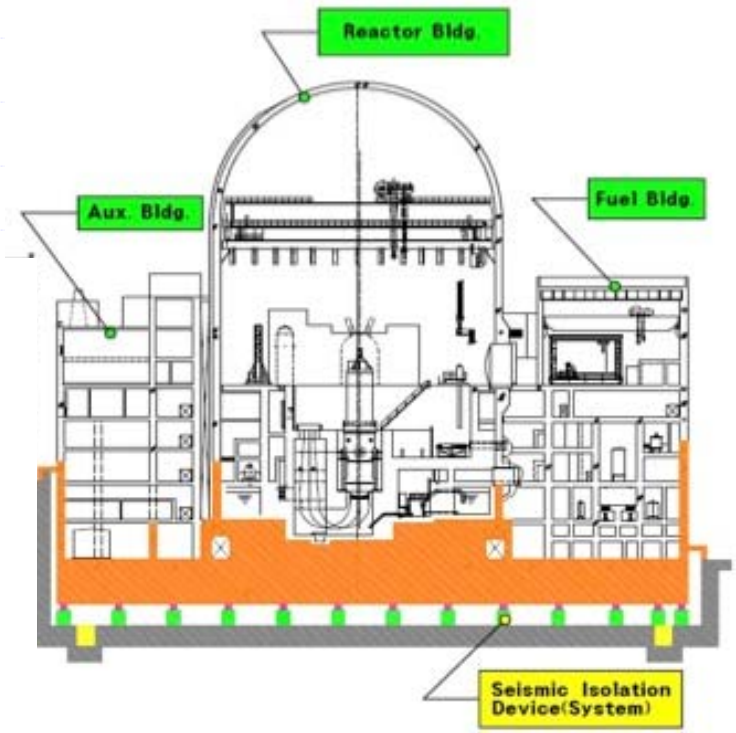
Outline

1. Motivation and Introduction
2. Project Scope PGSFR
3. Project Scope APR1400
4. Selected Analytical Findings
5. Experimental Test Program
6. Hybrid Simulation Test Results
7. Characterization Test Results
8. What is needed next?

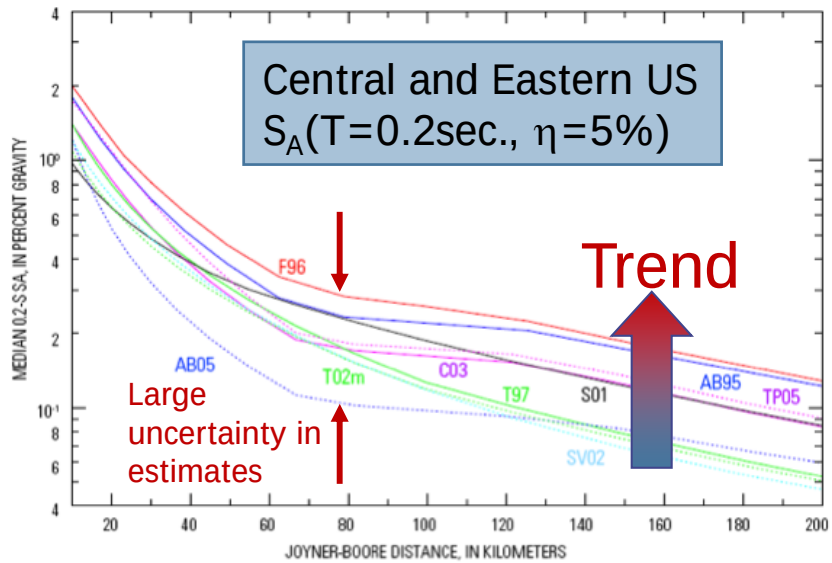
Motivation for Seismic Isolation

- Seismic isolation is one of the most efficient solutions to reduce the dynamic response of buildings and other structures to seismic events
- Flexible isolation devices are placed beneath the super-structure to decouple the ground movement from the superstructure movement
- Very effective way to protect the superstructure from earthquake hazards and reduce seismic demands in the NPP superstructure



Motivation for Seismic Isolation

- Substantially reduce demands and increase safety margins for new types of structures and new mechanical systems and components (SFR)
- Provides ability to use standard plant designs in areas with higher seismic hazards
- Enable plant to adapt to changes in seismic hazard
- Can accommodate new reactor technologies
- Facilitate restoration of operations and resumption of revenue generation following significant seismic events



Very firm rock conditions (from Mark Peterson, USGS)

UCB Work on SI of Critical Facilities

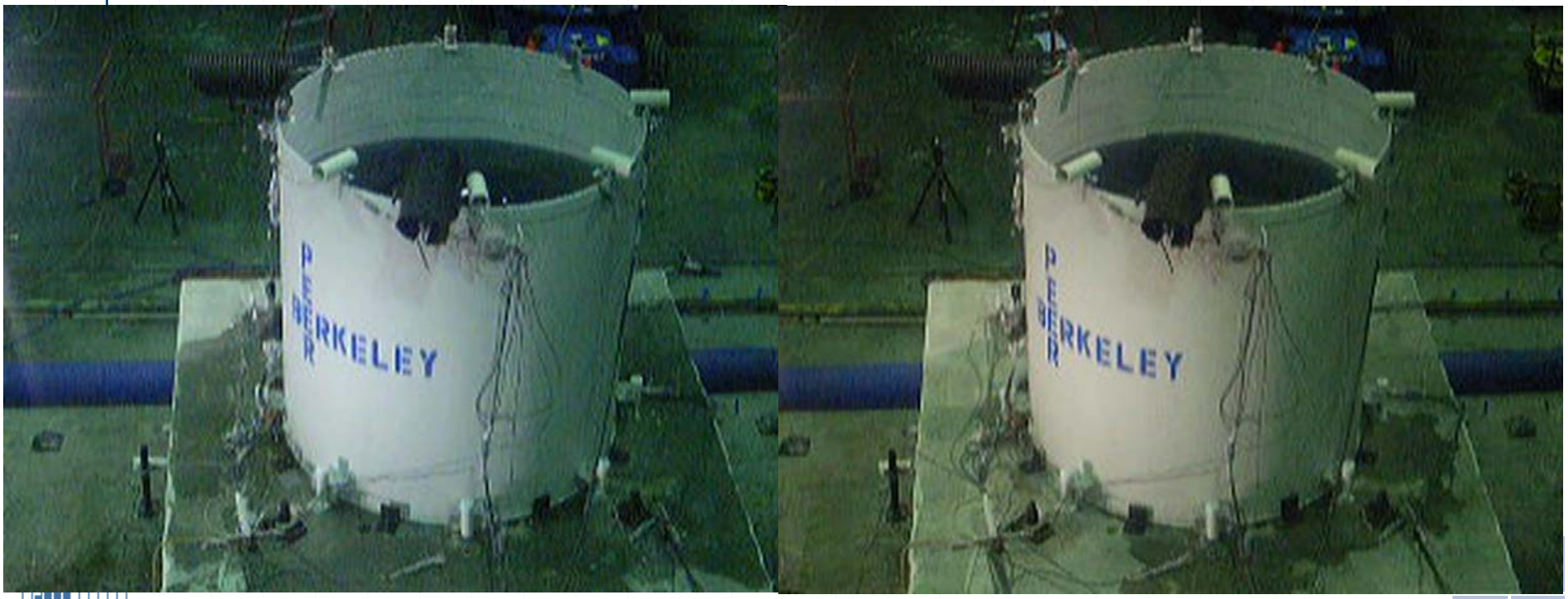
- Long history of innovation, research, guideline development and application
  - Jim Kelly, Steve Mahin, others
- Nuclear facilities
  - Jim Kelly and others were very involved in 1980s in developing ideas for seismic isolation of LMFBRs with various NRB, LRB and HDR bearings
- 2010+
  - EPRI
  - KEPCO (APR 1400 and PGSFR)
  - IAEA (Hybrid Simulation to validate concepts)

Research on Industrial Structures

SI of Fluid Storage Tanks

Seismic isolation may increase long-period content of motions in structures, and this may effect some components (e.g., fluid storage tanks, cranes, piping systems, etc.)

Recent work focuses on LNG tanks.



Fixed Base Isolated

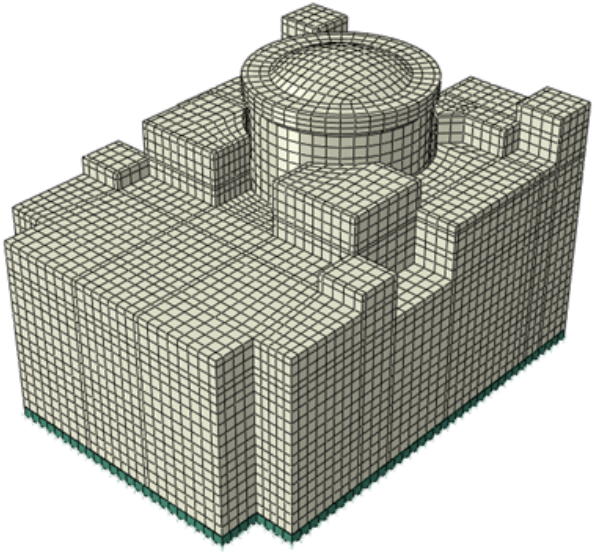
Calagaru and Mahin, 2013

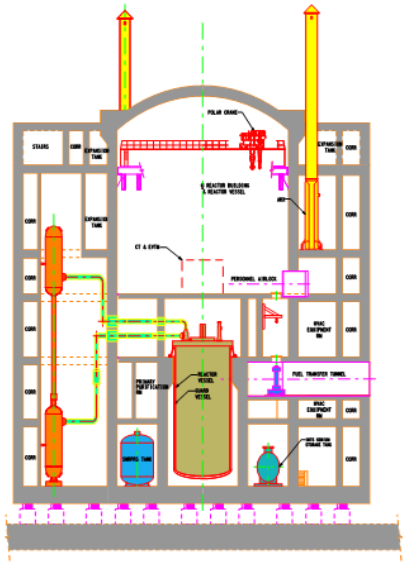
Current Hybrid Shake Table Studies

LRB and TP friction bearings, using hybrid shake table to assess effects of SSI, multidirectional input, bearing stability, and hard stops on response

Project Scope for PGSFR Study

- KEPCO E&C is involved in the development of a Prototype Gen-IV Sodium-Cooled Fast Reactor (PGSFR)

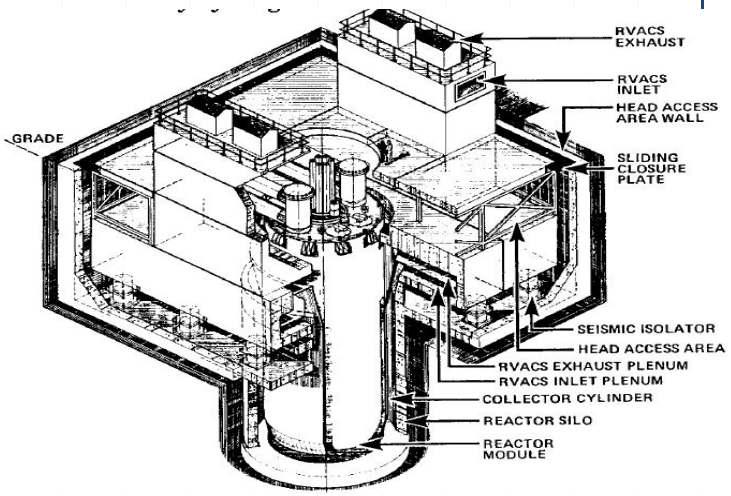




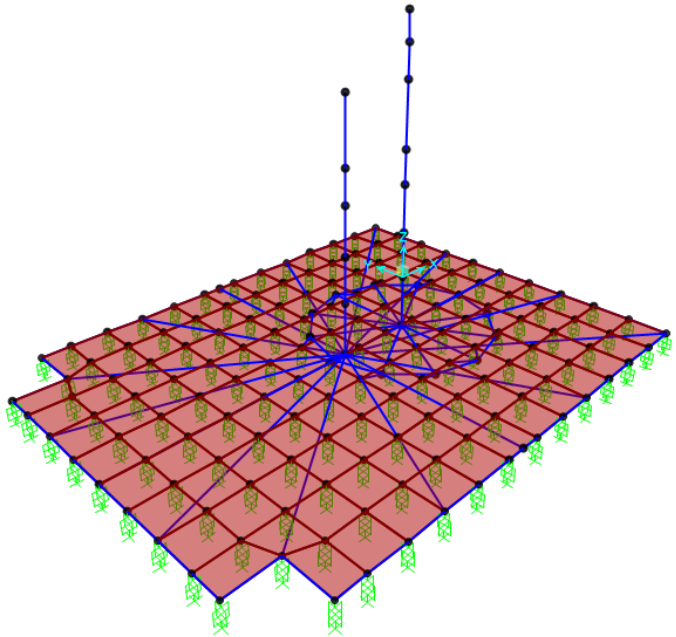
- PEER assembled a panel of experts in earthquake engineering, structural dynamics, nuclear engineering, risk assessment, aircraft impact, and construction to provide technical consultation on the seismic isolation design and aircraft impact analysis of the PGSFR

Project Scope for PGSFR Study

- PEER performed an extensive literature survey on past work related to seismically isolated Fast Breeder Reactors
- To support design efforts by KEPCO E&C, PEER conducted preliminary dynamic studies to evaluate the behavior of the isolated PGSFR when subjected to seismic and aircraft impact loading conditions
- Assess findings and identify research items that should be considered in future phases of the overall project

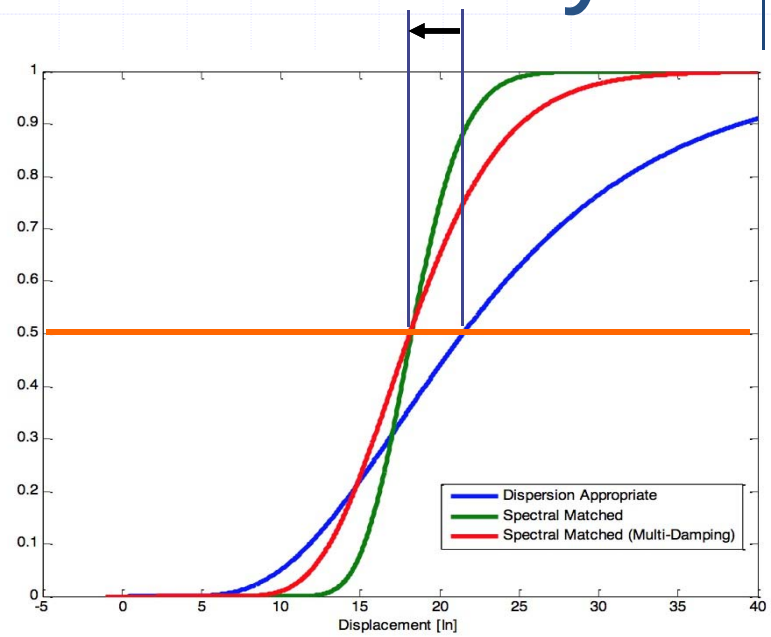


PRISM (Tajirian and Kelly 1990)

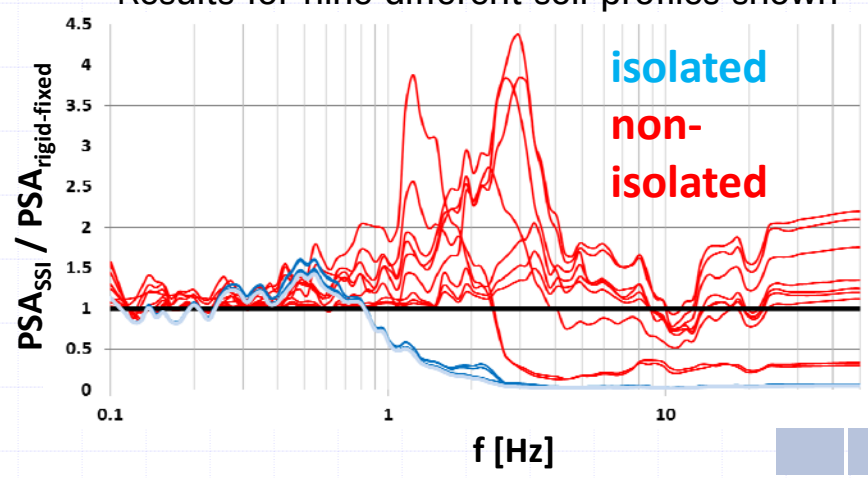


Project Scope for APR1400 Study

- Ground motion selection consistent with practice, and guidance by NRC and others
- Modeling of isolation bearings and isolated systems (focus on traditional models)
- SSI (comparing/improving models and results: frequency domain vs. NLRHA)
- Dynamic analyses of APR 1400 with and without SSI focusing on DBE (NRC & EUR GMRS)

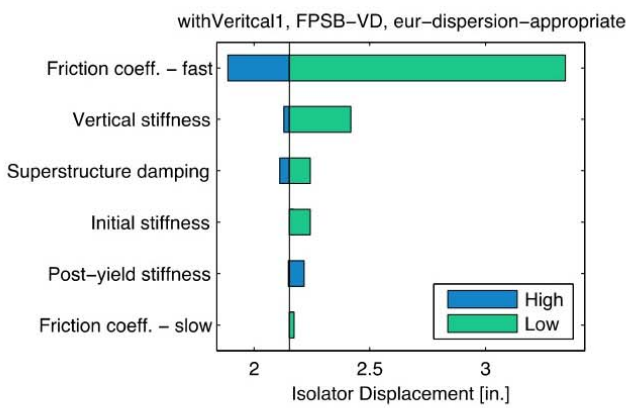


Results for nine different soil profiles shown

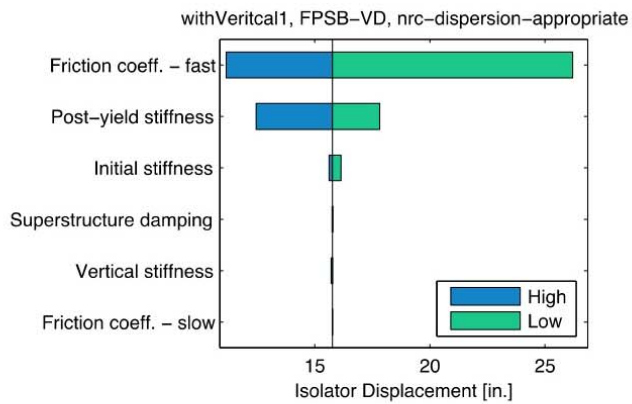


Project Scope for APR1400 Study

- Large scale sensitivity study (without SSI)
- Parametric studies for Beyond Design Basis Events (near-fault pulses, long duration motions, impact vs. isolator/umbilical capacities, vertical excitation)
- Preliminary aircraft impact analysis
- IAEA WG2.3 benchmark analyses
- Hybrid simulation tests of full-size candidate bearings



(a) FBRF – EUR dispersion-approp.



(b) FBRF – NRC dispersion-approp.

Fig. 3.20 **Median peak isolator displacement of the center bearing for the two ground motion sets.**

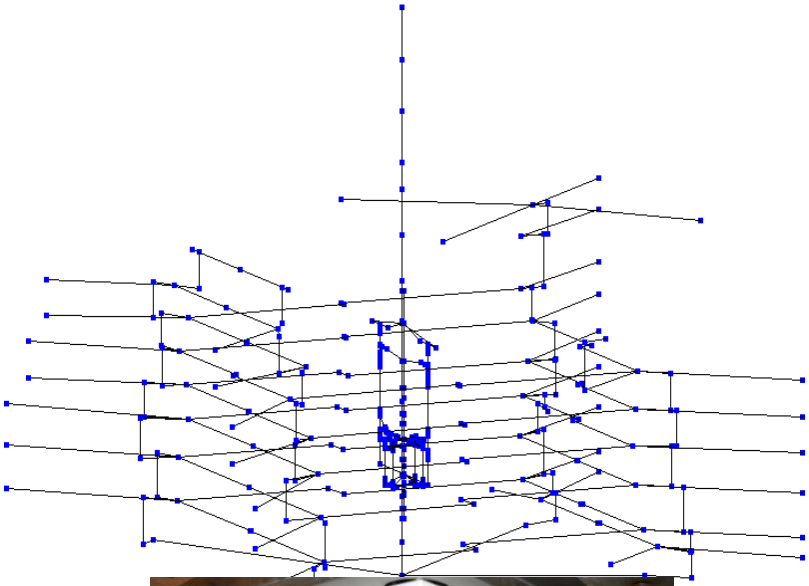
PEER

Motivation for Hybrid Testing

- On a shaking table the testing of large structures such as NPPs is impractical due to the size, weight and strength limitations imposed by the simulator platform
- Using hybrid simulation
  - The linear-elastic plant superstructure can be modelled analytically
  - Only the nonlinear isolator behavior needs to be tested physically
  - Large axial loads due to gravity and axial load fluctuations due to overturning and vertical input can be captured
- Need a testing facility that can be converted to perform real-time hybrid simulations on large full-scale isolators

Hybrid Simulation Concept

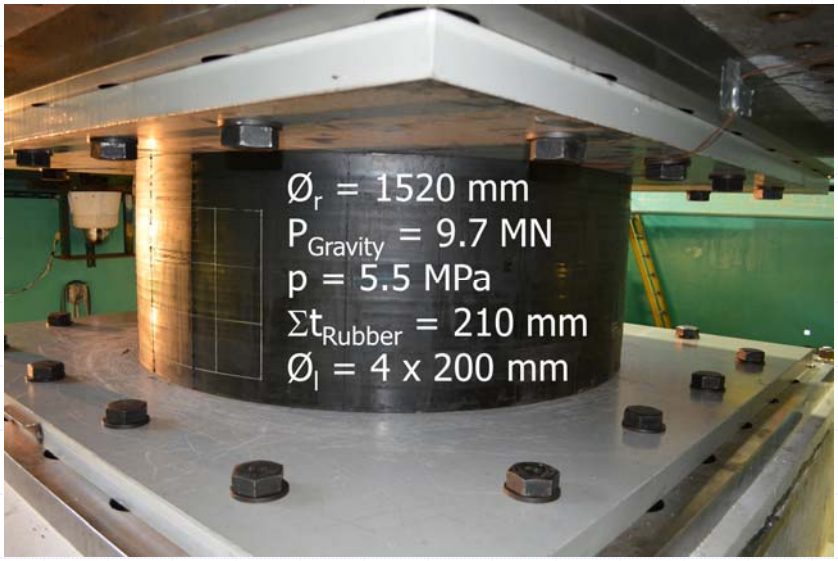
$$\mathbf{M}\cdot\ddot{\mathbf{u}}+\mathbf{C}\cdot\dot{\mathbf{u}}+\mathbf{P}_{\mathbf{r}}\left(\mathbf{u},\dot{\mathbf{u}},\ddot{\mathbf{u}}\right)=\mathbf{P}\left(t\right)$$

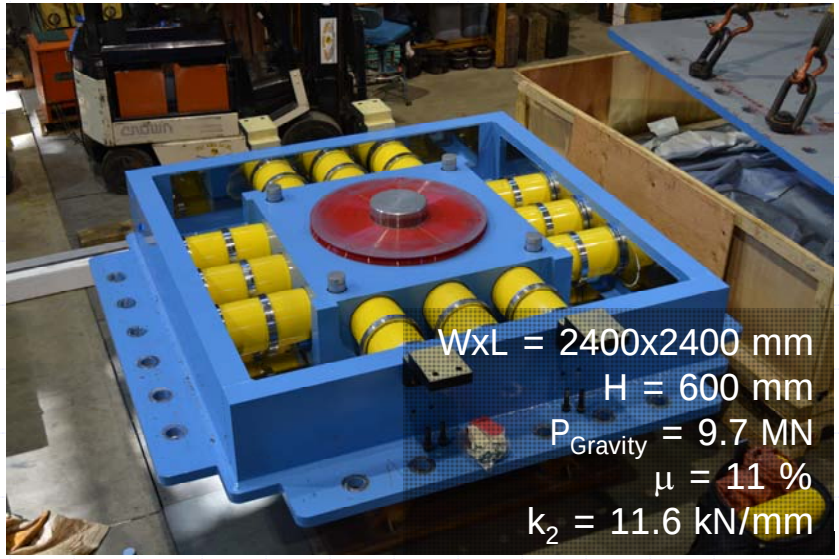


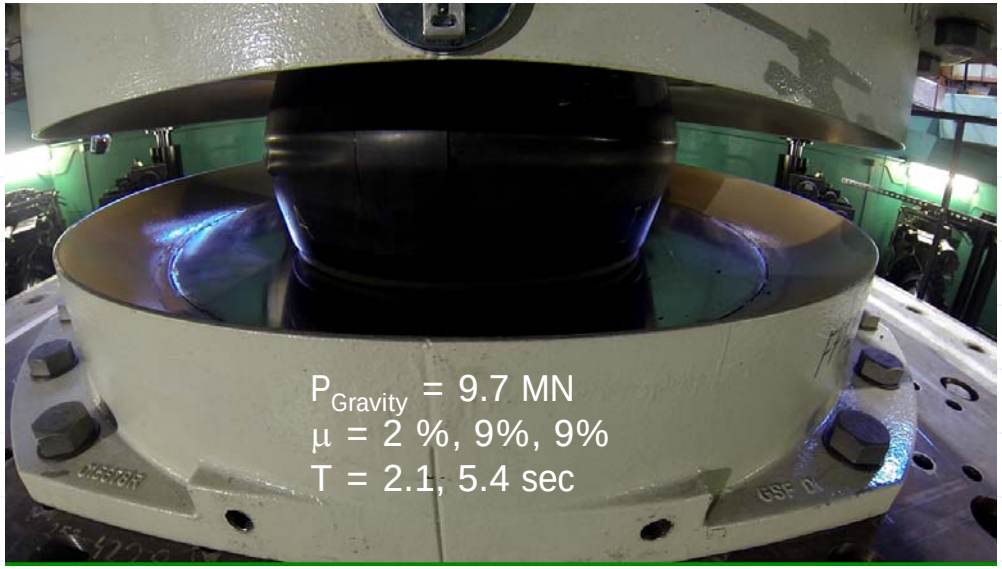
Prototype Structure

Korean Advanced Power Reactor (APR1400)

Three Bearing Designs

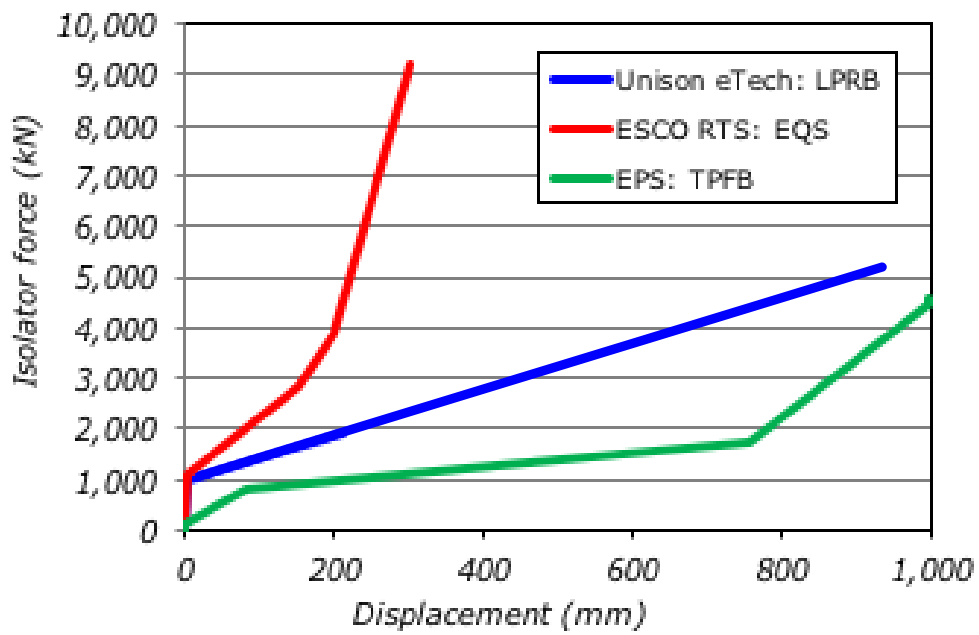




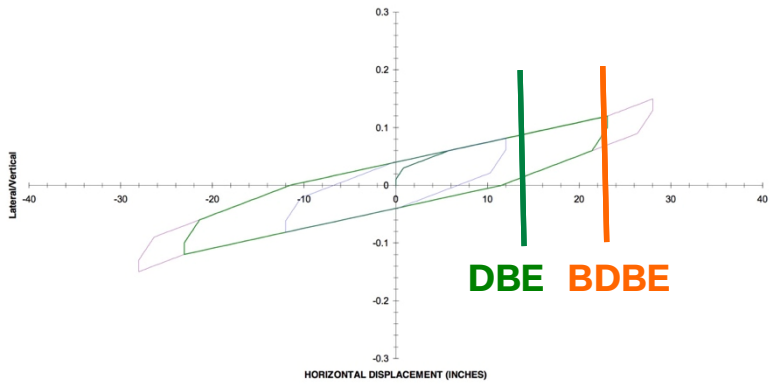


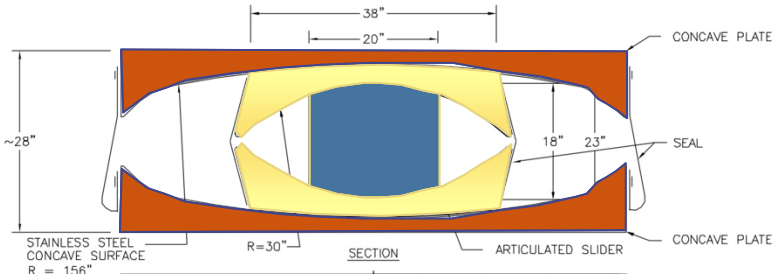
Three Bearing Designs

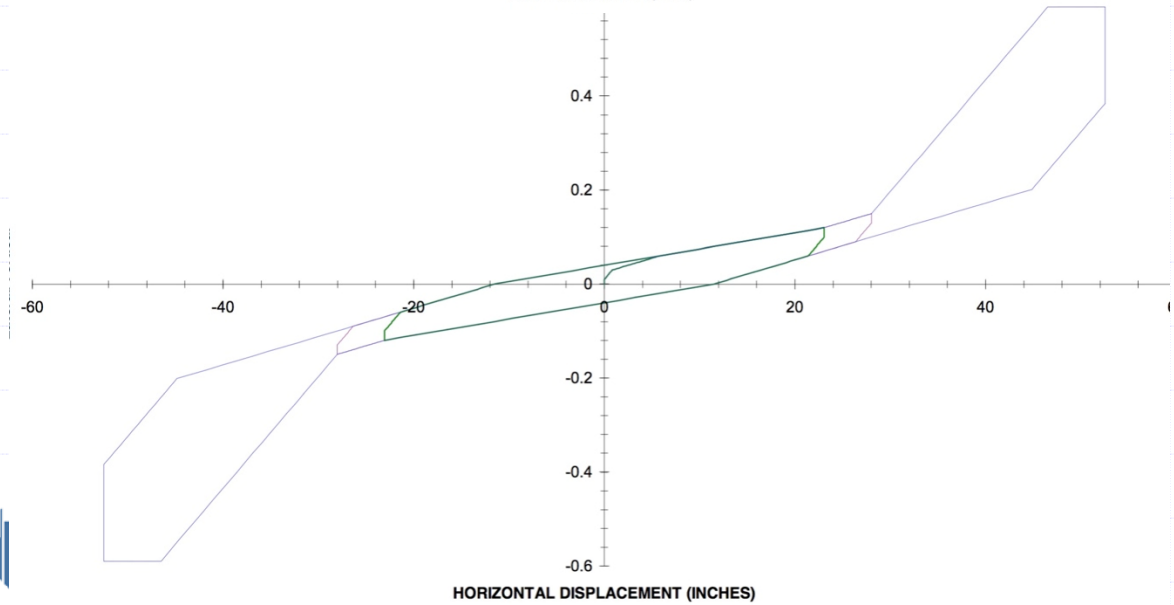
Isolation bearing	Design displacement, D_d (mm)	Lateral force at D_d (kN)	Q_d (kN)	Plan dimension (mm)	Height (mm)
Unison eTech (LPRB)	210	1,900	1,010	1,520	533
ESCO RTS (EQSB)	152	2,920	1,090	2,900	607
Earthquake Protection Systems (TFPB)	584	1,510	730	1,980	711



Built-in soft stop for large events



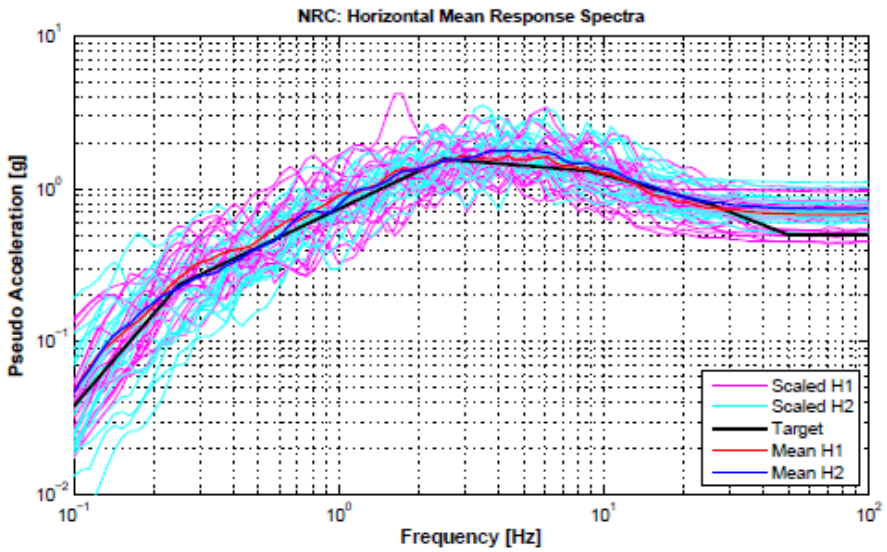


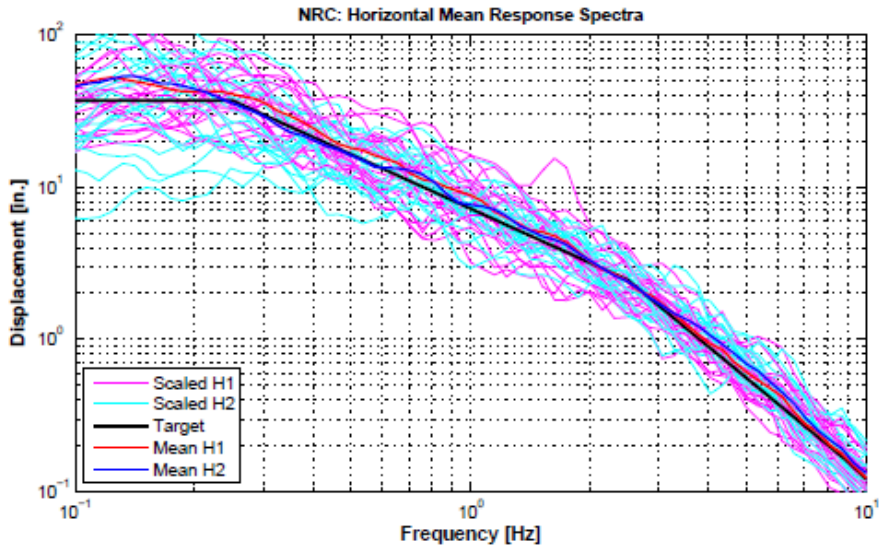


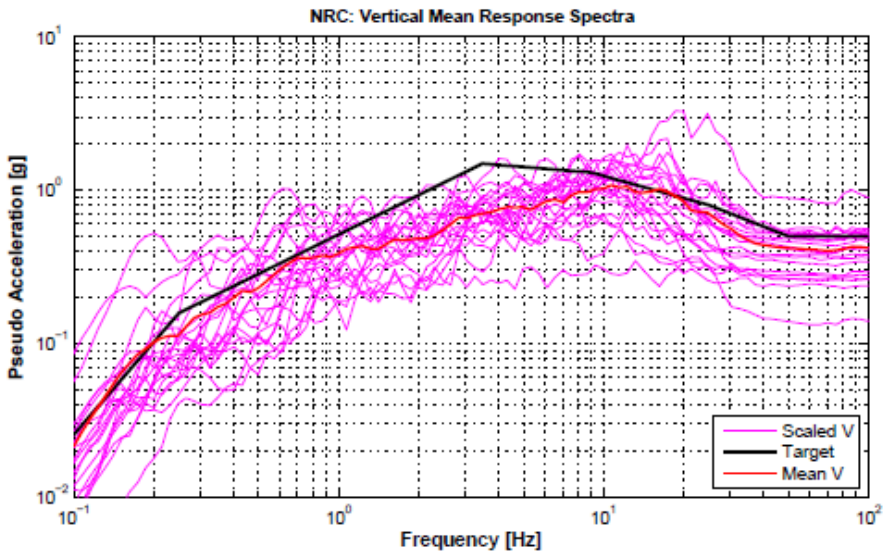
To accommodate bigger events, one can:

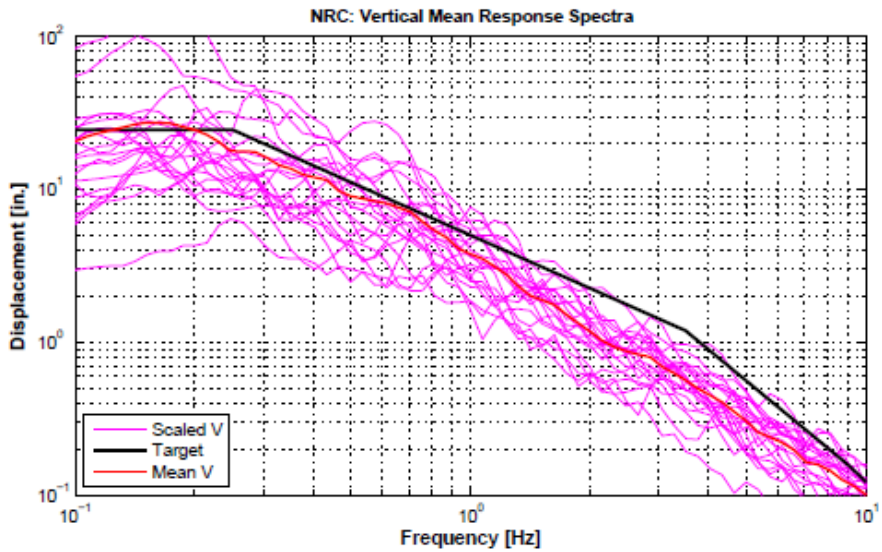
- Use larger displacement capacity bearings
- Increase deformation hardening capabilities of bearing to slow bearings
- Use hard stop
- Use combination of hard stop with cushioning to slow impact effects.

NRC Set: Response Spectra









NRC RG1.60: Spectral Matching

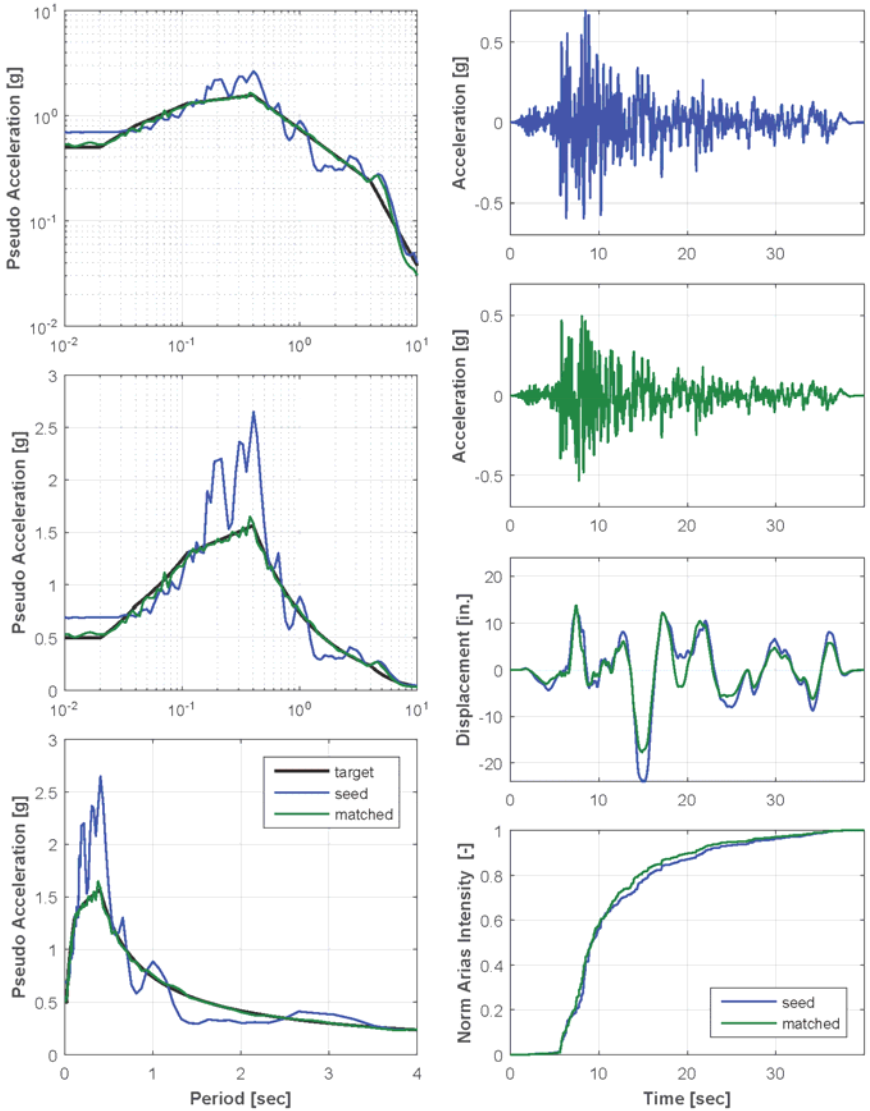


Figure NRC-REC03-A: Spectral Matching and Time Series, NRC RG1.60
Ground Motion: REC03
Component: 1

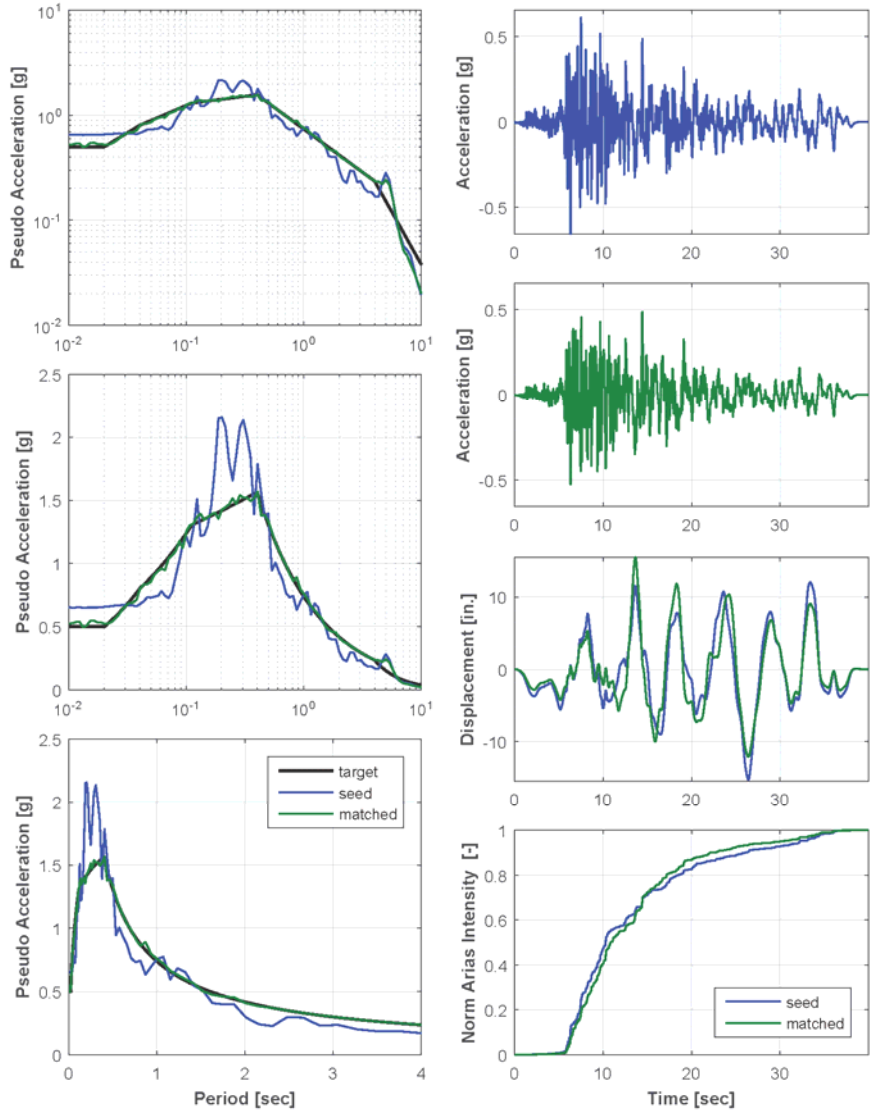
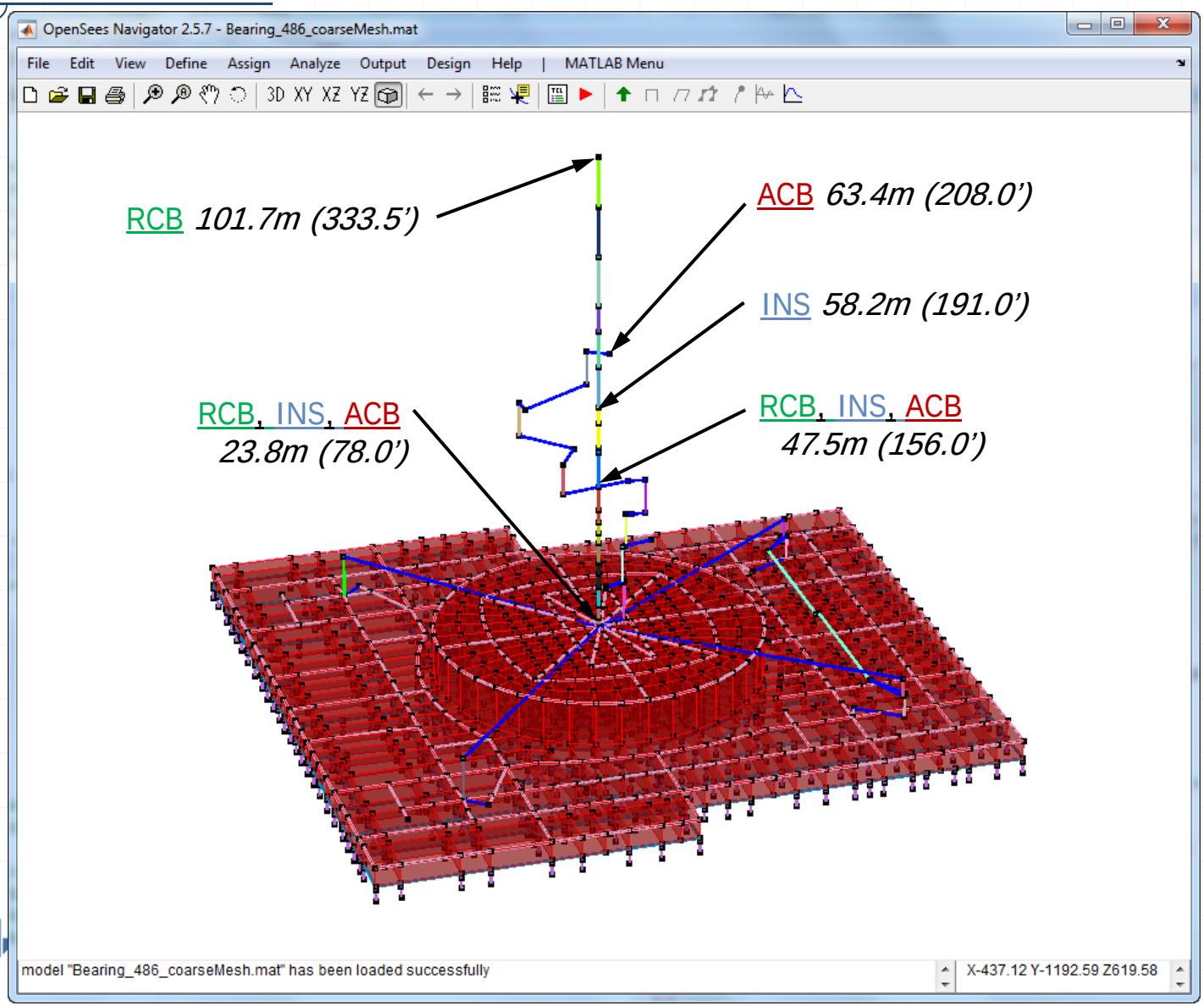
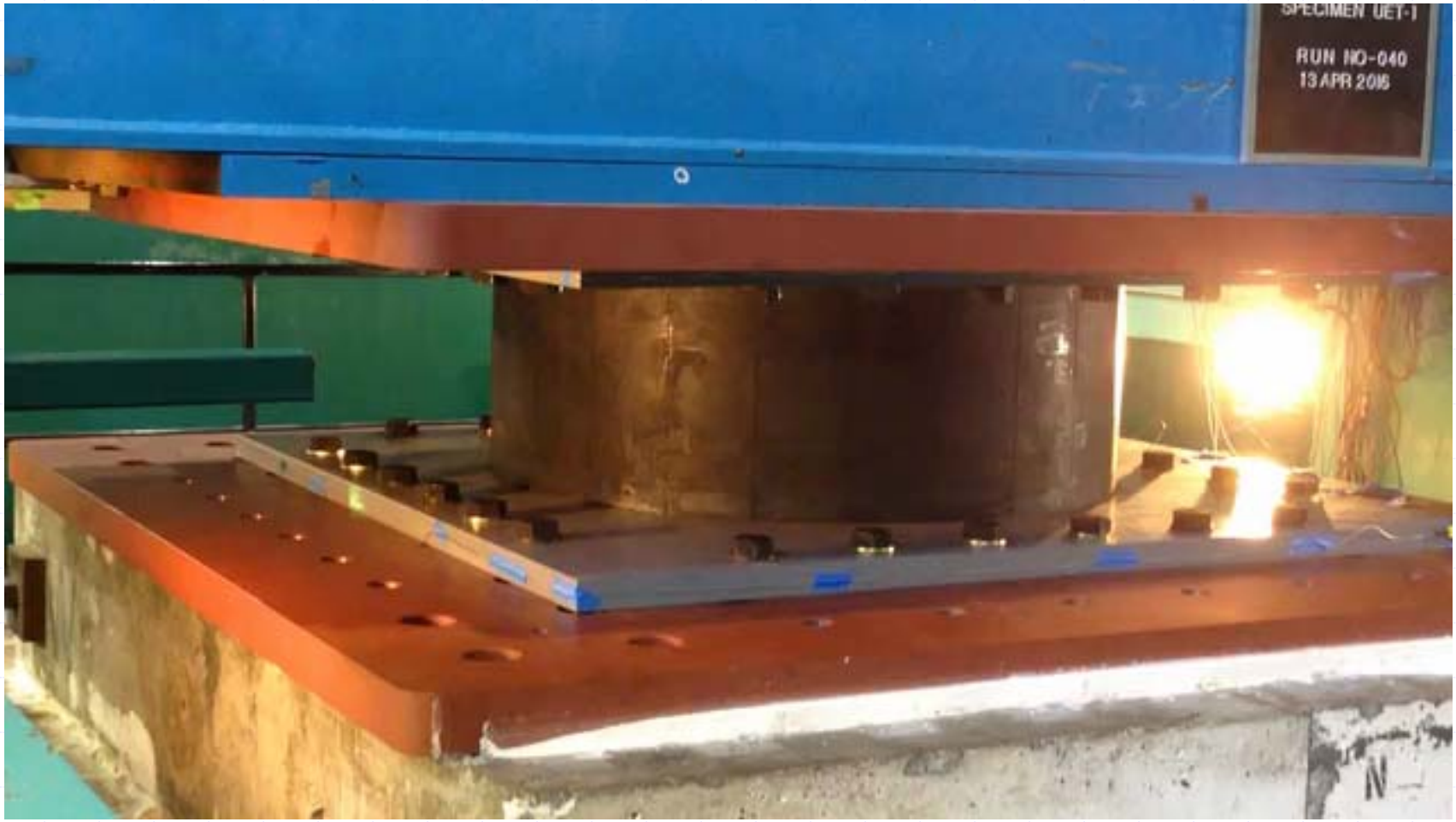


Figure NRC-REC03-B: Spectral Matching and Time Series, NRC RG1.60
Ground Motion: REC03
Component: 2

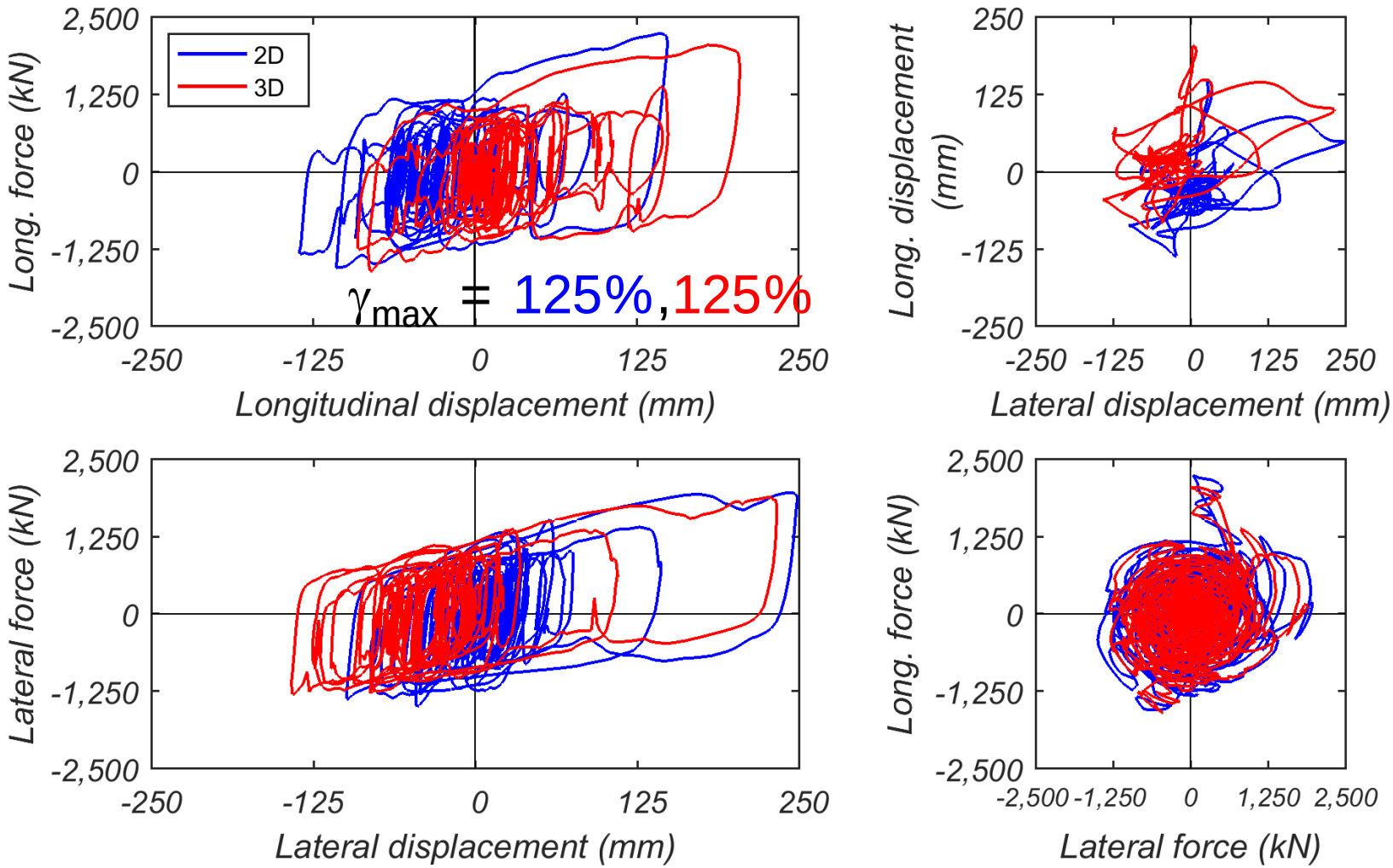
Result output locations



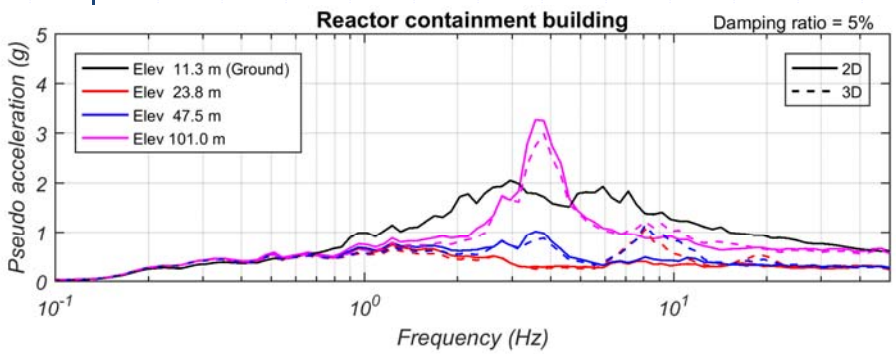
2D Hybrid Simulation (LPRB)

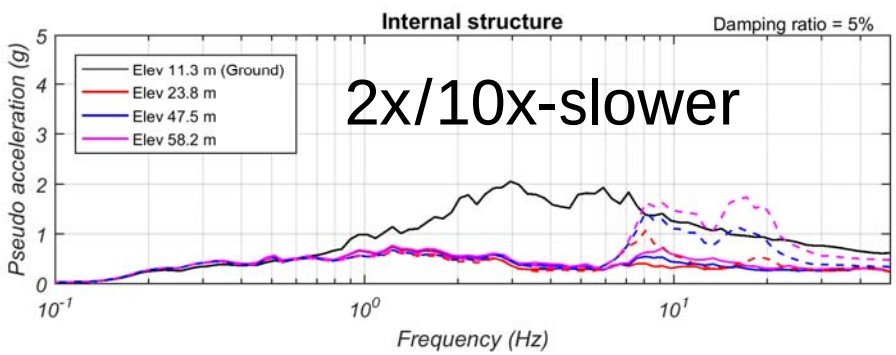


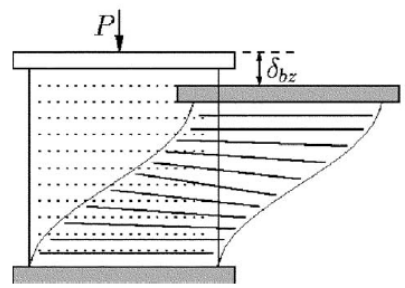
2D 2x-slower vs. 3D 10x-slower (LPRB)

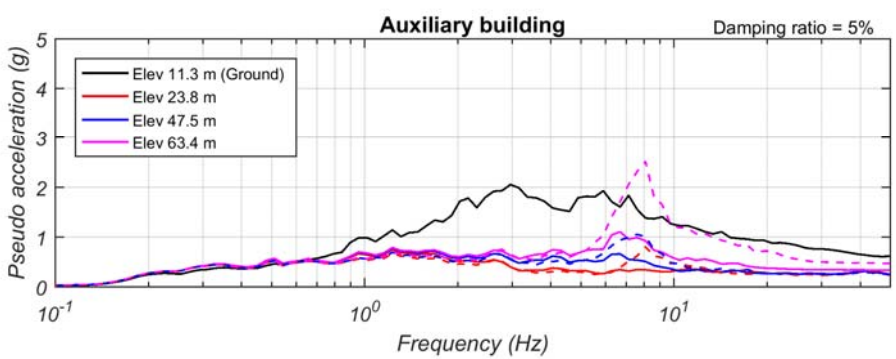


2D vs. 3D (LPRB)

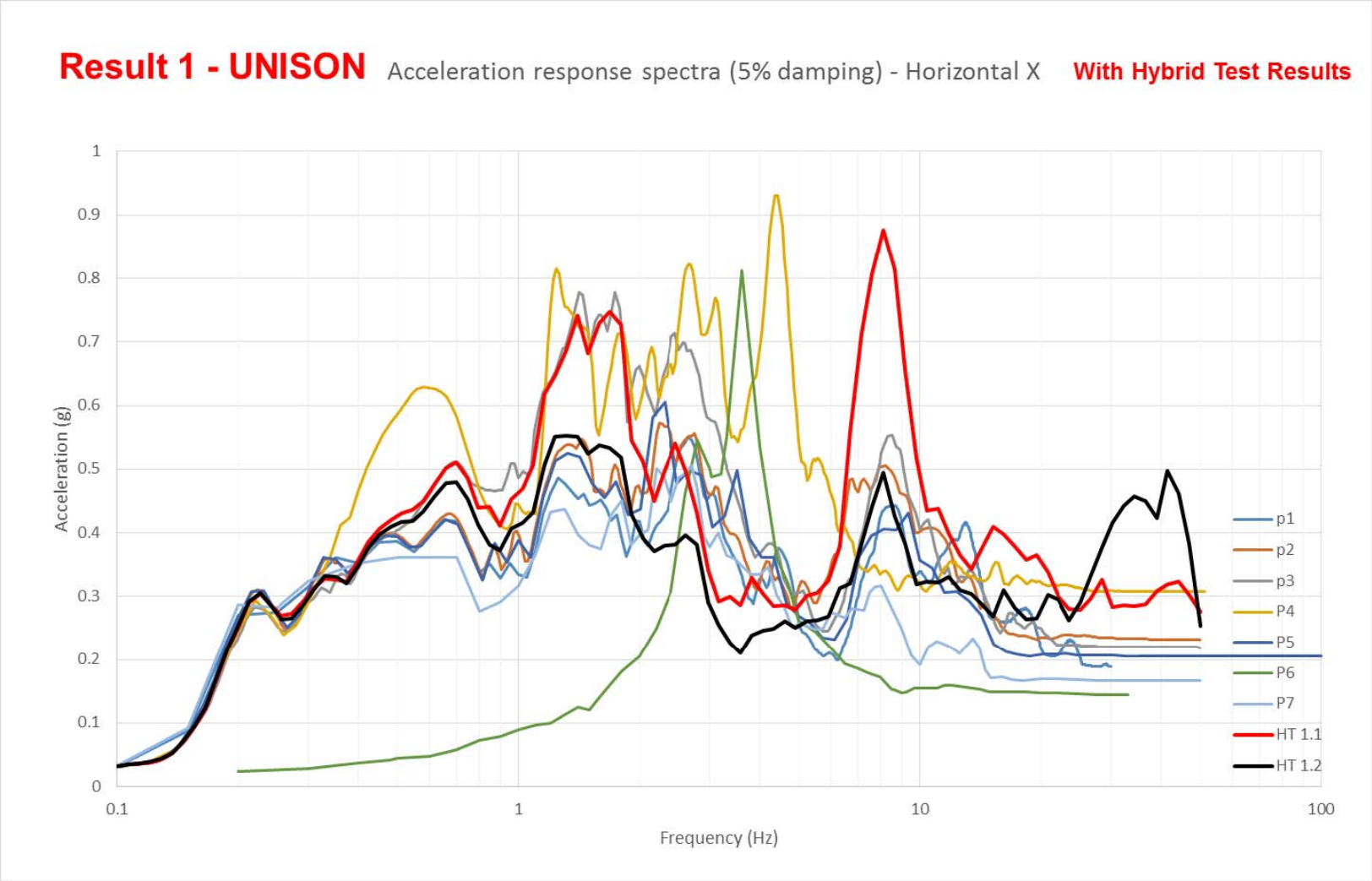

Reactor containment building
Damping ratio = 5%
Elev 11.3 m (Ground)
Elev 23.8 m
Elev 47.5 m
Elev 101.0 m
2D
3D
Pseudo acceleration (g)
Frequency (Hz)


Internal structure
Damping ratio = 5%
Elev 11.3 m (Ground)
Elev 23.8 m
Elev 47.5 m
Elev 58.2 m
2x/10x-slower
Pseudo acceleration (g)
Frequency (Hz)

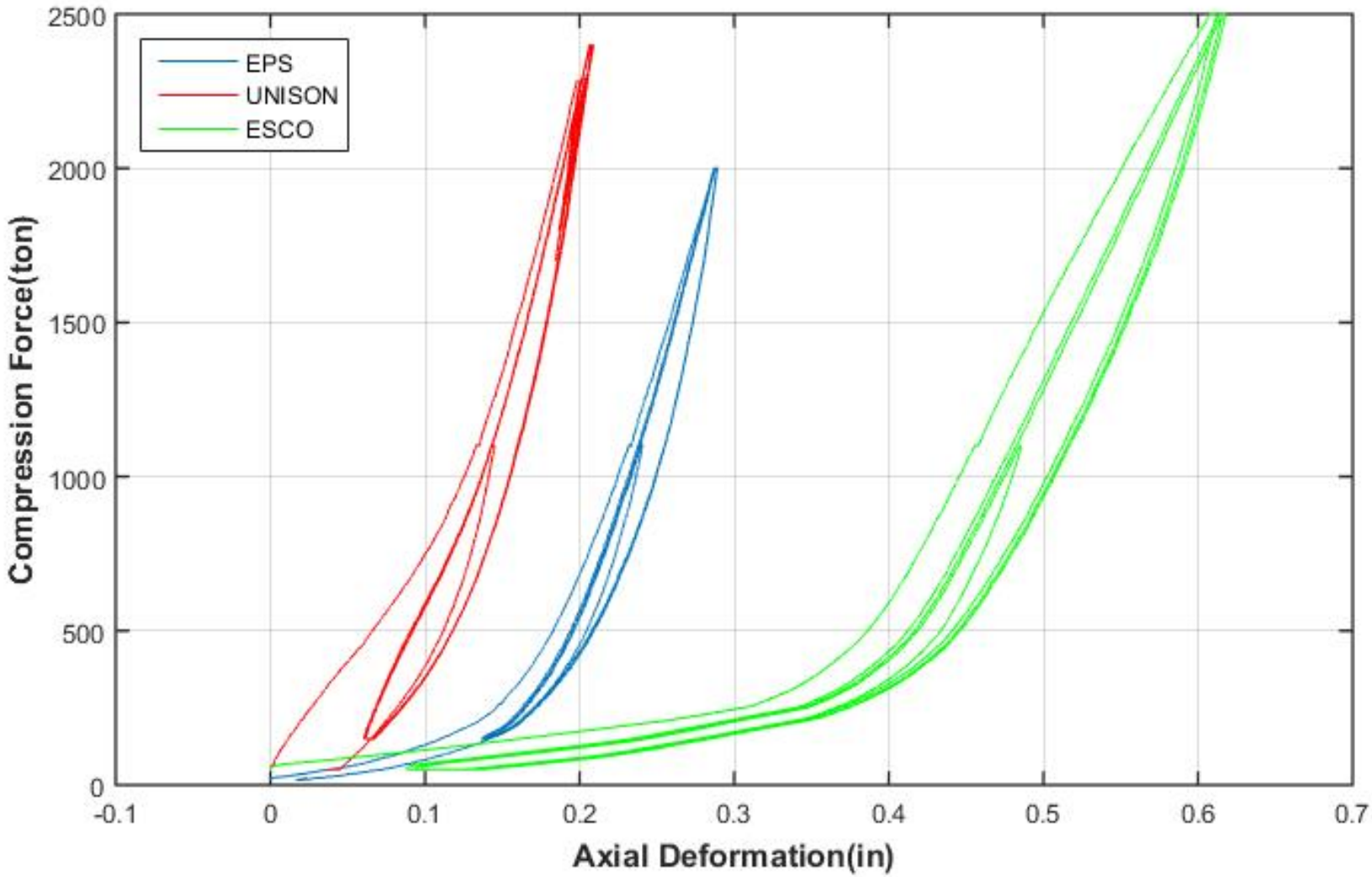

P
δ_{bz}


Auxiliary building
Damping ratio = 5%
Elev 11.3 m (Ground)
Elev 23.8 m
Elev 47.5 m
Elev 63.4 m
Pseudo acceleration (g)
Frequency (Hz)

IAEA WG2.3 Benchmark Analyses



Axial Response under Compression



Failure Test (LPRB): $\gamma_{failure}$ = 430%

Experimental Testing Summary

- The SRMD bearing test machine was successfully converted to perform rapid (3D) and real-time (2D) hybrid simulation tests for large hybrid models with full-size experimental bearings.
- It was demonstrated that it is possible to use a high-performance computing platform with parallel processing capabilities (OpenSees*SP*) to perform real-time hybrid simulations of large structures with many DOFs, such as nuclear power plants.
- The real-time execution of the hybrid simulations had a moderate effect on the hysteresis loops of the LPRB and TFPB but a significant effect for the EQSB.
- All three bearing types showed substantial vertical–horizontal coupling behavior which affected horizontal floor response spectra.
- Numerical bearing models should thus capture rate, temperature and vertical-horizontal coupling effects.

What is needed next?

- Perform beyond design basis experimental tests to study bearing and plant behavior in these extreme conditions (only need limited additional funding to complete this!)
- Based on the test results, develop analytical bearing models to capture the isolator behavior near failure
- Improve numerical bearing models to include temperature effects, vertical-horizontal coupling effects and static vs. dynamic friction effects (including adhesion)
- Further investigate plant and bearing behavior for larger than expected loading conditions (including moat wall impact and how to slow down the plant to reduce the super structure response at impact)
- Investigate the effect of subduction zone events in terms of the behavior of the isolators under severe long duration motions and determine the adequacy of numerical bearing models to capture such effects
- Perform further studies on pulse/near-fault effects

What is needed next?

- Further investigate 3D isolation concepts
- Most importantly, the analytical and experimental studies confirmed that seismic isolation is very effective in reducing in-structure response and increasing safety margins.
- To gain more experience, it should therefore be applied to other power plant structures such as EOB and similar buildings.

Questions?
Discussion