Response study of Nuclear Power Plant Using Vertical and 3D isolation

Newton Maharjan[1]

[1]*Postgraduate Student at Tongji University, Dept. of Civil Engineering, Tongji University, Shanghai, China*

Abstract - *Vertical Isolation technology can be a beneficial factor to many aspects of base isolation technology, previously adapted in the sensitive structures, like nuclear structures. The importance to the vertical and wholesome 3D isolation can be seen in recent years, where the preservation of expensive devices within a structure is of significant necessity. So, it is crucial to design the isolation system properly. A 3D lumped-mass stick model was established to study the seismic response of AP1000 nuclear structure under three-directional input motions, with scaled seismic waves obtained from PEER database. The effect of changing characteristic parameters of isolation systems on the seismic response of nuclear structures was studied. The bilinear model of lead rubber bearing (LRB) is adjusted to change the frequency of vertical isolation and responses of floors for three dimensional input wave according to the spectral response input in the structure. The frequency changes in vertical direction range from 3- 60 Hz. By monitoring dynamic response using damping, floor response spectra at different positions and response displacements of the isolators were compared while controlling the response of base mat on which model is laid. The result shows quantitative description of the resultant obtained from the deformation and force ascertained on the isolator due to change in the vertical frequency due to the input wave. The results also show that change in the frequency of vertical isolation has different degrees of effects on the seismic responses of the nuclear structures and behavior pattern of isolators under the proposed structure in the research (AP1000).*

Key Words: AP1000; three-directional motions; vertical isolation; bilinear model; floor response spectra; nuclear power plant; lead rubber bearing (LRB)

1. INTRODUCTION

A significant progress has been made during the last decade to reinforce the structures and mitigate the impending disasters throughout the structures. Among various ways to the mitigation of these disasters, such as Earthquake, Wind et cetera, one such way is seismic isolation. Seismic isolation is not a new technique, but it has been refined throughout the decades to provide the best possible outcome through various disasters and while this technique is vastly influential in seismic prone areas, the significance of it cannot be neglected for other similar emergencies such as wind disasters.

First documented seismic isolation strategy can be acclaimed to a medical doctor from the northern English city of Scarborough, who proposed and patented the idea of a new construction method, where a building be built on "free joint" and a layer of fine sand, mica, or talc between super and substructure for building to slide during the earthquake [1]. Many enhancements have been made to this technology since then.

Vertical isolation system is the focused area of this research and has been one of the evolving fields of research. Isolators do not generally prevent the transmission of vertical forces due to seismic activities into the structures, whereas horizontal ground motion is reduced efficiently. Efforts to combine horizontal seismic isolation with vertical vibration isolation date back to the early development of seismic isolation systems, driven by the power and utility industries focused on the protection of large equipment. Multiple researchers have independently developed 3D isolation systems by modifying the design parameters of laminated rubber bearings.

Under some circumstances, isolation systems can amplify or add to the vertical vibrations similar to those experienced in a fixed-base structure. For instance, elastomeric bearings can have flexibilities that, by themselves or in arrangement with the flexibility of the structural system, shift the effective vertical frequency of the isolated system into an amplified range of the vertical pseudo-acceleration spectrum [2]. As such, the vertical response could be worse than that experienced by a fixed-base structure. Sliding bearings are typically quite stiff in the vertical direction so that the vertical response may be similar to that for a fixed-base structure. Nevertheless, if vertical excitations become large, uplift can occur unless tension-capable bearings were used. While reasonable improvement may be acceptable in some applications, the uplift and reseating performance of the bearing system may result in impact loads that produce additional vertical vibrations in the structure.

In case of structures that hold highly sensitive equipment and other various delicate items to acceleration, e.g., Nuclear Power Plants (NPP), Hydro Power Plants, et cetera, significant attention needs to be provided for prevention of horizontal-vertical coupling behaviour that may occur in different isolation systems to a varying degree. Generally, this coupling can happen in fixed-base structures, but various other types of isolators may show this behaviour when subjected to certain conditions. In many nuclear applications, bearing designs generally result in a fundamental vertical frequency on the order of 20-35 Hz. For conventional buildings, this frequency may be 10 Hz or lower. However, vertical movement of the plant may be a concern under wind and other service conditions, and, in particular, a base-isolated plant may pitch and roll during seismic excitations, with accelerations varying over the height of the plant. Thus, careful study is needed to identify the optimum design of the bearings in such cases so that adequate protection is provided by the increased vertical flexibility of the bearings, where horizontal pitch, roll, and rotational movements are not excessive.

1.1 Types of Vertical and 3D isolation

There are various types of vertical isolation systems, one of the ways could be increasing the vertical flexibility of elastomeric bearings, which will result in the shift of fundamental vertical frequency of isolated body from the ground motion predominant frequency. However, this may result in pitching motion, as it might result in the amplification of horizontal acceleration in upper structures. Hence, adding damping devices can be one of the solutions to this problem.

1.1.1 Lead Rubber Bearing (LRB)

One of the very first methods of the 3D isolation system was developed in Japan, by Kajima, which utilised steel laminated natural rubber bearing (vertical frequency = 5Hz) and oil dampeners that provided substantially reduction in a vertical rocking motion and flexible vertical design. Similarly, this use of laminated rubber bearing was also explored in United States nuclear facilities by Aiken. The research in the United States progress till designing a specific 3D isolation device and testing the performance characteristics for individual 1/4th length scale bearing. This explored new possibilities with the use of elastomeric isolators with the effective implementation of isolators in horizontal and vertical directions. Even though this isolator shows high promising results, the successful implementation of 3D isolations to any building would have a high probability of constraining the horizontal isolation period to somewhat smaller than the one used today.

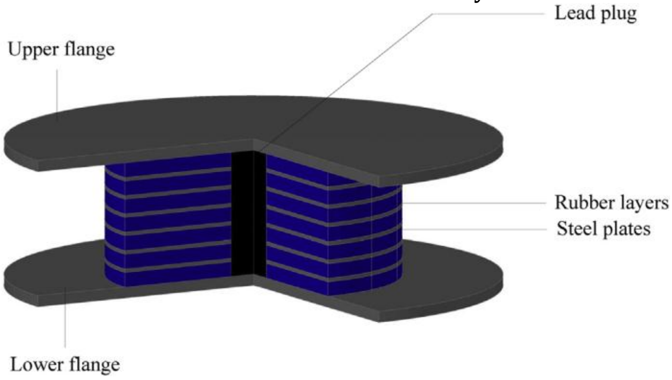


Figure 1: Lead Rubber Bearing

1.1.2 GERB System

The GERB system is also one of the 3D isolation systems for the protection of structures that were developed by a company that specializes in vibration isolation. The GERB system involves of massive helical steel springs arranged in an assembly that is flexible both horizontally and vertically, utilizes helical springs—with similar flexibility in all three directions—and viscous dampers, which was designed for seismic and vibration isolation of diesel and turbo generators, but there was a limitation to this system as a strong coupling between vertical and horizontal motion if the bearing offset laterally, the vertical vibrations would affect the lateral displacement of bearing due to geometric nonlinearities [3]. The GERB system had been tested on the shake table at Skopje, Macedonia, and implemented in two residential buildings in Santa Monica, California, the USA before 1994 which were shaken vigorously in the 1994 Northridge Earthquake.

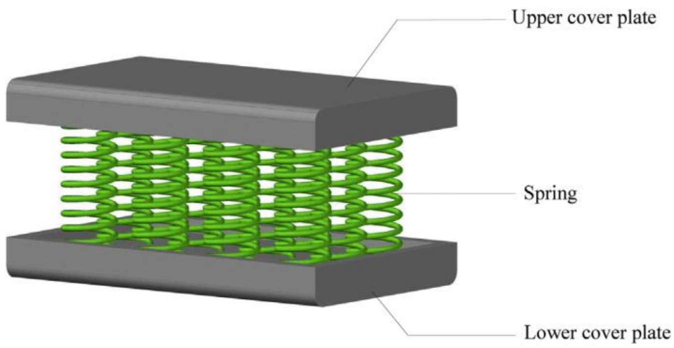


Figure 2: GERB System

Some other types of available technologies to control the 3D vibration are the Hydraulic 3D isolation system, Coned Disc Springs. The hydraulic 3D isolation system consists of natural rubber bearing upon which a vertically oriented hydraulic cylinder is placed. The role is similar to the rolling seal type air spring system, but the operating pressure under operations is raised to 15 MPa, and under earthquake, conditions are raised to 20 MPa [2]. The concerning issue with this system was seal leak between the piston and cylinder, the probability of attaining the desired damping and, friction characteristics of the piston-cylinder system with lateral loads applied. Coned Disc Springs provide vertical isolation for individual components within horizontally isolated NPP against the vertical components of motion, which is perhaps the more economical approach to achieve 3 Dimensional protections. A commercial solution for 3D isolation is accessible through Shimizu Corporation in Japan and has been applied in at least one 3-story apartment building [4]. Each device comprises a laminated rubber bearing on a steel frame that conducts the loads to three air springs and three shear force diffusing vertical sliders. An oil damper system—two oil dampers linked by cross-coupled pipes—delivers both vertical and rocking suppression. The system is quite complex and costly.

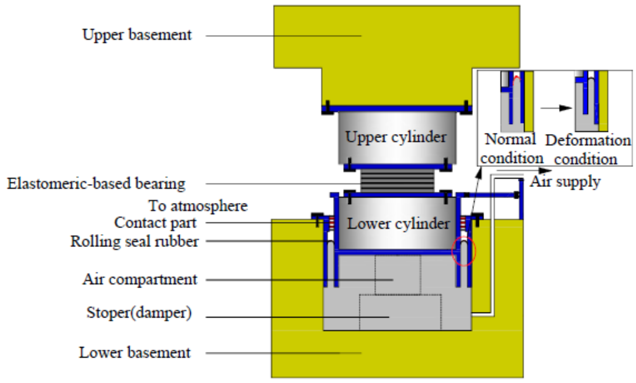


Figure 3: Rolling Seal Type Air Spring

Three-dimensional isolation might be implemented more efficiently for new designs of small modular reactors where the isolation plane could be added at or near the elevation of the centre of mass of the plant. In this case, the overturning moment that would give rise to rotations about a horizontal axis is reduced. Several relevant development studies have been completed in Japan linked to 3D isolation of nuclear facilities.

Over the past decade, renewed interest in nuclear power has led to several new studies in the United States on the use of isolation technology for NPPs. The Multidisciplinary Center for Earthquake Engineering Research (MCEER), headquartered at the University of Buffalo, has produced two notable reports in the past five years [5]. The model used for this study consisted primarily of the reactor building along with the internal structure, without significant consideration given to auxiliary structures. In addition to the fixed-base scenario, Huang and Whittaker also developed a set of design scenarios for Friction Pendulum (FP), LRBs, and low-damping rubber bearings (LDRBs). This portion of the study confirmed the expected reductions in spectral demands, as well as showing a decrease in construction costs with the use of isolation.

Another study was taking place at the University of California Berkeley titled, "Advanced Seismic Base Isolation Methods for Modular Reactors" [6]. The paper was written in collaboration between the civil and environmental engineering and nuclear engineering departments; this report examined some of the same issues that were addressed in the previous two releases and came to similar conclusions. The report, however, focused on the development and isolation of small modular reactors and addressed some additional issues, including impact by aircraft on isolated structures, torsional response due to mass and stiffness eccentricities above the isolation plane, the location of the isolation plane (at the top, middle, or bottom of the SMR), likewise.

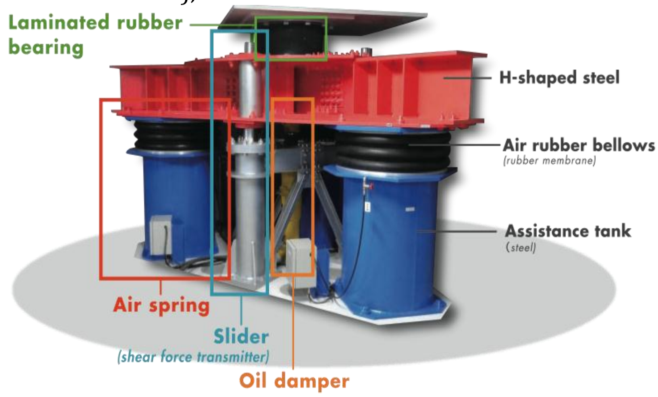


Figure 4: 3D Isolation

2. Analysis result using Vertical and 3D isolation

2.1 Modelling

The analysis takes us into the new passive nuclear power plant, AP1000, as a prototype for analysis and evaluation. As the AP1000 model, there are three parts included: Auxiliary and Shield Building (ASB), Steel Containment Vessel (SCV), and Containment Internal Structures (CIS). The model is designed based on the previous response-history analysis done in the ABAQUS model. The base mat below the stick model has the dimension of, length of 79.248m and width of 48.643m for analysis purposes. The model is based on a simplified 3D lumped mass stick model.

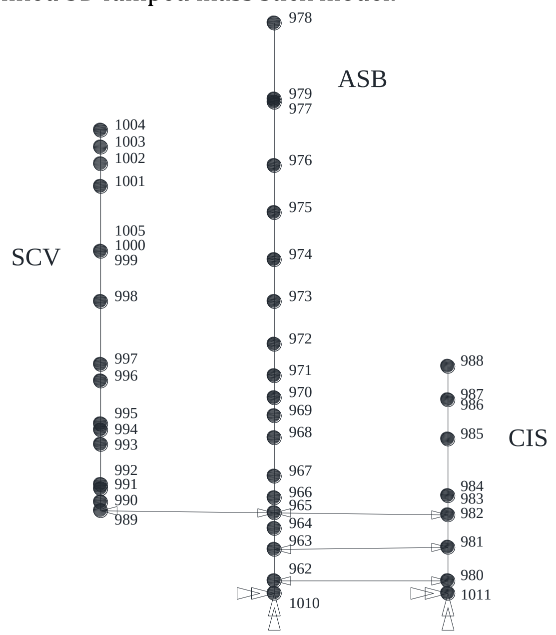
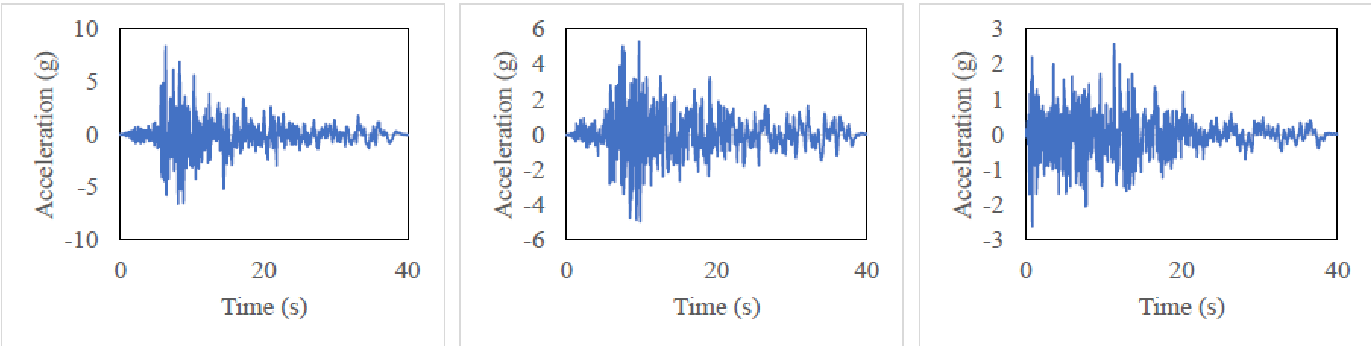


Figure 5: Lump Mass Stick Model AP1000

Table 1: Isolator properties

Case no.	Supposed Isolation Device	Vertical Properties			Horizontal Properties		
		Frequency f_v (Hz)	Stiffness k_v (kN/m)	Damping ξ_v	Frequency f_h (Hz)	Stiffness k_h (kN/m)	Damping ξ_h
1	Lead Rubber Bearing	60	1.8x 10^7	5%	0.492	3.0x 10^4	5%
2	Thick Rubber Bearing	8	9.8 x 10^5	10%			
3	Thick Rubber Bearing	5	3.2 x 10^5	13%			
4	Thick Rubber Bearing	3	1.2 x 10^5	20%			



(a) (b) (c)

Figure 6: Input Motion (186 Imperial Valler-06) (a) X- direction, (b) Y- direction, and (c) Z direction

Additionally, as illustrated in Figure, node pair 965-982 is coupled in two horizontal directions to simulate in-plane connection, and node pairs 980-962, 981-963, 989-965 are coupled in six degrees with Multi Point Constraints (MPC) beams to simulate a complete rigid connection. The bottom elevations of ASB, SCV, CIS sticks are 18.44m, 30.48m, 18.44m in proper order, and their total heights are 83.10m, 55.44m, 33.07m, respectively. The mass ratio of ASB, SCV, and CIS in the whole model is 86%, 3%, and 11%, respectively. In the study of acceleration responses, the top points named 978, 1004, 988 in ASB, SCV, CIS sticks, and 481 in the base mat, are considered.

The representative model of AP1000 was analyzed using Nonlinear response history analysis in SAP2000, to examine the effect of different 3D isolation systems and compare the response of each model of isolator with one another.

2.1.1 Isolator Parameters

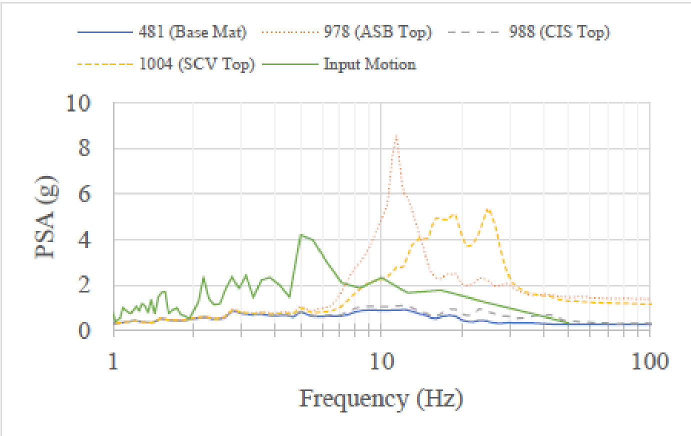
In this paper, we focused on investigating parameter characteristics of lead rubber isolators for AP1000 sticks isolation model. The isolator is designed to be bilinear and has a plan dimension of 1400mm with a total height of 258 mm. The lead core diameter used is 180 mm with 31 no. of steel plates, while 32 number of rubber layer with 5 mm thickness were used for simulation. The elastic modulus of the lead is 15995.92 MPa, and the designed strain value is 200% for the isolator. The number of isolators used is 408 for the base mat to be decked onto. The case properties can be seen in Table 1.

The designed isolation period from the calculations presented can be noted as 2 seconds, and the number of isolators are 408. During the parameter testing of the isolators, K2, Qd, K1, and Kv are 2949.178kN/m, 241.07kN, 30004kN/m and 18 X 10^6 kN/m. A high value of the vertical stiffness is selected to prevent the rocking effect while effective isolation.

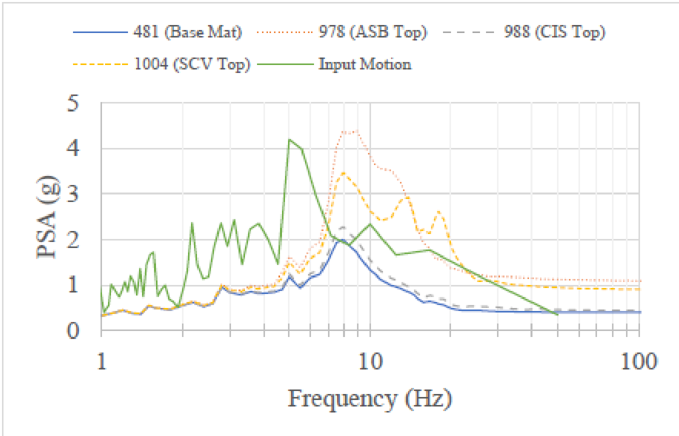
2.2 Response of the isolators

Table 2: Modal Information

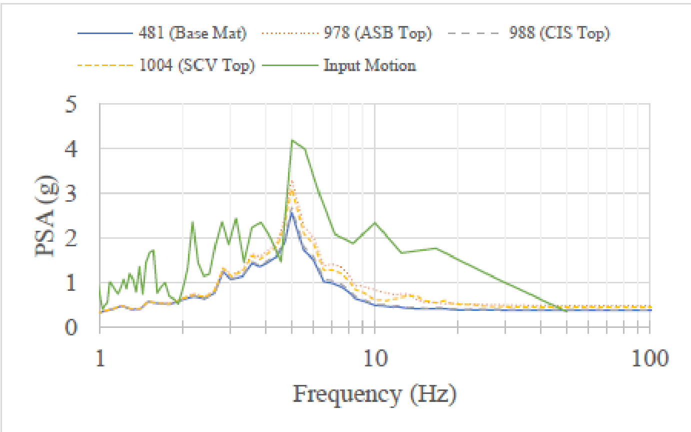
Mode no.		1	2	3	4	5	6	7	8	9	10	11
Case 1	Freq. (Hz)	0.494	0.494	0.569	3.645	3.913	5.881	5.889	8.926	10.515	11.020	**11.395**
	Dir.	UX	UY	RX	UX	UY	UX	UY				**UZ**
Case 2	Freq. (Hz)	0.494	0.494	0.563	3.606	3.831	5.854	5.861	**7.938**	8.926	10.449	10.910
	Dir.	UX	UY	RX			UY	UX	**UZ**			
Case 3	Freq. (Hz)	0.493	0.494	0.561	3.571	3.800	**4.939**	5.841	5.843	8.926	10.334	10.869
	Dir.	UX	UY		UX	UY	**UZ**	UX	UY			
Case 4	Freq. (Hz)	0.493	0.494	0.560	**3.086**	3.547	3.790	5.83	5.840	8.926	10.178	10.848
	Dir.	UX	UY	RX	**UZ**			UX	UY			



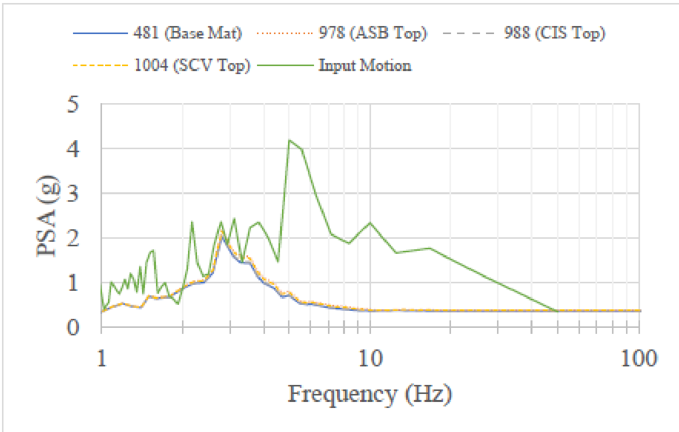
(a)



(b)



(c)



(d)

Figure 7: Comparison of PSA among different frequencies, in vertical direction for different joints in elevation (a) 60 Hz, (b) 8 Hz, (c) 5 Hz, and (d) 3 Hz

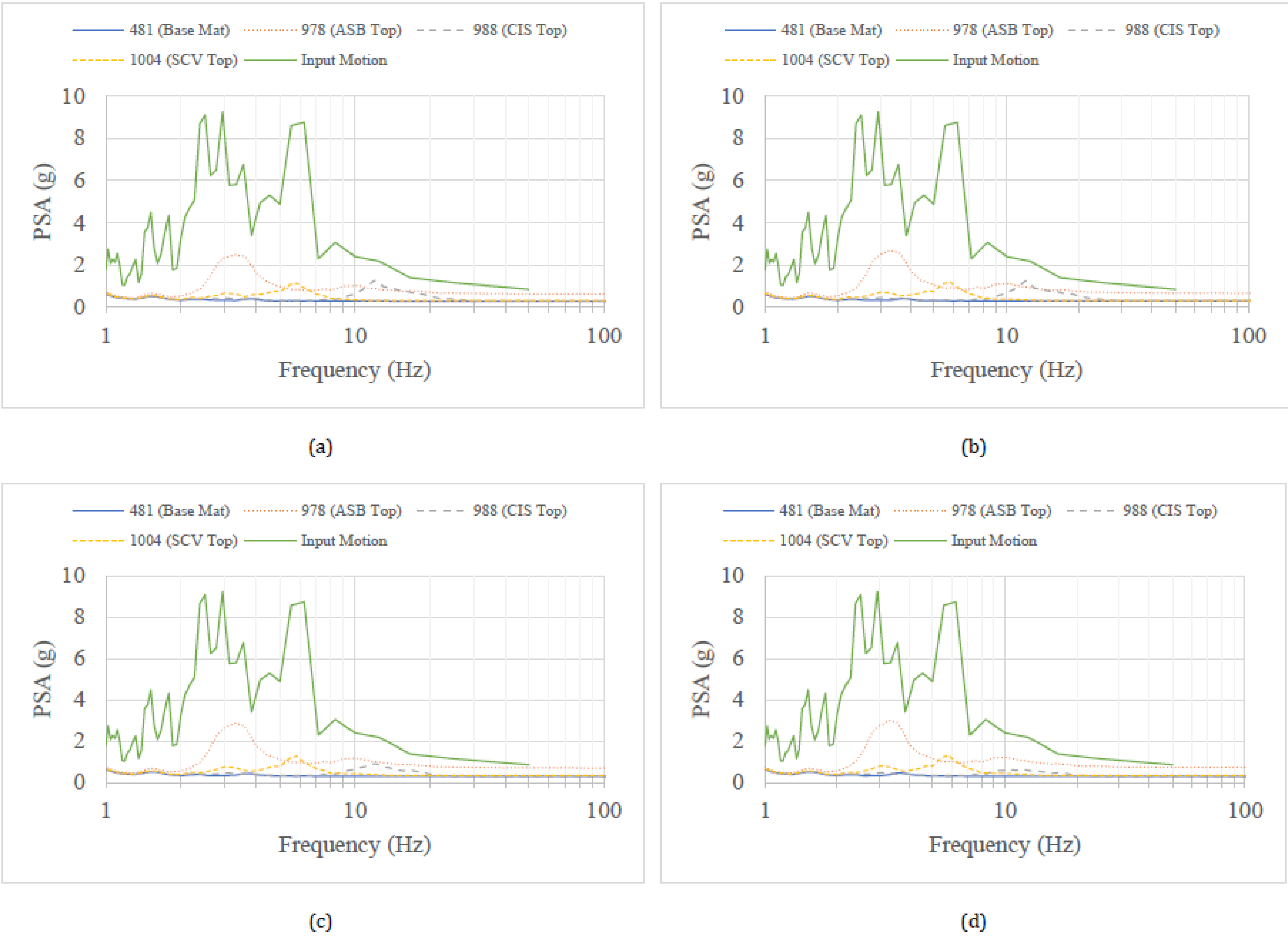


Figure 8: Comparison of PSA among different frequencies, in horizontal direction for different joints in elevation (a) 60 Hz, (b) 8 Hz, (c) 5 Hz, and (d) 3 Hz

To begin research the model was first tested for natural fundamental frequency of the structure and the first translation in vertical direction was taken into account, which can be seen from Table 2.

This model of AP1000 is held over by 408 number of isolators, and response of each isolator would be infeasible. Hence, we discuss the response of center isolators in this section while comparing deformation of isolator in

horizontal and vertical direction, can be seen in Figure 10. From the figures we can see that response of horizontal deformation of isolator orbit is same for almost all of the cases from 60 Hz to 3 Hz. It can be seen from comparison of vertical deformation that the amplitude of response increases as the frequency decreases from 60 Hz to 3Hz, f_v.

Comparison of response of isolator, at center, among axial force and shear force X and the shear force Y is illustrated in Figure 9. The response isolator for shear force X and shear force Y shows no significant large changes for frequency 60 Hz to 3 Hz. The isolator shear forces show decrease from higher frequency, 60 Hz, to lower frequency 3 Hz, as the peak shifts over the time period devised.

2.3 Response of spectral accelerations and displacements of the superstructure

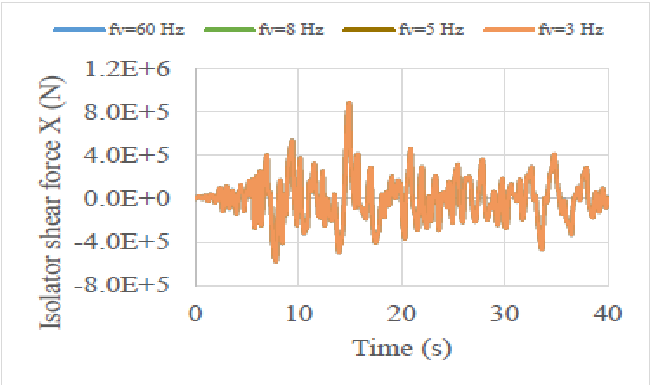
Pseudo spectral acceleration (PSA) in vertical direction and horizontal direction for isolated structure is shown in Figure 7, expressed in terms of g, the acceleration of gravity. It is seen that for the case of 60 Hz, the first peak translation is noted to be at 11.395 Hz. From table of the modal frequencies for different cases of vertical direction frequency it can be seen clearly there is amplification of spectra in vertical direction for ASB in the frequency noted.

The vertical spectral acceleration is seen reduced when this shift is made from 60 Hz to 8 Hz. This change can be noted significant when the frequency is reduced to 3 Hz, as seen in

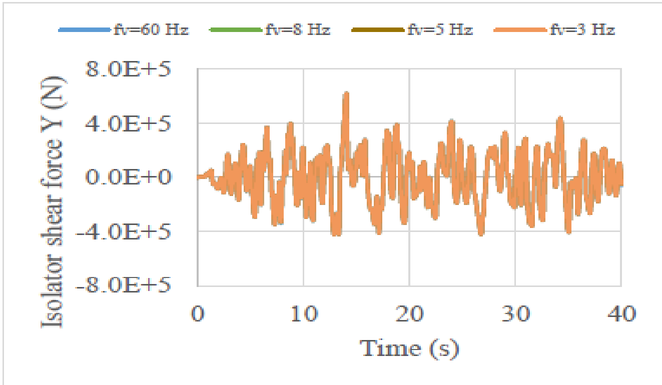
Figure 7. Considering the vertical spectral acceleration for ASB, SCV and CIS, following the reduction in the vertical frequency of the isolators, it can be seen that the reduction in frequency has similar behavior pattern of reduction in PSA for ASB and SCV but the pattern differs for CIS and Base mat as the natural vertical frequency of the CIS lies further in the range of 35-45 Hz and the peak of input wave ranges from frequency 5-6 Hz.

Hence, the reason for increase in the CIS behavior might because of the shift from natural frequency of the structure. It can be seen from Figure 7 the amplification of the value of PSA for CIS, when the vertical frequency is in range of 5 Hz.

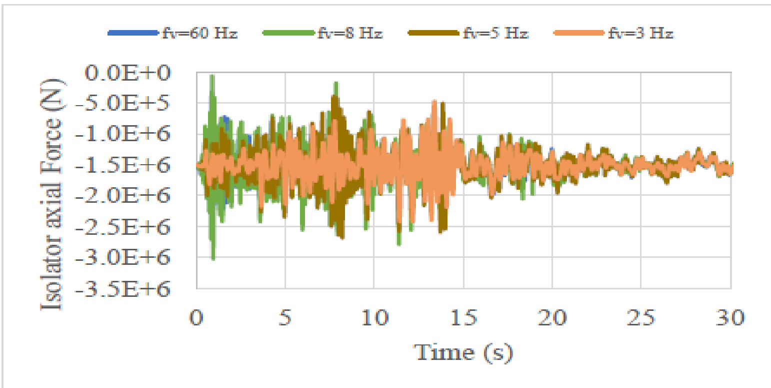
Even though the input motion consists of both X direction and Y direction components in horizontal direction, for this result we represent the data of horizontal spectral



(a)



(b)

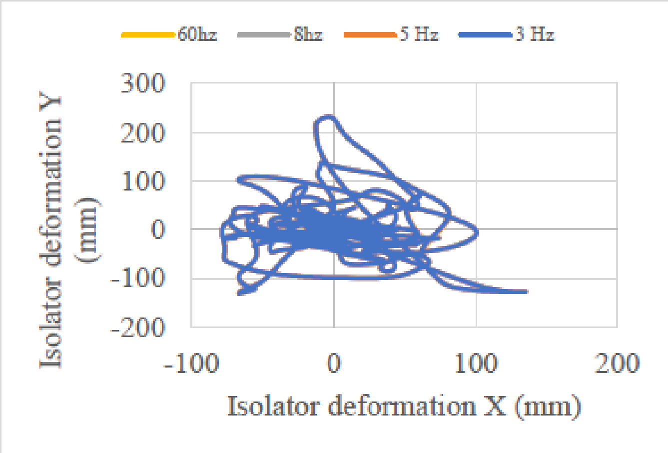


(c)

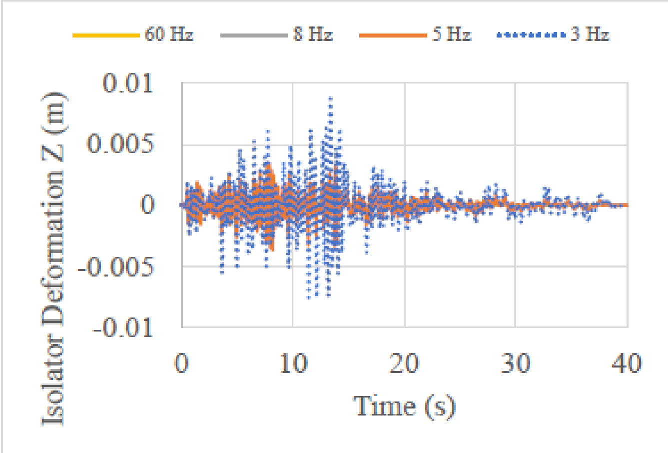
Figure 9: Response force comparison of the center isolator for one of the wave cases (a)Isolator shear force X for Case 1-4. (b) Isolator shear force Y for Case 1-4. (c) Isolator axial force for Case 1-4, corresponding to wave 186 Imperial Valler-06.

Table 3: Maximum Acceleration and Displacement for different cases

Remarks		Max acceleration (m/s²)			Max displacement (m)		
		ASB top	CIS top	SCV top	ASB top	CIS top	SCV top
Response	60 Hz	13.790	2.872	11.670	0.1693	0.1691	0.1692
	8 Hz	10.460	4.237	10.380	0.1695	0.1694	0.1695
	5 Hz	4.716	4.314	4.314	0.1702	0.1702	0.1702
	3 Hz	3.222	3.096	3.259	0.1709	0.1708	0.1709



(a)



(b)

Figure 10: Response deformation comparison of the center isolator among the different cases (a) Horizontal deformation for Case 1-4. (b) Vertical deformation for Case 1-4, corresponding to wave 186 Imperial Valler-06

acceleration in X direction. The horizontal frequency for the research has been kept at constant of 0.492 Hz. It can be seen from Figure 8, that horizontal spectra are amplified when they are met with their corresponding frequencies. The peak of CIS can be seen accelerate at frequency near 11 Hz which is similar to range of vertical peak acceleration, for the case of 60 Hz, this can be caused due to coupling effect.

From Table 3, the maximum observed acceleration on top of model is 13.790m/s^2. It can be noted how the behavior acceleration at the top of the structure varies, from the variation in acceleration values, in case of 60 Hz vertical frequency. This variation is slowly changes as the discrepancy within the variation of maximum acceleration value reduces when the vertical frequency is reducing, in case of 3 Hz. It was noted that during this process the displacement value increased in slight of 0.9-1.0% when decreasing the value of the vertical frequency from 60 Hz to 3 Hz.

3. CONCLUSIONS

1. Compared with each stick among these three with or without isolation, CIS has the minimum value of acceleration response, whereas ASB has the maximum value of acceleration response.

2. The increase in deformation of isolator can be seen when vertical frequency of the isolator is reduced, but this change can be noted as positive one as the Isolation system which complies with both vertical and horizontal isolation can be a significant improvement over the current generation of isolation techniques. Effectiveness of vertical frequency with the response to horizontal and vertical isolation can be seen when the frequency of isolation was kept at 3 Hz.

3. The comparison of maximum acceleration of the ASB, SCV and CIS showed the similar acceleration value in frequency 3 Hz whilst a difference of significance can be seen when the model was kept at isolation frequency represented by frequency 60 Hz, in a way such that 60Hz>8Hz>5Hz>3Hz.

4. A significant increase in isolation of vertical direction was seen when the vertical frequency of the isolation device was reduced from 60 Hz to 3 Hz, hence shifting the resulting peak response of the structure. The effect of the change in the vertical direction parameters could be seen in the horizontal direction but could be noted as insignificant as compared to the changes observed in the vertical response of the structure.

From earlier studies on the isolator with similar frequency, as presented in one of the papers by Zhou. Et al., it can be seen that the vertical response spectrum of the superstructure with the frequency of isolator of 3 Hz can efficiently reduce the vertical in-structure responses for AP1000 model, studied here.

The study did not participate vertical isolator frequency below 3 Hz as in previous experimentation by various researchers it was found that below the stated frequency a rocking motion was noticed which is an undesirable component for this study, hence requirement of possible rocking suppression devices was noted to continue with the experiment.

The study concludes with result of performance effectiveness of 3D isolation when the frequency is 3 Hz with 20% damping in vertical direction and 0.492 Hz with 5% damping in horizontal direction, compared to the other frequencies discussed, in this paper.

This paper is an excerpt from an extensive thesis research of a graduate course of topic "Nonlinear Response Study of Structures Using Vertical and Three Dimensional Isolation Systems". The research incorporates 20 different waves scaled according to the geometric mean scaling method. The wave discussed in this paper is a part of the research and not the whole research itself.

ACKNOWLEDGEMENT

I would like to thank Prof. Zhou Zhiguang, Tongji University, for his patience and guidance throughout the process of this research.

REFERENCES

[1] Farzad Naeim and James M. Kelly. Design of Seismic Isolated Structures. 1999.

[2] Zhiguang Zhou, Jenna Wong, and Stephen Mahin. Potentiality of Using Vertical and Three-Dimensional Isolation Systems in Nuclear Structures. Nuclear Engineering and Technology, 48(5):1237–1251, 2016.

[3] Gordon P. Warn and Keri L. Ryan. A Review of Seismic Isolation for Buildings: Historical Development and Research Needs. Buildings, 2(3):300– 325, 2012.

[4] Osamu Takahashi, Hiromasa Aida, Junji Suhara, Ryoichiro Matsumoto, Yasuo Tsuyuki, Takafumi Fujita, and Kozo Keikaku Engineering. Construction of Civil Building Using Three Dimensional Seismic Isolation System (Part 1, Design of Building Using Three Dimensional Seismic Isolation System). In The 14 th World Conference on Earthquake Engineering, 2008.

[5] Yin Nan Huang, Andrew S. Whittaker, Michael C. Constantinou, and Sanjeev Malushte. Seismic demands on secondary systems in base-isolated nuclear power plants. Earthquake Engineering and Structural Dynamics, 2007.

[6] E Blanford, E Keldrauk, M Laufer, M Mieler, J Wei, B Stojadinovic, and P F Peterson. ADVANCED SEISMIC BASE ISOLATION METHODS FOR MODULAR REACTORS. Technical report, United States, 2010.