Developing New Regulatory Guidelines on Seismic Isolation of Japan and the US

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Japan Nuclear Energy Safety Organization (JNES)
T.Iijima, N.Takamatsu, H.Abe

United States Nuclear Regulatory Commission (U.S.NRC)
A.Kammerer, A.Whittaker, N.Chokshi
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IV. IAEA ISSC EBP Seismic (Base) Isolation Task
I. Background

- SI is an effective tool for improving seismic safety
  - Not only for high seismicity areas but middle/low seismicity areas as well
  - SI can be used for both buildings and equipment
- Effectiveness recognized in discussions at the 2010 Kashiwazaki International Seismic Safety Symposium and demonstrated in the March 11, 2012 earthquake in the good performance of the emergency response buildings in Fukushima Daiichi and Daini
- IAEA ISSC EBP is now developing a technical guidance document that will summarize Member States’ nuclear application and design experience
II. JNES Activities

Guidance Development

Technical Review Guidelines for Seismic Isolation Structures
II.1 BACKGROUND

  - Possibility of applying seismic isolation into NPP

- Achievements of seismic isolation research and development by industry-academia-government over the past two decades in Japan.

- Recognition of seismic isolation effectiveness against earthquakes at NPP sites. (Kashiwazaki-Kariwa NPPs, Fukushima NPPs)

Base-isolated Building at K-K Site
(Administration Building)
II.2 SUMMARY OF TECHNICAL REVIEW GUIDELINES

FEATURES OF THE GUIDELINES

- Covers all stages of NPP lifespan and all types of Seismic Isolation
  - Guidance for each stage of NPP life span: design, comprehensive safety evaluation, construction and operation
  - Guidance provided for both base isolation and equipment isolation to address the needs of both newly constructed and existing NPPs

- Scope of Applying Area
  - High Seismicity Areas: Improvement of seismic safety and cost
  - Moderate to Low Seismicity Areas: Standardization of seismic design for structures and equipment regardless of site condition
## APPLICATION OF EACH TYPE OF SEISMIC ISOLATION

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Plant Situation</th>
<th>Building Isolation</th>
<th>Equipment Isolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Type</td>
<td></td>
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</tr>
<tr>
<td>Existing</td>
<td>○</td>
<td>○</td>
<td>○</td>
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<tr>
<td>Newly Constructed</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Next Generation</td>
<td>Newly Constructed</td>
<td>○</td>
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</tbody>
</table>

- Diesel generator

Used for horizontal motions, vertical motions, or a combination of both.
DESIGN OF SEISMIC ISOLATION

(1) Requirements for Design Base Ground Motion

Basic Requirements

• DBGM is based on the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities. (September, 2006)
  - The earthquake ground motions to be formulated with and without the site specific epicenter

Additional Requirements
(consideration of the SI characteristics)

• to contain appropriate long period components corresponding the natural frequencies of base isolated structures
  - Horizontal 2 to 5 second, Vertical 0.5 to 1 second, in general
• to consider massive earthquake far from the site as needed
## (2) Requirements for Isolation Devices

<table>
<thead>
<tr>
<th>Isolation Device</th>
<th>Available Elements</th>
<th>Basic Function &amp; Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Isolator</strong></td>
<td>Rubber bearing</td>
<td><strong>Supporting Function</strong> to long term vertical load of superstructure and to maintain the function under the condition of horizontal deformation caused by earthquakes</td>
</tr>
<tr>
<td></td>
<td>Roller bearing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sliding bearing</td>
<td></td>
</tr>
<tr>
<td><strong>Damper</strong></td>
<td>Steel rod damper</td>
<td><strong>Damping Function</strong> to retain necessary damping capacity under design condition (displacement, velocity, etc)</td>
</tr>
<tr>
<td></td>
<td>Oil damper</td>
<td></td>
</tr>
</tbody>
</table>

### Design of Rubber Bearing

- In general, the rubber bearing should be used in linear range.
- Allowable design stress area of rubber bearing should be appropriately determined considering the characteristics of axial force – shear force relationship which is based on testing.

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### (3) Requirements for Seismic Isolation System

#### Design Seismic Force
- Design seismic force complying with seismic classification of structure/component is used.

#### Analysis Model
- Analysis model should be able to:
  - demonstrate response motion unique to base-isolated structures such as rocking motion
  - estimate seismic force, acceleration and displacement on the isolation devices, the superstructure and the substructure
- The properties of the isolation devise (stiffness, damping ratio, etc.) for analysis model should be:
  - based on tests of the devices
  - include the change due to environment conditions and aging.

#### Combination of Seismic Loads
- The horizontal and vertical seismic load should be combined by appropriate method considering the vibration characteristic of the base-isolated structures.

#### Other Consideration
- Reducing gap of centers of gravity and rigidity
- Interfaces between isolated and non-isolated structures
  - requirements for crossover components (ref. next slide)
- Other external load
  - wind, lightning, tsunami, flooding, fire, etc.
(4) Interfaces between Base-Isolated Structures and Non-Isolated Structures

Design of Crossover Component

- Crossover components must be appropriately designed and maintain required safety function against the design base earthquake with high confidence.

Available Measures for the Crossover Piping

routing arrangement, expansion joint

**Design of crossover piping**

- **S, B class**
  - Slender caliber?
    - Yes
    - high temperature & pressure
      - Yes
      - Flexible joint
    - No
  - No
- **C class**
  - Flexible joint
  - Layout types

**Shaking table test of piping**

simultaneous inputs of both horizontal and vertical vibration
(5) Combination of Loads and Allowable Limits

Combination of Loads

- Seismic loads and other internal loads (earthquake independent or dependent events)
  - The combination should comply with Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities. (September, 2006)

Allowable Limits

- Allowable design displacement limit of isolation device must be appropriately determined. Following methodologies are available;
  - Displacement limit based on the ultimate displacement of the critical component (isolation device, crossover component)
  - Displacement limit determined to make CDF and CFF satisfy the performance goal

- The allowable design limits of superstructures should comply with Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities. (September, 2006)
4. SEISMIC RISK ASSESSMENT

Recognition of Residual Risk

- In the case of applying base isolated structures, efforts must be made to reduce “residual risk” as much as possible.

Evaluation Methodology

- Seismic risks can be evaluated by probabilistic safety assessment methods, specifically, seismic PSA methodology is available.
5. CONSTRUCTION
Pre-Operation Testing
• Quality control for the procurement, production, inspection, installation, and testing of isolation devices shall be conducted
• Specific functions of isolation devices/system shall be checked in advance of operation.

6. OPERATION
Regular Inspection
• The Base-isolation structures shall undergo regular inspections.

Inspection Before Restarting
• Before restarting NPP after an earthquake, the inspection shall be conducted in order to confirm the performance of isolation devices/system.
  – presence of damage to isolation devices, pedestal, interfaces, etc.
  – current positions of superstructures
II.3 PROSPECTS FOR APPLYING SEISMIC ISOLATION INTO NPPs

- Utilities plan base-isolated administration building at NPP sites.
- NISA proposed thirty measures based on lessons learned from Fukushima nuclear accident in order to improve the safety of NPPs.
  - to improve seismic capacity of equipment related to external power (Measure No.2, 3)
  - to enhance multiplicity and diversity of emergency AC power (Measure No.7)

Emergency DG with Air Fin Cooler
Emergency Gas Turbine
III. US NRC Activities

• Background and regulatory activities
• Overview of the NUREG
• Proposed performance-based criteria
• Additional guidance on SI analysis, design, and operation
Background and Regulatory Activities

- 2008 NRC began new research in SI
- NRC research addressed key items
  - Vertical and beyond-design-basis loading
  - Development of performance-based criteria
  - Development of deterministic “rules of thumb” to meet performance criteria
  - New tools for numerical simulation
  - Testing of full size isolator systems at large loads on eDefence to confirm analysis tools and models
Background and Regulatory Activities

- Draft NUREG starting final review June 2012
- Many comments received internally and externally (currently being incorporated)
- Publication expected late 2012
- Additional research to be published as NUREG/CR reports
- Regulatory Guide on SI to be developed
Contents of the NUREG

- Introduction
- Brief History Of SI
- Basics Of SI
- Mechanics Of Isolators
- US Codes And Standards
- International Regulatory Guidance
- Modeling Techniques
- Performance Objectives and Acceptance Criteria
- Additional Recommendations
- References
Efforts for consistency between the US and Japan benefitted from a long-standing NRC-JNES bi-lateral cooperation program.

Designs that meet both sets of guidance can be developed.
Performance-based risk-informed approach

Considerations:

- The isolators cannot be allowed to fail and may not be in any realistic accident sequence.
- The SI system is a singleton with more stringent design criteria than conventional construction.
- The concepts of FOSID and HCLPF should be incorporated to the extent possible, recognizing that isolators are inherently non-linear.
- The extended-DBE concept discussed in the Near Term Task Force Report should be incorporated.
- The potential for cliff edge effects must be removed through use of a hard stop.
Performance-based risk-informed approach

Considerations:

• Assurance of performance incorporates both prototype and production testing to demonstrate quantifiable confidence levels and performance reliability.

• Guidance must consider how seismic isolation systems could fit within a certified design framework. (Design of the Basemat up is certified and isolators tuned to the site)

• The approach should be technology neutral enough to be extended to new designs, such as for small modular reactors.

• Realistic approaches for achieving clear and technically based performance targets should be described.
## Isolators and/or Isolation system

<table>
<thead>
<tr>
<th>Hazard and Associated Risk Parameter</th>
<th>Isolation unit and system design and performance criteria</th>
<th>Approach to demonstrating unit performance</th>
<th>Performance expectations</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMRS+</td>
<td>100% confidence in the isolators achieved through production testing of each isolator</td>
<td>Super structure and internals designed to ISRS from the DBE ground</td>
<td>moat sized for &lt;1% prob. of impact</td>
</tr>
</tbody>
</table>

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.
<table>
<thead>
<tr>
<th>Hazard and Associated Risk Parameter</th>
<th>Isolators and/or Isolation system</th>
<th>Super-structure</th>
<th>Connections/umbilicals</th>
<th>Moat/Hard Stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation unit and system design and performance criteria</td>
<td>Approach to demonstrating unit performance</td>
<td>Performance expectations</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Extended DB GMRS</strong></td>
<td><strong>90% confidence in each isolator achieved through prototype testing to the CHS displacements</strong></td>
<td><strong>&gt;90% confidence in umbilical functionality</strong></td>
<td><strong>&lt;10% chance of structure impacting moat</strong></td>
<td><strong>moat designed for EDB impact loads</strong></td>
</tr>
</tbody>
</table>

4) The analysis can be performed using a single composite spectrum or separately for the 10-5 MAFE response spectrum and 167% GMRS.

6) SC 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.
Clearance to Hard Stop

A hard stop assures survivability
Scope of the Guidance

- Guidance focuses on technologies with track record in US and accepted by US practitioners: lead rubber, low-damping rubber and friction pendulum bearings.

- Guidance is provided for horizontal systems; vertical isolation systems could be allowable.

- Guidance is focused on traditional designs, though it can also be used for SMRs if given design-specific enhancements.

- Isolation of equipment or floor isolation is allowable, but is not extensively addressed in the NUREG.
Guidance: Hazards and Additional Loading

• Additional seismic monitoring equipment must be incorporated along the edge of the basemat.

• The SI system must be protected against, or designed for fire, high winds, flood, etc.

• Consideration should be given to extreme loadings such as aircraft impact and explosions.

• Fire protection systems for the SI systems are safety related equipment.

• Design should address LOSP and other emergency conditions. Passive systems should be used.
Guidance: Analysis and Design

• Design must:
  • incorporate a hard stop
  • meet the performance criteria
  • allow for isolator inspection and replacement

• Analyses must account for:
  • long-term change in properties
  • variability of properties
  • rocking, rotation, and other 3D responses
Guidance: Modeling

- Three options: 1) coupled time domain, 2) coupled frequency domain, and 3) multi-step.
- Coupled 3D time domain modeling and the multi-step approach have no usage restrictions.
- Coupled frequency domain can only be used with low damping rubber bearings and in certain limited circumstances.
- Input motions must have appropriate long-period content and duration.
- The isolator unit numerical model must be validated against actual data.
Guidance: Operational

• An in-unit inspection program is required
• Inspection plan must address aging/degradation
• The isolators must recover quickly enough to withstand large aftershocks within tens of minutes.
• Isolators should have an inherent property that passively re-centers the system.
• The protection of the seismic isolation system should be included in emergency and severe accident mitigation planning where appropriate
Guidance: Quality

• Professional peer review must be incorporated into the design and development process.

• QA/QC procedures should be developed based on ANSI/ASME NQA-1-2008. 10 CFR 50, Appendix B requirements are applied to the isolator units.

• QA/QC approach for testing in ASCE 7-10 can be used as a base, but be enhanced to meet the criteria in the NUREG.
IIV IAEA ISSC (International Seismic Safety center)

EBP (Extra Budgetary Program)

WA2 (Seismic design and qualification)

Base Isolation Task
Output: Base isolation technical report integrating the technical guidelines and input provided by participating Member States.
General Contents of the Common Part

1. Introduction
   1.1 Purpose of Technical Report
   1.2 Overview of Seismic Isolation
   1.3 History of Seismic Isolation and Current Use

2. Basic Considerations for Applying Seismic Isolation Systems
   2.1 Applicable Facilities
   2.2 Site and Seismic Conditions
   2.3 Directions of Isolation
   2.4 Peer Review
   2.5 Definition of Technical Terms

3. Basic Safety Considerations

4. Design Requirement
   4.1 Design Base Earthquake
   4.2 Design of Isolation Device
   4.2.1 Basic Elements of the Isolation Devices
   4.2.2 Basic Performance Requirements for the Isolation Devices.
   4.3 Design of Base-Isolated System
   4.3.1 Design Concept of Base-Isolated Systems
   4.3.2 Input Seismic Motion
   4.3.3 Analysis Models
   4.3.4 Analysis Methods
   4.3.5 Allowable Limits
   4.3.6 Combinations of Loads
   4.3.7 Other Considerations for Design of the Base Isolated Structures
   4.4 Interfaces between Seismic Isolated Structures and Non-Seismic Isolated Structures
   4.5 Considerations for Other External and Internal Events

5. Considerations on Beyond Design Basis

6. Seismic Risk Assessments

7. Quality Control and Maintenance of Isolation Device
   7.1 Requirements for Manufacturing Stage
   7.2 Requirements for Construction Stage
   7.3 Requirements for Operation Stage

8. Appendices
<table>
<thead>
<tr>
<th>ACTIVITIES</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1Q</td>
<td>2Q</td>
<td>3Q</td>
<td>4Q</td>
</tr>
<tr>
<td>Kick off meeting</td>
<td></td>
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<tr>
<td>Activity 1: Arrangement of technical report</td>
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<td>Activity 2: Gathering resources from member states</td>
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<tr>
<td>Activity 3: Integration of documents (by IAEA Experts)</td>
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<tr>
<td>Activity 4: Compiling final technical report</td>
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</table>
Thank you for your kind attention

QUESTIONS?
US NRC Extra Slides

Q&A
The NRC ESSI Simulator

• See the presentation/paper in this conference by Prof. Jeremic of UC Davis

• Seismic isolator component has been developed by Prof. Whittaker (U. Buffalo)

• Information and downloads at: http://sokocalo.engr.ucdavis.edu/~jeremic/NRC_ESSI_Simulator/
eDefense Shake Table Testing

- NRC funded research by Prof. Ryan at the University of Nevada Reno
- Results to be used for validation of numerical tools and models
<table>
<thead>
<tr>
<th>JNES</th>
<th>NRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Does not specify types of isolators. Provides design and review criteria to address a broad range of possible SI approaches.</td>
<td>Specifies three types of isolators (LDR, LR, and FP) as generally appropriate and two types (synthetic rubber and high-damping rubber) as inappropriate. Does not preclude other types of isolators and provides a list of activities to demonstrate the appropriateness of new isolator designs.</td>
</tr>
<tr>
<td>Deterministic design with design criteria provided up to DBE</td>
<td>Performance-based with GMRS+ and EDB incorporated as part of design basis</td>
</tr>
<tr>
<td>Consideration of residual risk using seismic probabilistic safety risk analysis</td>
<td>Explicit criteria for extended-design-basis ground motions</td>
</tr>
<tr>
<td>Focused on foundation isolation for new NPPs and equipment and floor isolation for existing NPPs</td>
<td>Focuses only on foundation isolation for new NPPs, but does not preclude other uses</td>
</tr>
<tr>
<td>Includes horizontal &amp;vertical isolation</td>
<td>Focuses on horizontal isolation</td>
</tr>
<tr>
<td>Prefers time-history method and allows for modified SRSS (all maximums combined)</td>
<td>Only allows time-domain non-linear 3D modeling most cases</td>
</tr>
<tr>
<td>JNES</td>
<td>NRC</td>
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<tr>
<td>Designs can be developed that meet both sets of criteria, though the NRC criteria appear to generally more stringent due to explicit beyond design basis criteria. A direct comparisons of design bases cannot be made without specifying a test site because the hazard assessment methods differ.</td>
<td></td>
</tr>
</tbody>
</table>
• Both guidance documents address considerations:
  • Long-term change in properties
  • Performance of umbilicals
  • Rocking and rotation
  • Testing of isolation units to determine or verify mechanical properties
  • Incorporation of variability of properties in analyses
  • Validation of analytical models against testing data
  • Uniaxial properties of the isolation units
  • Use of earthquake records rich in long-period motion
  • Other external events and loading conditions
• Both guidance documents recommend:
  • Design should assure that vertical load bearing capacity is maintained at all times, including under extreme loading conditions
  • The isolation system is safety-related unless they support a non-safety related structure
  • Passive (as opposed to active) isolation devices are preferred to address the potential for loss of offsite power after an earthquake
  • Inspection and maintenance programs should be developed and isolators should be replaceable if needed
  • A post-earthquake inspection program should be developed
  • Seismic monitoring equipment should be installed
  • The system should be designed to withstand the loss of multiple isolators; and adequate performance after the loss of one isolator unit must be demonstrated
  • Implementation of quality control systems consistent with safety-related equipment must be developed
• Professional peer review must be incorporated into the design and development process.

• Review of numerical models of isolators
• Review of the SSI analysis and the in-structure response spectra
• Review of displacement and force calculations for the isolator units and all associated structures, systems, and components
• Review of the analysis and design of the umbilicals
• Review of the analysis and design of the hard stop
• Review of the seismic monitoring program
• Review of the prototype test program
• Review of the production (quality control) test program
• Review of the isolator inspection and post-installation testing program
• Review of post-earthquake inspection protocols
• Review of design or protection measures against other external events.
Additional Guidance: Modeling

• Coupled frequency domain can only be used with low damping rubber bearings (essentially linear) without damping and in certain limited circumstances. The following preclude use:
  
  • The shear strain expected for the chosen intensity of shaking (CHS) exceeds the shear strain at the onset of stiffening
  
  • Coupling of the vertical and horizontal responses is likely at the shear strain expected for the chosen intensity of shaking (CHS)
  
  • Cavitation is expected in the LDR bearings for the chosen intensity of shaking
Additional Guidance: Modeling

• Multi-step includes the following:
  • Step 1: Development of seismic input design response spectrum (SIDRS) through SSI analyses using a simple structural model. Either time or frequency domain approaches can be used, but in the later approach the equivalent isolator must be developed.
  • Step 2: Nonlinear response-history analysis of the isolated superstructure using coupled 3D time domain modeling. The SIDRS is used as input below the isolation system.
Additional Guidance: Types of isolators

• Guidance focuses on technologies with track record in US and with stable properties over time
  • Natural rubber bearings
  • Lead rubber bearings
  • Friction pendulum bearings
  • Neoprene bearings have never been used in the US due to the large change in material properties with time (changes >30%, while changes >10% are not accepted by US practitioners)
  • High damping bearings are inappropriate due to scragging