Risk-informed design of seismic isolation systems for nuclear facilities

Andrew Whittaker, Ph.D., S.E.
Professor and Chair
Director, MCEER
Department of Civil, Structural and Environmental Engineering
University at Buffalo
Outline

• Regulatory guidance for seismic isolation
  – Performance expectations
  – DOE and NRC commonalities
  – US seismic isolation hardware
• Risk calculations in DOE and NRC space
• On-going nuclear-related studies
Earthquake simulators

- Two high-performance simulators
- 7m by 7m platforms
- Located in a trench
- 50T payload/simulator
- 0 to 50 Hz at 50T
- Equipment qualification
  - 6 components of input
  - Substation equipment; A/E/M/P systems; NPP; tanks
  - IEEE 693, AC 156, GR 63 Core, NQA-1
Geo laminar box

- 1D input
- 6m tall; 5m by 2.7m in plan; 80m$^3$ of soil
- Instrumentation
  - Shape arrays
  - Acceleration, displacement
- Soil-foundation interaction
- Soil-structure interaction
- Validation of numerical codes
  - Site response
  - SSI
Nonstructural simulator

- Two-level systems
- Large displacement (± 1m), high velocity (2.5 m/s), frequency (5 Hz)
- Impose acceleration and drift histories simultaneously
- Systems of acceleration and displacement-sensitive components
- Derive fragility functions
- Tested to date
  - Non-load bearing walls
  - Piping systems
  - Hybrid nonstructural systems
Actuators

• Three dynamic
  – 100T, 1.5m/sec, ±0.5m
• Two static
  – 200T, ±0.5m
• Strong wall, floor
• Tests to date
  – Steel, SC and concrete walls
  – Steel braced frames
  – Hybrid simulations
Regulatory guidance for isolation
Seismic isolation
Regulatory guidance for isolation

- ASCE 4-14, Chapter 12: analysis, design, testing
- ASCE 43-**, Chapter 10: design, testing
- Seismic isolation NUREG
- Horizontal isolation only
- *Surface*-mounted nuclear facilities
- Prequalified seismic isolators: LRB, LDRB, FPB
- DOE and NRC provisions applicable in principle to
  - Components and systems
  - Deeply embedded facilities
  - Small modular reactors
  - Three-dimensional isolation systems
- Prequalification of alternate systems
Regulatory guidance for isolation

• Performance expectations of ASCE 43, SDC 5
  – FOSID at MAFE = E-5
  – DBE = DF * UHS at E-4 = GMRS
  – 1% NEP for 100% DBE shaking
  – 10% NEP for 150% DBE shaking
• Analyzable for beyond design basis loadings
  • Definitions differ for DOE and NRC applications
• Reliable numerical models of isolators
  – Validated by full-scale dynamic testing
• Modeling and analysis of isolated structures
• Prototype and production testing
Regulatory guidance for isolation

• Fully coupled, nonlinear time-domain
  – Soil (LB, BE, UB), isolators, SSCs
  – ABAQUS, LS-DYNA, NRC ESSI
  – Used for all types of isolators
  – 3D soil domain, domain reduction method
  – Apply ground motions at boundary of model

• Full coupled, frequency domain
  – LDR bearings

• Multi-step
  – Frequency domain analysis to compute SIDRS; equivalent linear models of isolators
  – Ground motions matched to SIDRS
  – Nonlinear analysis of isolated superstructure
Regulatory guidance for isolation

• Performance statements
  • Isolators suffer no damage in the DBE
    • Confirm by testing all isolators
  • Isolated facility impacts surrounding structure
    • 1% NEP for DBE shaking; 10% NEP for BDBE shaking
  • Isolators sustain gravity and earthquake induced axial loads at 90%-ile BDBE displacement
    • Confirm by prototype testing
  • Safety-critical umbilical lines sustain 90%-ile BDBE displacement with 90% confidence
    • Confirm by testing and/or analysis
Regulatory guidance for isolation

• Prototype tests
  – 3 minimum of every type and size
  – Dynamic tests to interrogate isolator behavior
    • Design basis and beyond design basis
    • Clearance to the stop (CS)
    • Cycles consistent with EDB shaking demands
  – Damage acceptable for CS tests

• Production tests
  – Isolators identical to prototype isolators
  – QA/QC testing of all isolators
  – Static or dynamic tests
    • Design basis loadings
  – No damage acceptable for design basis tests

• ASME-NQA-1 quality program, or equivalent
Isolators and isolation systems

• Addressed for US practice
  – Low damping natural rubber
  – Lead-rubber
  – Spherical sliding (FP) bearing

• Acknowledged in the NUREG/ASCE 4/ASCE 43
  – High-damping rubber
  – Synthetic rubber (neoprene)
  – EradiQuake
  – 3D isolation systems
Isolators and isolation systems

• Procedures and rules for
  – Low damping natural rubber
  – Lead-rubber
  – Friction Pendulum type

• Stable, predictable hysteresis
Isolators and isolation systems

• Developments funded by USNRC
  – Focus on behavior under extreme loadings

• Verified and validated models per ASME
  – OpenSees, ABAQUS and LS-DYNA
  – Friction Pendulum bearing
  – Low damping rubber bearing
    opensee.berkeley.edu/wiki/index.php/ElastomericX
  – Lead rubber bearing
    opensee.berkeley.edu/wiki/index.php/LeadRubberX
  – High damping rubber bearing
    opensee.berkeley.edu/wiki/index.php/HDR
Risk calculations
Sites of nuclear facilities in the US
Sites of nuclear facilities in the US

- Return periods for $S_a$ at 1 s
Seismic hazard curves
Seismic hazard curves

• Defined as multiples, $m$, of GMRS+
  – Computed in terms of average of multiples of spectral ordinates at 1 s and 2 s
  – $DF = 1$
Median fragility curves: NRC space

• Isolation system and individual isolators
  – Assumed fully correlated
  – Lognormal distribution parameters
  – Variability small for high quality isolators
  – Median 110% EDB GMRS displacement ≥ 90th percentile EDB GMRS displacement
Risk calculations: NRC space
Risk calculations: NRC space
Median fragility curves: DoE space

- Isolation system
  - Assumed fully correlated
  - Lognormal distribution parameters
  - Variability small for high quality isolators
  - Median 165% (220%) DRS displacement = 90th percentile 150% (200%) DRS displacement
Risk calculations: DoE space
Risk calculations: DoE space
On-going nuclear-related studies

• PRA methodologies to address isolation
  – Huang et al. 2009, Lungmen NPP

• Nonlinear SSI analysis
  – Numerical and physical simulations
  – Hybrid simulations

• RC and SC shear walls
  – Design procedures and fragility functions

• Missile impact on RC and SC walls

• Isolation of components and subsystems
  – Integration with SSI
On-going nuclear-related studies

- Component isolation
  - 3D isolation possible
  - Component geometry and fragility
    - Different from LLWR
    - Isolator design for non-seismic fragility
  - Alternate isolator(s)
    - Family of component isolators
    - Extend Chapter 10(12) of ASCE 4(43)
    - Expand seismic isolation NUREG
  - Fully coupled time domain analysis
    - Seismic input filtered by structure
Acknowledgments

- Manish Kumar
- Michael Constantinou
- US Nuclear Regulatory Commission
- US Department of Energy
- Justin Coleman
- Annie Kammerer
- Jose Pires
- Robert Budnitz
- Jim Johnson
- Robert Kennedy
Isolators and isolation systems

• Qualification of *other* types of isolators
  – Dynamic testing of prototype isolators for BDBE demands
  – Development of V+V numerical models of the isolator capable of predicting response under extreme loadings
    • Isolator MUST be “analyzable” for extreme loadings
  – Basic chemistry, lab tests and field applications to show that mechanical properties do not change by more than 20% over design life
  – System level testing using 3D inputs
  – V+V of numerical tools to predict response of the isolation system