Economy and Standardization applying Seismic Isolation for a Microreactor, BeSMART

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1. Introduction

Seismic design is a dominant cost driver preventing true replication and modular standardization of nuclear power plants, including LWRs, SMRs, and advanced microreactors. The most impactful contributor is the need to tailor safety-class structures and equipment to site-specific seismic demand, which directly penalizes nth-of-a-kind (NOAK) economics.

A key reason nuclear plant designs cannot be mass-produced is the site-specific seismic load case. Even when thermal power, core design, and primary systems are identical, the seismic hazard level forces the changes to: reinforced concrete thickness and rebar ratios, embedded structures and basemat design, equipment anchorage and support frames, qualification margins for safety-class components, layout and interface details (pipes, penetrations, seismic gaps). This breaks the economic premise of modularization and NOAK learning.

In addition traditional 2D nuclear seismic isolation (2D SI) [1-3] focuses mainly on horizontal isolation, but cannot sufficiently reduce vertical accelerations, even largely amplify vertical ones[4]. So many safety-class items are sensitive to vertical accelerations and high-frequency vibration. This motivates a 3D seismic isolation (3D SI) approach.

Application of a 3D SI system for nuclear facilities has been explored for various nuclear reactor types, such as KALIMER (Sodium Fast Reactor) [5, 7-9], JSFR [6], STARLM, Kairos [10], Kemmerer [11], and BeSMART [12,13].

The application of two cost-cutting solutions on generic advanced reactor designs ((1) seismic base isolation, (2) risk- and cost-based seismic design optimization), and the benefits of SI for nuclear power plant buildings, in terms of the possible impacts on overnight capital cost were investigated [14, 15].

This study compares seismic responses of a gas cooled microreactor module under fixed-base, and 3D isolation subjected to DBE of 0.3g PGA. This paper also preliminarily evaluates the effectiveness of 3D-SI applied at the Reactor Building (RB) for a 5 MWe gas-cooled microreactor, with emphasis on ISRS and safety-class equipment response.

2. Plant and Equipment Description

The reference microreactor RB is designed as a reinforced concrete structure with partial embedment: Width 19 m x Depth 34 m x Height: 29 m with embedment of 15 m.

This geometry reflects typical microreactor deployment needs: compact footprint, high shielding requirements, and below-grade protection.

The Reactor Pressure Vessel (RPV) is made of 316H with Diameter 3.5 m x Height 10 m, housing graphite blocks, fuel assemblies, internals, Primary Heat Exchangers (PHX), Circulators, CRDM housings, and vessel support skirt/anchors.

3. Seismic Design Basis

3.1 Design Basis Earthquake (DBE)

DBE is adopted from the Certified Seismic Design Response Spectra (CSDRS)[16] with PGA of 0.3g (horizontal and vertical directions), and 3 components of artificial time histories compatible to the CSDRS are generated using P-CARES[17].

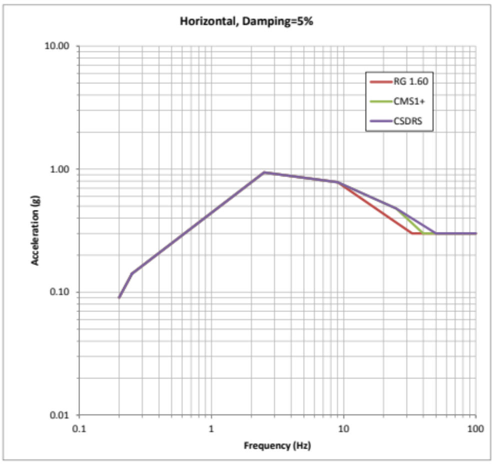


Fig.1 Comparison of 5%-Damped APR1400 CSDRS, CMS1+ DRS, and NRC RG 1.60 DRS - Horizontal

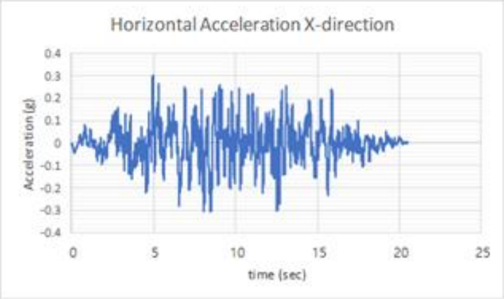


Fig. 2 Horizontal Artificial Acceleration Time History (PGA=0.3g=116.6 in/s^2, 1g=386.09 in/sec^2).

3.2 Key seismic responses: ISRS / FRS

For safety-class nuclear design, equipment demand is governed by: ISRS or Floor Response Spectra (FRS). These spectra often amplify high-frequency content dramatically in fixed-base structures, leading to costly qualification requirements.

4. Modeling and Methods

4.1 Structural dynamic models

Two structural configurations are compared:

- Case A: Fixed-base RB with RPV
- Case B: 3D seismic isolated RB with RPV

The building and RPV are represented using a lumped-mass stick model sufficient to generate ISRS at key elevations (basemat, mid-elevation, ground equipment floor, Overhead crane support, roof for RB, and diagrid to support graphite blocks and Fuel Assemblies, PHX for RPV and internals.

4.2 3D isolation representation

3D SI is implemented using:

- Horizontal isolators (low lateral stiffness, high damping)
- Vertical isolation elements (reduced vertical stiffness, controlled uplift, tuned damping)

The 3D isolator as shown in Figure 3 includes a LRB for horizontal isolation of 0.5 Hz, a disc spring stack for vertical isolation of 2.0 Hz, and a guide tube to prevent lateral buckling of the disc springs and ensure smooth multidirectional movement.

The design shear strain of 3D isolators to be within 100% at design vertical load at DBE (0.3g in horizontal and vertical directions), and maximum shear strain of 300% at BDBE 0.5g in horizontal directions.

Damping of the 3D isolator is determined 15% for horizontal direction and over 7% for vertical direction, respectively, to meet the requirements to be more than 12% but limited to 24% in horizontal directions [18], and 7% or more in vertical directions.

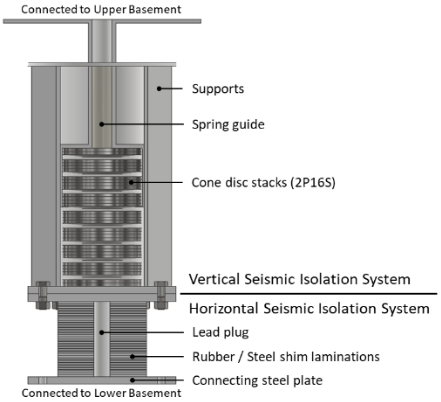


Fig. 3 Schematics of Integral 3D-LRB [12][13]

4.3 Modeling & Numerical Methods

Two structural configurations are compared:

Case A: Fixed-base RB with RPV and internals, and safety components attached to RPV

Case B: 3D SI RB with RPV

The building is represented using a lumped-mass or FE stick model sufficient to generate ISRS at key elevations (basemat, mid-elevation, equipment floors, Overhead crane, and roof, etc.).

The RPV and internals, and safety components attached to the RPV are modeled as another simplified six nodes lumped mass stick model rigidly linked to Reactor Building.

The 3D Isolators (depending on weight of RB and SSCs to be isolated) are modelled by simplified linear stiffness and damping coefficients for 3D SI system as shown in Figure 4.

$$K_h,\ K_v = m\,\omega^2 \qquad (1)$$

$$C_h,\ C_v = 2\,\zeta\, m\,\omega \qquad (2)$$

Where $\omega = 2\pi f$, $f_h = 0.5$Hz, $f_v = 2.0$Hz, $\zeta = 0.15$ for horizontal, and $\zeta=0.07$ for vertical isolation system.

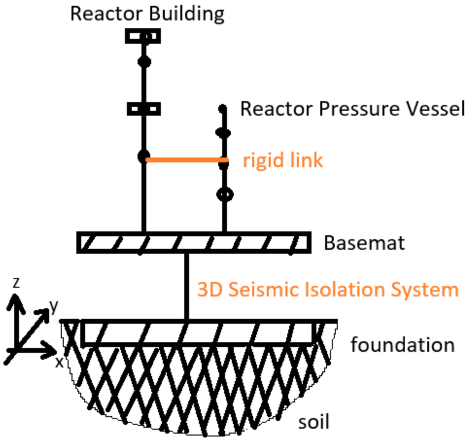


Fig.4 Simplified 3D seismic isolation system model

Linear time-history analyses were carried out using the ANSYS [19].

4.4 Equipment response evaluation

Equipment response is preliminarily evaluated by comparing ISRS among cases and identifying peak spectral acceleration reductions in the frequency bands relevant to: RPV support modes, graphite block modes, PHX/circulator support frame modes, CRDM housing high-frequency modes, and support locations at Refueling Handling Machine and at Overhead crane.

5. Results & Discussion

Comparisons are made between fixed-base and 3D isolated systems. Seismic responses include isolator displacements, and horizontal and vertical acceleration responses as typically shown in Figure 5. Preliminary results show substantial reductions (example: at RPV Support) in horizontal acceleration (1.1 g to 0.2 g of max. acceleration, 0.5 g to 0.2 g of ZPA over 3Hz) and vertical acceleration (1.0 g to 0.4 g of max. acceleration, 0.6 g to 0.45g in frequency range of 4~30Hz) in the 3D SI system compared to the fixed-base system.

5.1 Fixed-base seismic amplification

Fixed-base nuclear buildings typically exhibit strong ISRS amplification at mid- to high-frequency ranges, Large vertical accelerations due to rigid basemat coupling, High equipment anchorage loads and nozzle loads. This results in heavier supports, more complex snubbers/restraints, increased welding and QA scope, and larger rebar quantities and embed plates.

5.2 3D isolation reduces ISRS and improves qualification margin

3D-SI provides Reduction of peak ISRS at safety-class equipment support floors, Suppression of vertical acceleration that dominates CRDM and internal component design, and Lower high-frequency content, which is the primary driver for expensive equipment qualification testing.

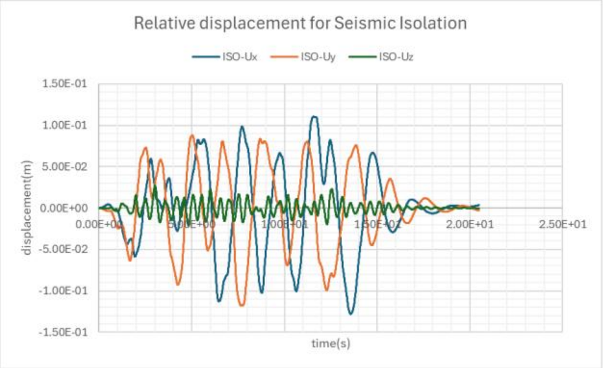
5.3 Equipment-specific implications on Seismic Isolation

For Reactor Pressure Vessel (RPV), lower skirt anchor loads, reduced overturning moments, lower internal support stress demand, and reduced need for stiffening rings and thickened vessel supports.

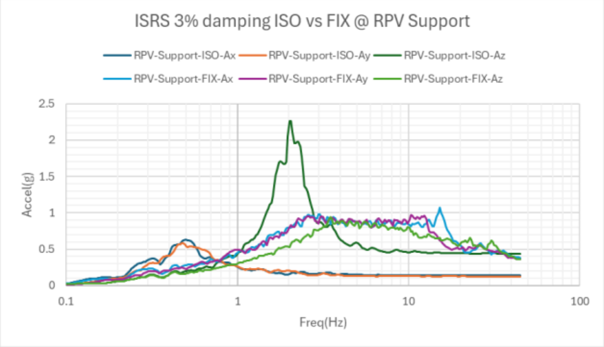
For Graphite blocks and fuel assemblies, reduced rocking/impact risk, lower acceleration-driven relative displacement, improved core restraint margin.

For Primary heat exchangers and circulators, reduced nozzle loads, reduced support frame demand, lower bearing and rotating equipment vibration excitation.

For CRDM housings, major benefit from reduced vertical ISRS peaks, simplifies qualification and reduces conservative overdesign.



a) Relative Displacement History for 3D SI



b) ISRS at RPV Support

Fig. 5. Seismic Displacement/Acceleration Responses (3D SI System/Fixed base)

6. Cost Benefits and Standardization of NOAK Modules for BeSMART

Seismic design drives cost not only through concrete and steel but through: qualification test campaigns, equipment redesign loops, site-specific re-analysis, QA documentation and regulatory re-review, interface changes across modules.

Under 3D-SI for a BeSMART deployment logic, cost benefits arise from a standardized equipment qualification envelope, reduced need for site-specific structural redesign, reduced safety-class support mass, reduced rebar and embedment complexity, and reduced schedule risk.

Seismic isolation expands the standard design applicability to the NOAK since a central NOAK problem is that designs cannot claim that the module is identical across all sites, where seismic hazard differs.

3D-SI changes the paradigm rather than tailoring the RB and equipment, since the isolation system becomes the adjustable interface, allowing a fixed standardized reactor module, a standardized equipment qualification basis, and a site-adaptable isolation.

A realistic NOAK pathway is standard design certification of RB, RPV, and equipment under bounded ISRS.

Site-specific licensing is limited to isolator properties, displacement clearance checks, foundation interface checks. This sharply reduces the scope of site-specific re-review.

7. Conclusions

This paper highlights that seismic load cases are a major hidden cost driver preventing standardization across LWRs, SMRs, and advanced reactors. For a 5 MWe gas-cooled microreactor, 3D seismic isolation applied at the RB substantially reduces ISRS amplification and vertical seismic demand for safety-class equipment including the RPV, internals, graphite blocks, fuel assemblies, PHXs, circulators, and CRDM housings.

The key conclusion is that 3D SI is not only a seismic protection technology but also it is a standardization technology.

Accordingly, a strong recommendation is made to incorporate 3D-SI as a core design feature for BeSMART microreactor deployment, enabling NOAK replication and materially improving cost competitiveness.

Future work will include manufacturing and testing the prototype 3D isolator, moat design and analysis, displacement demand for 3D isolation system, probabilistic fragility analysis and soil-structure interaction modeling, and quantification of the economic benefits of employing 3D SI system to microreactors and SMRs, even LWRs.

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