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DESIGN OF INTEGRAL 3D SEISMIC ISOLATOR AND ITS SEISMIC RESPONSES FOR A NUCLEAR FACILITY

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INTRODUCTION

Yoo et al. (1997) pointed out that vertical seismic responses of nuclear facilities seismically isolated by 2D horizontal seismic isolation (SI) system are larger than those of fixed base structures. Yamazaki (2014) show that horizontal acceleration records become much less than the peak ground acceleration (PGA) but vertical acceleration records are larger in 2D Seismic Isolation of Emergency Facility, Lessons learn from Fukushima Daiichi NPP, the 11 March 2011 Tohoku Earthquake and Tsunami. There have been several attempts to develop 3D SI systems for nuclear facilities to reduce seismic acceleration responses in horizontal as well as vertical directions. Yoo et al. (1999) patented the 3D integrated LRB, and proposed vertical isolation frequency of 1~2Hz requiring the vertical acceleration responses of superstructure be less than zero period acceleration (ZPA) of the design input motion. Zhou, et al. (2016) and Zhu, et al. (2022) have shown that a vertical isolation frequency of 3 Hz can effectively reduce the vertical responses, whereas further to reduce vertical isolation frequency to 1 Hz causing rocking effect obviously.

ABSTRACT

This paper aims the development of preliminary designs of the integral 3D seismic isolator to be used for nuclear facilities, which consists of 2D laminated rubber bearing (LRB) and multi-stackings of disc springs with rigid surrounding container being capable of 3 directional free movements. This paper also evaluates the seismic responses of the nuclear facility, as an example, KALIMER (Korean Advanced Liquid Metal, Sodium coolant Fast Reactor, 150MWe) Reactor Building, equipped with the 3D SI system having equivalent stiffness and damping values of the developed integral 3D LRBs, subjected to artificial time histories (ATH) compatible to zero period acceleration (ZPA) of 0.3g as Design Basis Earthquake (DBE) in USNRC 1.60 Design Response Spectra (DRS).

The comparison of the seismic responses for the Nuclear Facility founded on among the Fixed Base, the 2D SI system, and the 3D SI system is made to demonstrate the effectiveness of the SI systems, especially, the integral 3D LRB SI system, which reduces both horizontal and vertical acceleration responses enhancing seismic capacity, seismic safety margin and economic benefits as well.

DESIGN FOR VERTICAL SI PARTS FOR NUCLEAR FACILITIES

It is necessary to develop the vertical design load to 870 tons in vertical isolation parts to fit the vertical design load capacity of 2D isolators for the 3D isolator to reduce the number of 3D isolators to be much less to 72 from 210 with design load to 320 tons for a nuclear facility of total mass of 63000 tons, while the vertical design load for a common 2D LRB is over 1000 tons (Yoo. et al. (2022)).

The preliminary vertical SI design part consists of 3 groups of multi-stacking disc springs with 3 parallel and 2 series (3p2s), positioned on the top of the top plate of the 2D LRB surrounded by a thick container keeping groups of multiple stacking disc springs to move up and down freely while following in-phase horizontal movement with 2D LRB, and the integral 3D isolator is shown in Figure 1.

For a single disc spring, using De=500 mm, t=37 mm, F=914900 N at s=0.5ho, where De is external diameter, t thickness, F force, ho free cone height of disc, and s deflection of disc resulting from applied load, respectively.

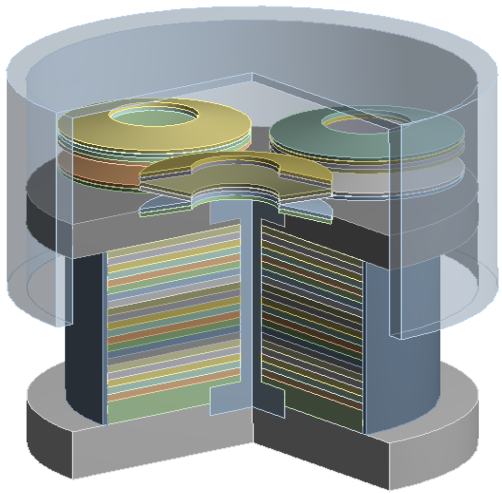


Figure 1. Schematics of integral 3D isolator (non-scale)

The typical stiffness deflection curves for combinations of disc springs are shown in Figure 2 and the case (d) of 3p2s combination is used for the vertical isolation.

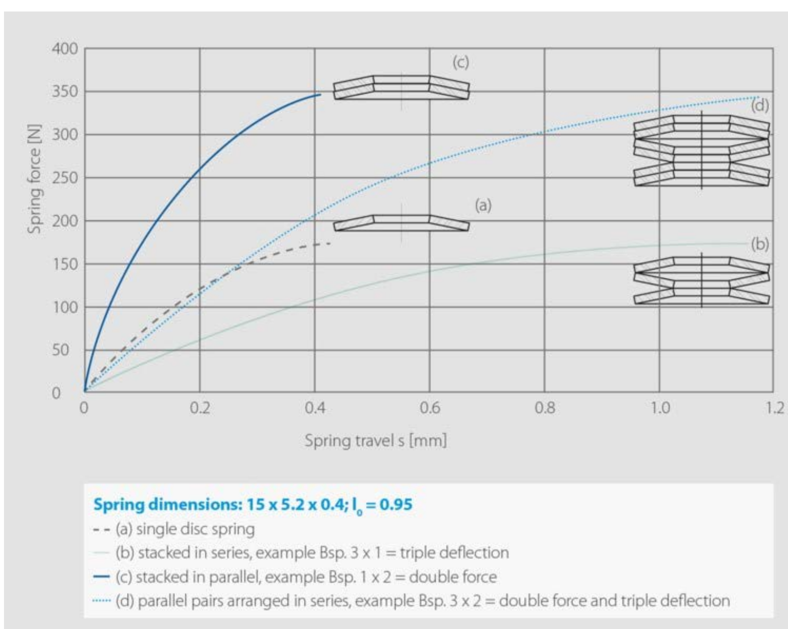


Figure 2. Static characteristics of combinations of disc springs

MODELING OF 3D SI AND REACTOR BUILDING

The Reactor Building (W 61m x D 40m x H 51m) of KALIMER (Liquid Metal coolant Fast Reactor, 150MWe) made of concrete shear walls and slabs weighs about 63000 tons, and is seismically isolated using 72 integral 3D–LRBs as shown in Figure 3.

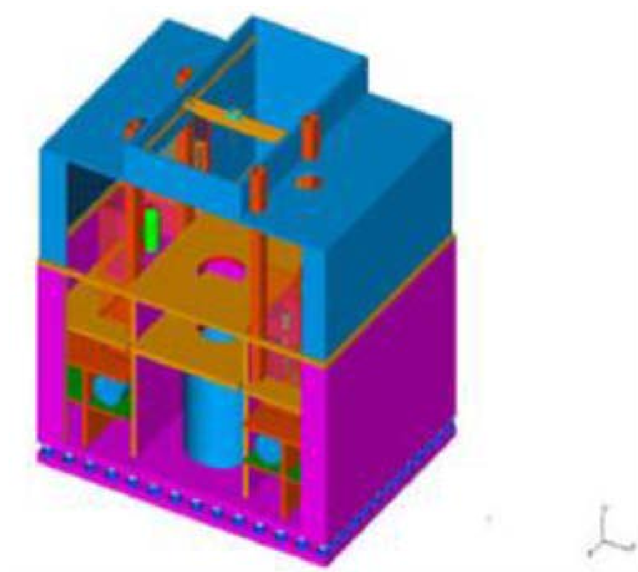


Figure 3. Schematics of 3D Seismically Isolated Reactor Building of KALIMER

The simplified Lumped Mass Beam Model of isolated Reactor Building is developed using beam elements, lumped mass, spring and dashpot in ANSYS as shown in Figure 4.

It is noted that the equivalent stiffness for the 3D Isolator in Model of 3D SI system in Lumped Mass Beam of Isolated Reactor Building are linearly amplified from those test data as shown as the case of (d) of 3p2s combination, and the equivalent damping values of 3% and 5% are conservatively assumed, respectively.

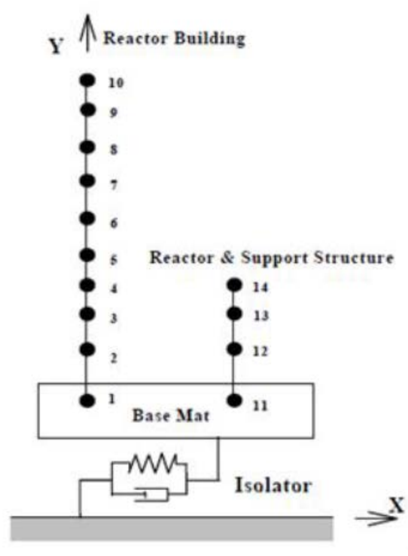


Figure 4. Lumped Mass Beam Model of 3D SI Reactor Building

MODAL PROPERTIES AND SEISMIC RESPONSES FOR NUCLEAR FACILITY EQUIPED WITH FIXED BASE, 2D, AND 3D SI

The modal analyses and the linear transient time history analyses for 3 cases of Fixed Base, 2D SI, and 3D SI of the Reactor Building are performed by ANSYS using the simplified lumped mass beam model when subjected to 3 components of ATH compatible to ZPA of 0.3g as Design Basis Earthquake (DBE) in USNRC 1.60 DRS.

Modal Properties

The calculated fundamental natural frequencies are 6.18 Hz in x direction, 6.26 Hz in y, and 14.85 Hz in vertical direction for the Fixed Base, 0.5 Hz, in x and y directions for 2D and 3D SI systems, while 12.64 Hz for 2D SI system, but 0.99 Hz for 3D SI system in vertical direction, respectively. The calculated modal properties are summarized as in Table 1.

Table 1: Modal properties for 3D, 2D seismic Isolation, and Fixed Base Reactor Building

3D isolation							
mode	frequency, hz	Effective Mass					
		x, kg	y, kg	z, kg	rx, kg·m^2	ry, kg·m^2	rz, kg·m^2
1	0.5025	0	62,986,000	0	28,712,000,000	0	0
2	0.5027	62,987,000	0	0	0	28,683,000,000	0
3 (수직)	**0.9985**	0	0	62,987,000	0	0	0
4	6.1877	0	0	0	0	0	19,823,000,000
5	8.5451	0	557	0	22,027,000,000	0	0
6	9.8412	291	0	0	0	28,683,000,000	0
7	18.0580	0	0	0	0	0	2,232,000,000
8	21.4560	20	0	0	0	27,270,000	0
9	22.6840	0	20	0	244,940,000	0	0
10	24.1500	0	0	244	0	0	0

2D isolation							
mode	frequency, hz	Effective Mass					
		x, kg	y, kg	z, kg	rx, kg·m^2	ry, kg·m^2	rz, kg·m^2
1	0.50248	0	62,986,400	0	28,711,600,000	0	0
2	0.50266	62,986,700	0	0	0	28,682,600,000	0
3	6.1877	0	0	0	0	0	19,822,800,000
4	8.5451	0	557	0	22,027,100,000	0	0
5	9.8412	291	0	0	0	28,683,100,000	0
6	12.646	0	0	52,566,100	0	0	0
7	18.058	0	0	0	0	0	2,231,950,000
8	21.456	20	0	0	0	27,270,100	0
9	22.684	0	20	0	244,942,000	0	0
10	29.318	0	0	0	0	0	844,351,000

without isolation							
mode	frequency, hz	Effective Mass					
		x, kg	y, kg	z, kg	rx, kg·m^2	ry, kg·m^2	rz, kg·m^2
1	6.1877	0	0	0	0	0	19,823,000,000
2	6.2619	0	31,422,000	0	50,948,000,000	0	0
3	7.2206	32,418,000	0	0	0	57,052,000,000	0
4	14.853	0	0	41,725,000	0	0	0
5	16.509	12,531,000	0	0	0	366,130,000	0
6	16.935	0	14,169,000	0	156,150,000	0	0
7	18.058	0	0	0	0	0	2,232,000,000
8	27.697	2,168,900	0	0	0	1,127,600,000	0
9	29.318	0	0	0	0	0	844,350,000
10	30.505	0	1,393,300	0	469,790,000	0	0

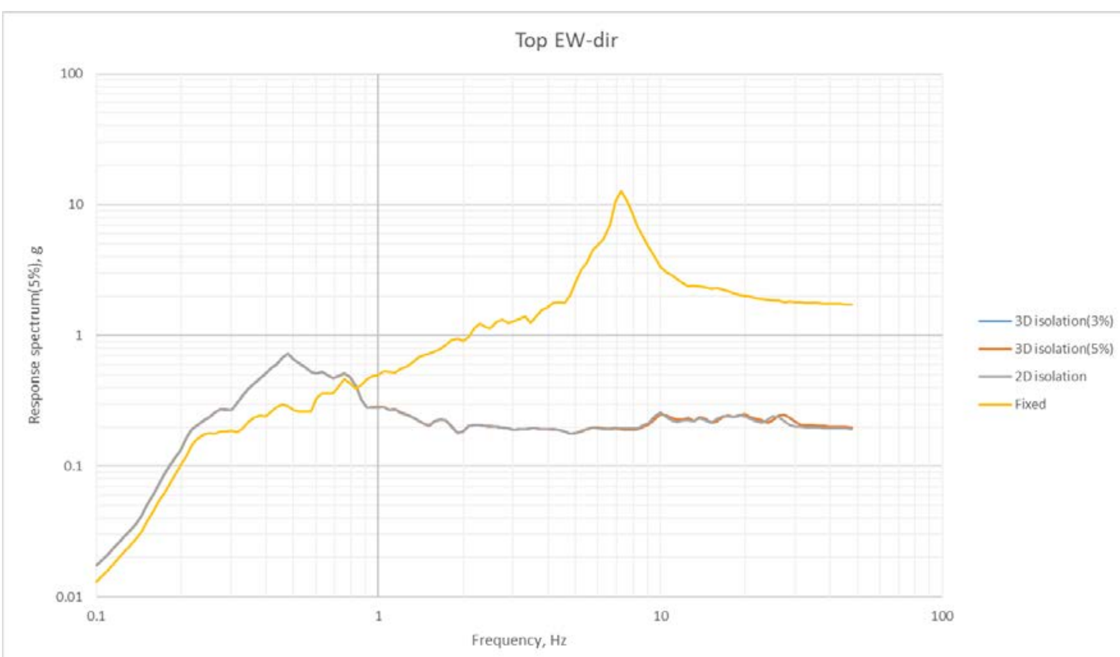
Seismic Responses

The calculated acceleration response spectra with 5% damping value at two different locations; one at Base Uppermat supported by SI systems (or at Fixed Basemat), and the other at Top of the Reactor Building isolated by 2D SI and 3D SI (or Top at Fixed Base) are as shown in Table 2, and Figure 5.

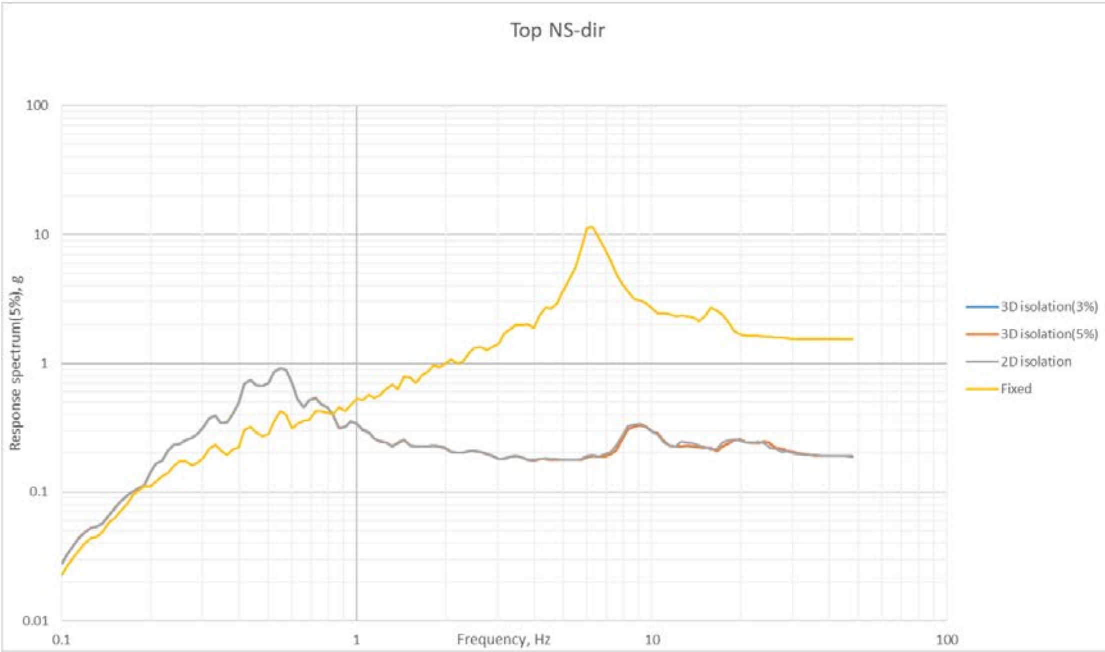
For the comparison of the effects of two different damping values of 3%, and 5% on the seismic responses for the 3D SI system, their maximum accelerations and relative displacements are also calculated and shown in Table 2.

Table 2: Peak Spectral Accelerations and maximum Relative Displacements in 3 directions for Fixed Base, 2D SI and 3D SI Reactor Building subjected to 0.3g

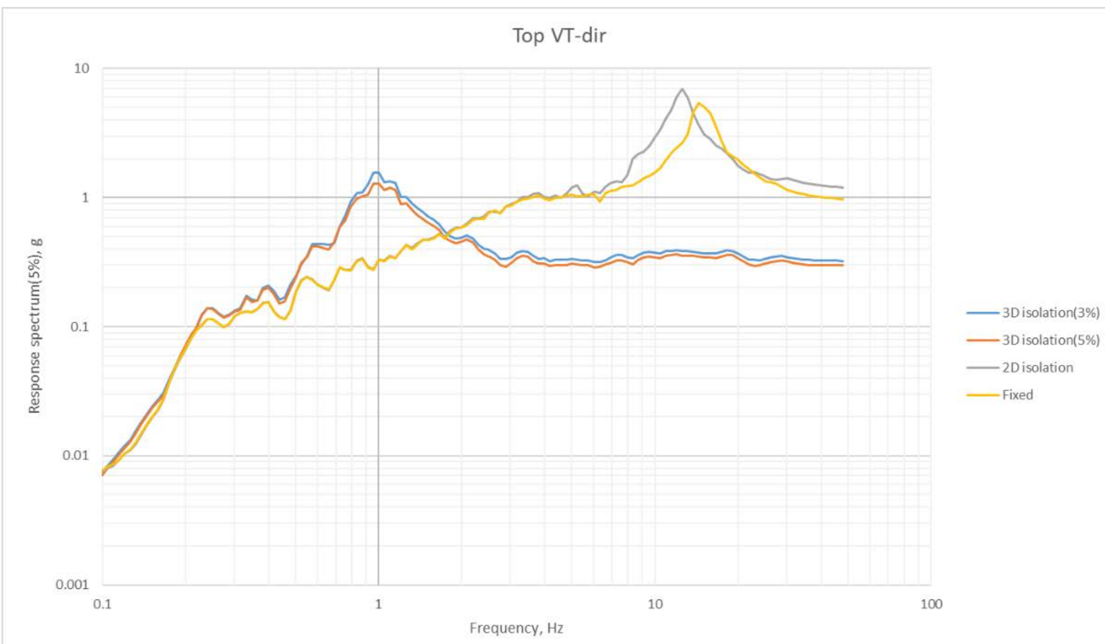
	x-direction (EW)			y-direction (NS)			z-direction (VT)			
location	fix base	2D SI	3D SI (v5%)	fix base	2D SI	3D SI (v5%)	fix base	2D SI	3D SI (v 3%)	3D SI (v 5%)
base acc.(g)	1.00	0.24	0.24	0.99	0.25	0.25	0.96	1.56	0.39	0.36
top acc.(g)	12.7	0.25	0.25	11.4	0.34	0.34	5.38	6.92	0.39	0.36
base disp (mm)	0.00	161.1	160.9	0.00	157.6	157.7	0.00	0.62	78.2	70.9
top disp. (mm)	8.33	162.1	161.9	10.4	158.9	159.0	1.07	1.90	78.7	71.3



a) Horizontal EW FRS 3% & 5% at Top of Reactor Building



b) Horizontal NS FRS 3% & 5% at Top of Reactor Building



c) Vertical FRS 3% & 5% at Top of Reactor Building

Figure 5. Acceleration Response Spectra in 3 Directions (a) EW, b) NS, c) VT) at Top for 3D SI, 2D SI, and Fixed Base of Reactor Building subject to 0.3g ZPA of ATH

It shows that at Base Uppermat, horizontal peak spectral acceleration (PSA) responses in 2D and 3D SI systems are much reduced to 0.24~0.2g flat in 1.5~50 Hz from 1.0~0.8g in 2~10 Hz frequency ranges of the Fixed Base and to 0.3g from 12.7g at Top in 6~12 Hz frequency ranges, and ZPA in 2D and 3D SI systems are also reduced to 0.19g from 0.3g of the Fixed Base.

However vertical PSA responses in 2D SI system are highly increased to 1.56g from 0.67g at Base and to 6.92g from 5.38g at the Top in 9~14 Hz ranges in Fixed Base, while that in 3D SI reduced to 0.2g flat in 1.8~50 Hz. And at Top, PSA, much further reduced to 0.3~0.2g, keeping flat with little amplification in 1.5~50 Hz from 12.7~11.4g in 6.3~7.2 Hz, and ZPA to 0.19g from 1.54g, respectively. The higher damping values of the SI systems show the less PSA and the smaller relative displacement.

The maximum calculated relative displacements for the Fixed Base and 2 different SI systems are summarized in Table 3, and the relative displacement response time histories for 3D SI, for example, are shown in Figure 6. The relative displacements in horizontal directions between Lower Basemat and Superstructure in 2D and 3D SI systems equipped with the same horizontal LRBs are equally amplified up to 161.1 mm, and 157.6mm in EW and NS directions, at Uppermat, respectively. Those in 3D SI equipped with 3D integral isolators are also vertically amplified to 78.2mm at Uppermat and 78.7mm at Top, respectively, but those are very small as 1.1 mm at Top for Fixed Base, and 1.9 mm at Uppermat for 2D SI.

The maximum relative displacement of 161.1 mm in horizontal directions for 2D and 3D LRBs equivalent to the shear strain of 57.9% (for total rubber thickness of 278 mm) is well within the design shear strain requirement of 100%. The vertical maximum relative displacement of 78.2 mm for 3D LRBs is also within tentative displacement requirement of 100 mm.

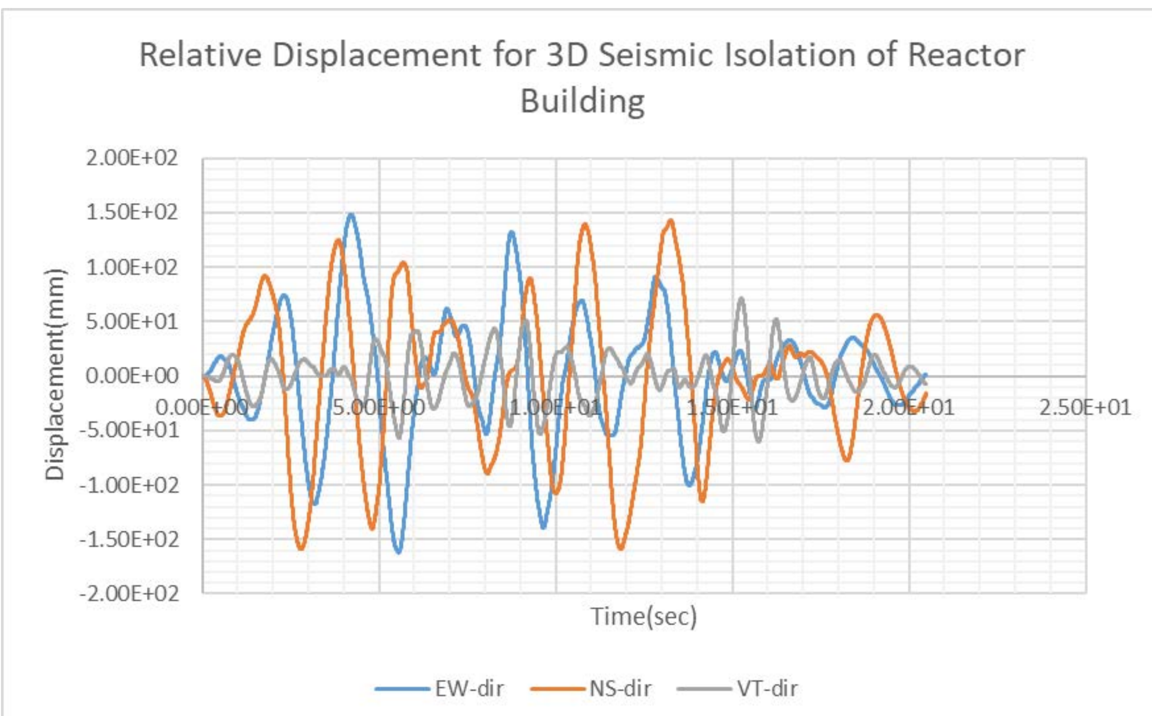


Figure 6. Relative Displacements in 3 Directions between Lower Mat and Superstructure for 3D SI of Reactor Building subject to 3 component ATHs of 0.3g ZPA

CONCLUSION

The conclusions of the evaluation of the seismic responses of 3D and 2D SI system and Fixed Base are as follows;

The design of an integral 3D isolator of design load of 870 tons is proposed using 3 groups of an industrial 3s2p combination of 50 cm diameter of disc springs on top of endplate of 150 cm diameter of commercialized horizontal 2D LRB with surrounding cylindrical container.

This paper evaluates the modal analyses and seismic responses of a Reactor Building using the 3D SI system having equivalent stiffness and damping values of the integral 3D LRBs, assuming linear amplification of industrial stiffness test data of 3s2p combination of disc springs, and conservatively 3%~5% damping values of the disc springs.

The dynamic time history analyses of the Nuclear Facility have been performed using the lumped mass beam model of the Reactor Buildings equipped with Fixed Base, 2D SI, and 3D-SI subjected to ATH compatible to the DRS of 0.3g ZPA, and their seismic responses are compared in acceleration responses and relative displacements.

The comparison of the seismic responses between Fixed Base, 2D and 3D SI systems also presents the effectiveness of 3D SI systems vertically reducing the amplified acceleration responses in 2D SI systems while keeping horizontal seismic responses equally reduced much more than those of the Fixed Base. The higher damping values of the 3D SI systems show the less PSA and the smaller relative displacement.

The relative displacements in horizontal directions between Lower Basemat and Superstructure in 2D and 3D SI systems are equally amplified up to 161.1 mm equivalent to 57.9%, while those in 3D SI are vertically amplified to 78.8 mm, still meeting the design requirements of 100% shear strain and 100 mm displacement.

The effectiveness of the proposed integral 3D SI system over 2D SI and Fixed Base on reducing seismic acceleration responses in 3 directions is promising enhancing seismic capacity and seismic safety margin for nuclear facilities, such as NPP, SMR, and Research Reactor, and any Nuclear facilities including civil structures in general.

Following further studies to verify the effectiveness of the 3D SI system applied for any Nuclear Facilities are recommended;

1) The design optimization and characterization tests of combinations of disc springs for 3D isolators, including damping values due to friction between disc springs

2) The integral 3D SI system dynamic downscale tests to verify the functionality for various types of reactor buildings containing reactor core, and its reactor internal structures, such as Control Rod Driving Mechanism, Shutdown Rod Driving Mechanism, and fuel assemblies.

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