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THREE-DIMENSIONAL SEISMIC ISOLATION OF SMALL MODULAR REACTORS USING METAMATERIALS AND ELASTOMERIC BEARINGS

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ABSTRACT

Seismic base isolation technology has significantly contributed to safeguarding structures from earthquake-induced excitations. Unlike the ductile detailing method, which increases the lateral strength of structures and introduces inelastic behavior, base isolation protects structures without much altering their conventional load-bearing design. This is particularly beneficial for nuclear reactor designs that often vary based on seismic conditions on the sites. A standardized design of advanced nuclear reactors would reduce the overall cost of nuclear construction. The existing designs predominantly emphasize horizontal isolation, depending on the gravity loads for safety against vertical earthquake excitations. However, it is crucial to consider increased vertical shaking at near-fault sites, which may be further amplified due to the provision of vertically stiff horizontal isolation bearings. This study proposes a three-dimensional isolation system combining a metamaterial-based periodic isolation system for attenuating seismic waves in the vertical direction with an elastomeric rubber bearing for isolation in the horizontal direction. A high-temperature gas reactor building is isolated using this proposed system to check its efficacy. The design and numerical modeling of the three-dimensional isolation system for adequate load-bearing capacity and frequency bandgap requirements for the HTGR building are discussed in detail. The paper extensively evaluates the effectiveness of the system through steady-state dynamic analysis, modal analysis, and fast non-linear time history analysis. While successfully reducing seismic response in both horizontal and vertical directions, the modal analysis reveals predominant shear deformations in combination with some rocking motions. The proposed isolation system provides a passive, simple, easy to construct solution for seismic safety and further assisting in standardization of advanced nuclear reactors.

INTRODUCTION

The wide-scale generation of nuclear power as a clean source of energy has been limited due to capital costs associated with the deployment of conventional reactors, seismic safety concerns, and non-standardization of safety-related nuclear structures/components. Recent developments in advanced reactors provide an opportunity for wider adoption and application of nuclear power. The small modular reactors (SMRs) intend to address concerns related to design, construction, operation, and safety. Consequently, researchers have explored standardized designs for advanced nuclear reactors by incorporating seismic base isolation technology, implemented either in the complete nuclear building or specifically for safety-class equipment (Parsi et al. 2022; Lal et al. 2023). The seismic isolation of safety-related nuclear structures is effective in reducing the earthquake forces in the horizontal directions, but the protection against vertical seismic excitation is limited (e.g., Kumar *et al.* (2013), Kumar and Kumar (2023)). The consideration of vertical seismic hazard is important for safety-related non-structural components, especially for near-fault sites (Beresnev et al. 2002). In such cases, two-dimensional (2D) isolation systems like rubber or sliding bearings might exacerbate the vertical effect. Therefore, three-dimensional (3D) isolation systems become essential for these conditions. The SMRs are suited for 3D isolation because of the small axial requirements on individual isolators and the ease of implementation when compared to conventional reactors.

The 3D isolation systems developed so far consist of Elastomeric rubber bearings (ERB) with low shape factor, GERB systems utilizing spring-damper devices, combined horizontal-vertical seismic isolation systems (rubber/sliding bearings + springs), hydraulic isolators, cable-reinforced 3D air springs, and rolling seal-type air springs ((Huffmann 1985; Buckle et al. 2002; Kageyama et al. 2003; Kashiwazaki et al. 2003; Suhara et al. 2003; Lee and Constantinou 2017; Zhu et al. 2022)). Though effective, these devices have one or more limitations such as low horizontal acceleration response reduction, limited vertical isolation, complexity, high cost, and dependence on continuous power supply. The metamaterial based periodic isolation systems (PIS) have gained popularity in the field of earthquake engineering due to its amazing wave filtering ability. The PIS can be in the form of one dimensional (1D), 2D, and 3D based upon the direction of repetition of unit cells. However, 1D-PIS cannot simultaneously filter out horizontal and vertical seismic excitations due to difference in their frequency content. While 2D and 3D PIS has complex geometry and in general PIS has impractical material and geometrical property requirements suited for filtering out typical frequency content of earthquakes (Witarto et al. 2016; Mu et al. 2020).

This study adopts the standardized design of a high-temperature gas reactor (HTGR) building, as presented by Parsi et al. (2022), to assess the effectiveness of 3D isolation system in such structures. A 3D isolation system (3D-IS) combining 1D-PIS and ERB is proposed to be used for the HTGR building. The 1D-PIS is designed to support the superstructural load and to generate low starting frequency (SF) with wide bandgap (BG) for attenuating the seismic waves in vertical direction. To achieve higher load bearing capacity, the soft rubber layers in unit cells of 1D-PIS are reinforced with steel shims without effecting its wave filtering ability. The ERB is designed to provide isolation in the horizontal direction using the concept of period lengthening. The independent working of the two components (1D-PIS and ERB) in the combined isolation system is ensured through provision of steel casing at the periphery of 1D-PIS. The steel casing will serve as the horizontal force transfer body while still facilitates the smooth vertical motion of 1D-PIS. A discrete modelling approach has been implemented in finite element software SAP2000 (CSI, 2023) for simulating the combined 3D-IS. A comprehensive numerical analysis showing the efficacy of the proposed system in isolating the HTGR building is conducted through steady state dynamic analysis, modal analysis, and fast non-linear time history analysis. The proposed system was found to be effective in isolating the structure both in horizontal and vertical direction. Nevertheless, the existing 3D-IS arrangement in the HTGR experiences rocking motion, even though the primary deformation modes remain predominantly shear. Exploring alternative configurations of these 3D-IS will be necessary in the future to further mitigate rocking motions.

SEISMIC METAMATERIAL BASED 1D-PIS

Seismic metamaterials are artificial periodic isolation systems with unique property of creating frequency bandgaps. The basic principle involves the destructive interference between scattered and incoming seismic waves, presenting a novel approach to seismic wave control distinct from traditional strategies. The effectiveness of 1D-PIS lies in its ability to generate a low starting frequency (0.1 Hz to 20 Hz) and a wide frequency bandgap typically found in earthquakes. The necessity for a low-frequency bandgap mandates the utilization of extremely low shear modulus materials in unit cells of 1D-PIS. This requirement confines the application of 1D-PIS to raft foundations beneath superstructures, where isolated 1D-PIS systems may experience reduced stability. Despite this limitation, this study explores the possibility of using the 1D-PIS as an isolated system for individual footings for vertical isolation. The 1D-PIS is encased in a steel casing to achieve stability against lateral deformation while retaining its ability to generate bandgaps for vertical wave attenuation.

PROPOSED 3D ISOLATION SYSTEM

HTGR buildings feature three safety-class components: the reactor vessel, steam generators, and a control rod drive mechanism, as illustrated in figure 1 (a). Seismic safety and design standardization are crucial for SMRs at any site. A 3D isolation system would be very beneficial in such a scenario. This section discusses the design objectives of the proposed 3D-IS for HTGR gas reactors. The 3D isolation system is a combined system which utilizes 1D-PIS for attenuation of vertical seismic waves and ERB for isolation in horizontal direction. The ERB is well known for its high vertical stiffness and low horizontal stiffness. The 1D-PIS has to be horizontally rigid to ensure complete horizontal force transfer from the ground to the ERB. The 1D-PIS should also have adequate load bearing capacity to sustain the superstructural load without compromising the frequency attenuation characteristics (i.e., bandgap and the starting frequency) in vertical direction.

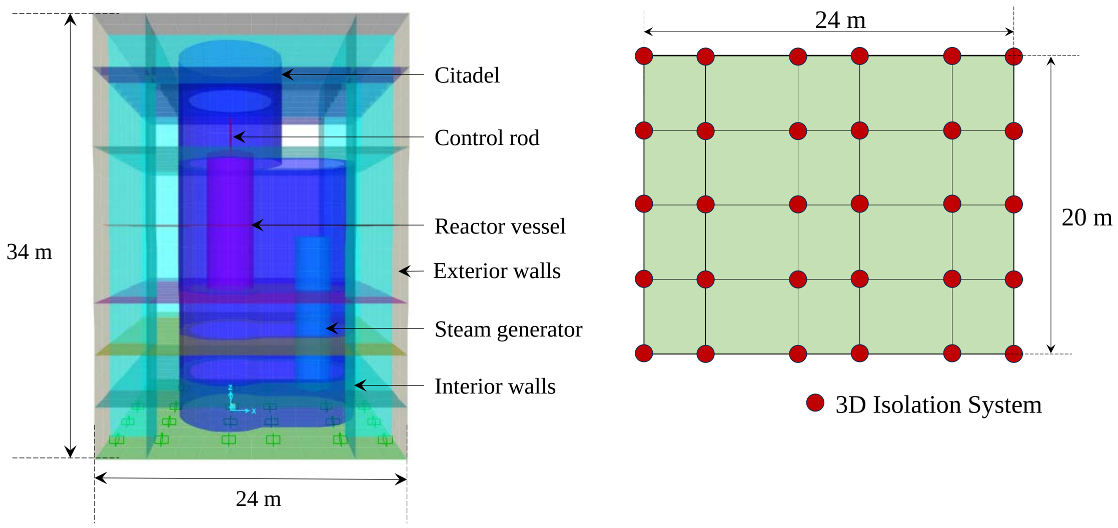


Figure 1. (a) HTGR building specifications (b) location of 3D-IS at the base

Design of 1D-PIS for Gravity Load

Designing a 1D-PIS as an isolated system for individual footings with sufficient load bearing capacity and a low-frequency bandgap (BG) is a challenging task, given the estimated mass of the HTGR building at approximately 11,500 tons. A two-layered unit cell with a low shear modulus material layer (e.g., rubber) and a high-density material layer (e.g., steel/concrete) is required with substantial thickness (Witarto et al. 2016) for generating distinct low frequency bandgaps. This introduces challenges in maintaining stability in low shear modulus material layer under high bearing pressure. For that purpose, in this study, the low shear modulus thick rubber layers in unit cells of 1D-PIS are reinforced with intermediate steel shims. The thickness of the rubber layer between the steel shims is decided based upon the shape factor required to achieve the desired stiffness (Buckle et al. 2002). Initially, to gain insight into the load distribution on each individual 1D-PIS resulting from the HTGR building load, the configuration of the combined 3D isolation system at the base is set, as shown in Figure 1 (b). Subsequently, the 1D-PIS is designed to ensure that its critical buckling pressure, calculated according to the equation provided in (Kelly 1967)) (equation 1 and 2), remains lower than the factored service load pressure ($P_{crit(design)} > P_{service}$), as depicted in Table 1. The critical buckling pressure is evaluated for both square as well as circular cross sections of 1D-PIS.

$$\frac{p_{crit}}{G} = \frac{\pi}{2\sqrt{2}} S\lambda \text{ for circular cross section} \tag{1}$$

$$\frac{p_{crit}}{G} = \frac{\pi}{\sqrt{6}} S\lambda \quad \text{for square cross section} \tag{2}$$

where, p_{crit} is critical pressure, G is shear modulus of rubber, S is shape factor, λ is aspect ratio (lateral dimension/rubber thickness).

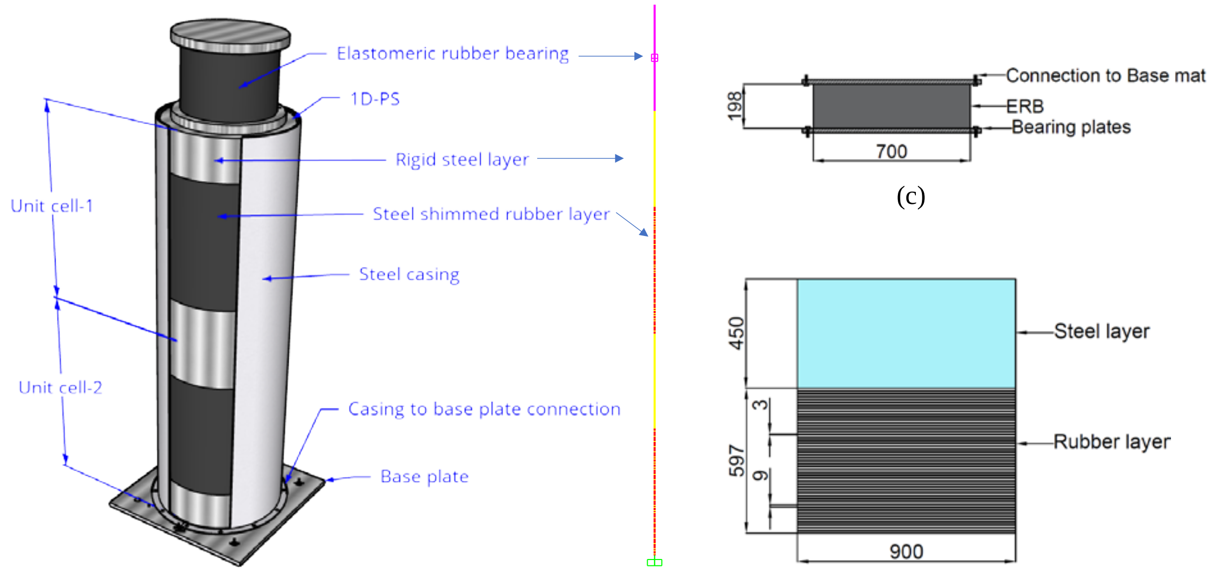
The thickness of individual rubber layer between the steel shims in the unit cells of the 1D-PIS was selected based on the desired load-carrying capacity. While the overall layer thickness was determined to align with the targeted frequency bandgap, as discussed in the following section. The components of 3D-IS are combined in such a way that the 1D-PIS is isolating the structure vertically without interference from ERB. Simultaneously, ERB isolates the structure horizontally without affecting 1D-PIS. To facilitate this, a steel casing surrounds 1D-PIS, enabling free vertical movement within the casing while restricting horizontal motion. The steel casing ensures complete horizontal force transfer to ERB and provides additional load-bearing capacity to 1D-PIS. A schematic representation of the proposed 3D-IS is shown in figure 2 (a).

Table 1: Critical buckling pressure of 1D-PIS

Factored load on individual PIS (kN)	Plan dimension (mm × mm)	Factored Pressure ($P_{service}$) (MPa)	Shear modulus of rubber (MPa)	Thickness of single rubber layer (mm)	Shape factor	P_{crit} for square cross section	P_{crit} for circular cross section
5651	900 × 900	7	0.2	9	25	12.80	11.10

Design and Numerical Modeling of 1D-PIS for Vertical Wave Attenuation

The 1D-PIS should have low SF and wide BG range, typically between 5 Hz – 20 Hz to effectively attenuate the vertical components of earthquakes. A 1D-PIS with two unit cells can provide sufficient isolation capacity (Witarto et al. 2016). Different material configurations of two layered unit cells were studied for attaining the desired attenuation characteristics (SF and BG) through transfer matrix method. The final design of 1D-PIS adopted for vertical isolation of HTGR building comprises of two layered unit cells having a 450 mm thick steel layer along with 450 mm thick steel shim reinforced rubber layer. Steel shims of thickness 3 mm have been used to reinforce the rubber layer at a regular interval of 9 mm to attain adequate load bearing capacity (as discussed in previous section). The geometric details of the adopted unit cell of 1D-PIS are shown in figure 2 (d).



(a) (b) (c) (d)

Figure 2. (a) Schematic representation of 3D-IS (b) Discrete stick model of 3D-IS in SAP2000 (c) Geometric details of ERB (d) Geometric details of unit cells of 1D-PIS

A discrete modeling approach is adopted for simulating 1D-PIS due to its computational efficiency. Unlike the ERB (named as rubber isolator link in SAP2000), the SAP2000 software package do not have a stiffness based inbuilt nonlinear link/spring elements. Thus, to simulate the 1D-PIS, each layer of the unit cells was manually built using frame section properties, as shown in the figure 2 (b). Also, to ensure accurate modelling of the 1D-PIS with steel casing at its periphery, constrained modulus of elasticity has been assigned to the material layers. The constrained modulus effectively depicts the infinite plan dimensions achieved through steel casing. Now, to represent the rigidity of steel casing in horizontal direction for complete horizontal force transfer to the ERB in the combined 3D-IS, rigid diaphragm constraint is used along the height of 1D-PIS model. The EBR was simulated using link element in SAP2000 with geometric and material properties as given in table 2 and figure 2 (c). The horizontal time period of the ERB with distributed load of HTRG building on each footing is 3.0 sec with vertical time period of 0.04 sec.

Table 2: Material and geometric properties of ERB

Diameter (mm)	Thickness of single rubber layer (mm)	Number of rubber layers	Shear modulus of rubber (MPa)	Shape factor	Effective horizontal stiffness (N/m)	Vertical stiffness (N/m)	Time period (sec)
700	6	25	0.6	29.2	1.72×10^{6}	7.85×10^{9}	2.96

Attenuation Characteristic of designed 1D-PIS

Steady-state dynamic (SSD) analysis is conducted to assess the frequency-based response of the 1D-PIS in the vertical direction within the range of 0.1 Hz to 50 Hz. Subsequently, the SF and the BG are determined by plotting frequency response function (FRF) curves, which is the logarithmic ratio of output response to input response. The FRF curves of the simulated 1D-PIS model in SAP2000 are plotted and validated using the transfer matrix method in figure 3(a). The frequency BGs of the 1D-PIS is between 11 Hz-30 Hz and 34.5 Hz-50 Hz for vertical wave attenuation. The 1D-PIS is then loaded with an equivalent HTGR building load on individual footings, and the FRF obtained is compared with the unloaded PIS case, as shown in figure 3 (b). The SF decreases (to 0.25 Hz) due to the superstructural load, consistent with the observations made by Witarto *et al.* (2018).

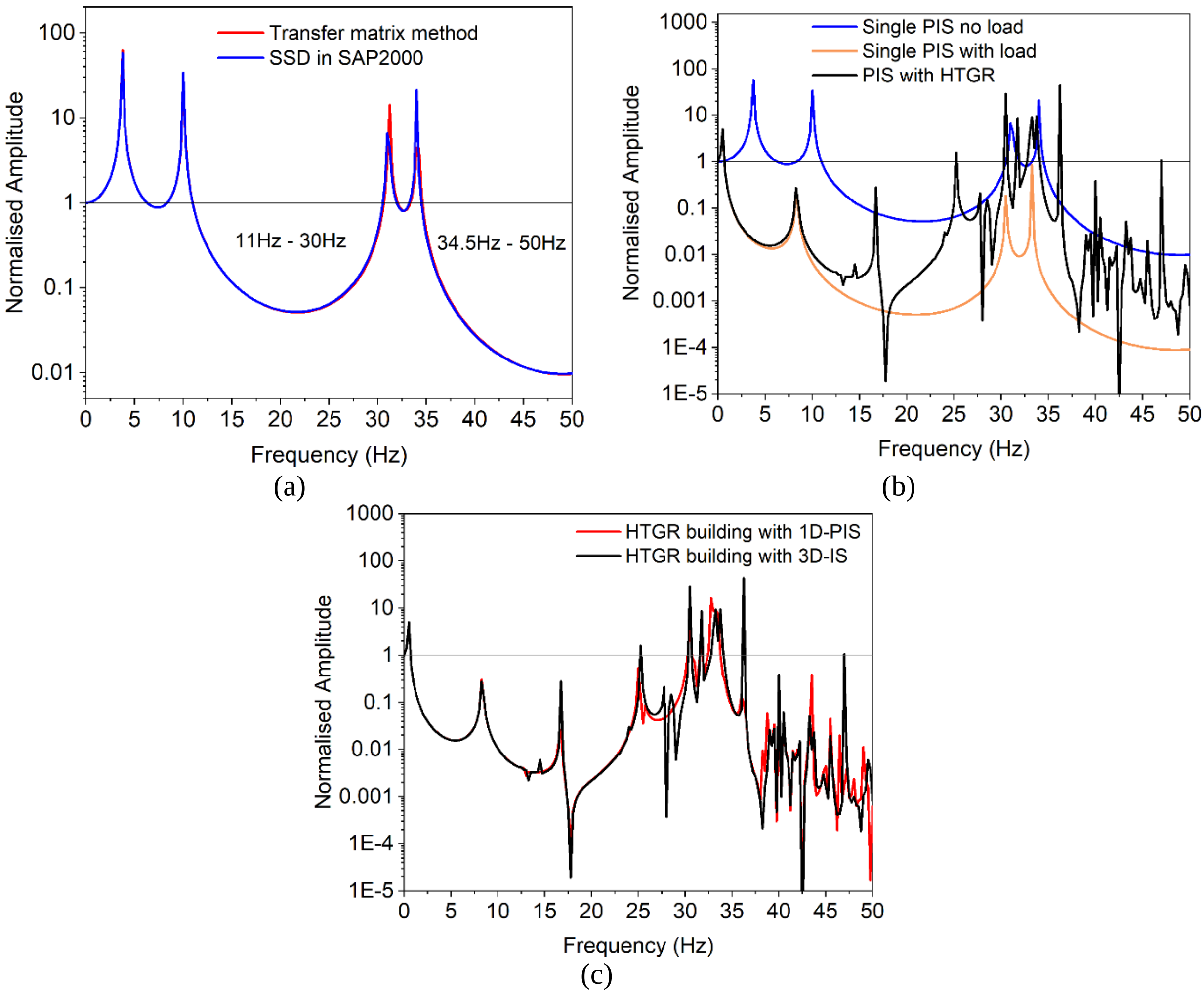


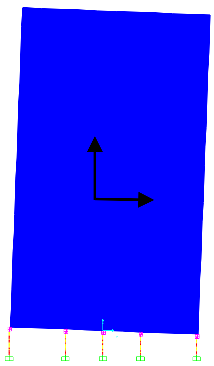
Figure 3. FRF curves for (a) validation of 1D-PIS discrete stick model (b) attenuation characteristics of 1D-PIS with HTGR (c) attenuation characteristics of 3D-IS HTGR with HTGR

SSD analysis is also conducted on the HTGR building equipped with 1D-PIS at the base (see figure 1 (b)), and the FRF results are obtained at the top-midpoint of HTGR. The obtained response aligns with the FRF of the loaded individual 1D-PIS. Additional kinks in the response are attributed to the resonance of various equipment within the HTGR building at specific frequencies. Finally, FRFs are assessed for the HTGR building installed with a set of 3D-IS. The FRF results in figure 3 (c) affirm that the presence of ERB at the top of the 1D-PIS does not impede the wave-filtering capability of the 1D-PIS.

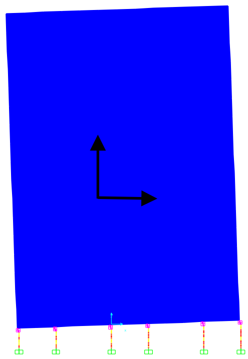
DYNAMIC ANALYSIS OF 3D ISOLATED HTGR BUILDING

Modal Analysis

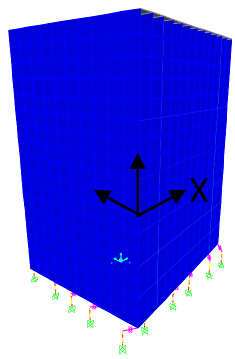
Modal analysis was conducted on the HTGR building isolated with the proposed 3D isolation system. The primary modes of vibration were identified as shear deformations, accompanied by rocking in both the x-direction and y-direction, illustrated in mode1 and mode2 of figure 4. However, the contribution of rocking motion is limited to 30% in these modes. Mode3 and mode4 represent torsion and vertical deformation modes in ERB and 1D-PIS, respectively. Rocking modes become more predominant in mode5 and mode6.



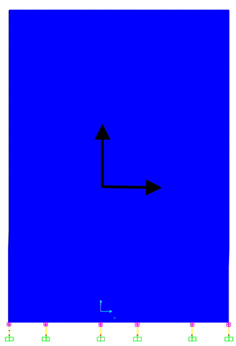
Mode1: Shear + rocking deformation
$T_1 = 6.8$ sec, $U_y = 70\%$, $R_x = 32\%$



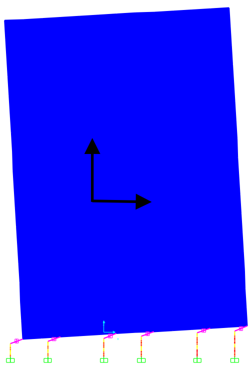
Mode2: Shear + rocking deformation
$T_2 = 5.8$ sec, $U_x = 72\%$, $R_y = 31\%$



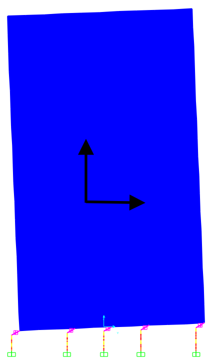
Mode3: Torsional deformation in ERB
$T_3 = 2.7$ sec, $R_z = 99\%$



Mode4: Vertical deformation in PIS
$T_4 = 2.2$ sec, $U_z = 99\%$



Mode5: Rocking + shear deformation
$T_5 = 1.7$ sec, $U_x = 28\%$, $R_y = 68\%$



Mode6: Rocking + shear deformation
$T_6 = 1.7$ sec, $U_y = 29\%$, $R_x = 66\%$

Figure 4. Mode shapes of HTGR building isolated with 3D-IS

The introduction of a vertical isolation component in the standardized design of the HTGR results in rocking motions, attributed to the high height-to-width ratio of structure. Suppressing rocking motions poses a challenge in 3D isolators (Lee and Constantinou 2018). Nevertheless, in the current design, shear deformations and vertical deformations are the dominant modes (mode1 to mode4).

Consequently, the authors have opted to conduct time history analysis on the current proposed configuration of 3D-IS in the HTGR building. However, future research must explore additional possibilities to mitigate rocking motions in the structure, potentially through the introduction of friction pendulum bearings at the peripheral points of structure. This approach may also aim to reduce the time period of the modes. It is important to note that investigating various isolator arrangements under the HTGR building goes beyond the scope of this paper.

Time History Analysis

The effectiveness of the proposed 3D-IS in isolating the HTGR building was evaluated through time history analysis. Fast non-linear time history analysis was conducted in SAP2000 with a constant nominal damping of 2% applied to the entire structure. Ground motions, varying in magnitude, frequency, and total period, were selected to examine the performance of the 3D-IS in isolating the HTGR building. Time histories of earthquakes, namely Bishops-1984, Anza-2001, Imperial Valley-1979, Loma Prieta-1989, and Chi-chi-1999, were adopted from the PEER NGA database (Pacific Earthquake Engineering Research Centre 2023). The HTGR building was subjected to both horizontal and vertical components of these earthquakes, and the response at the top-midpoint was compared with the input ground motions, as shown in figure 5.

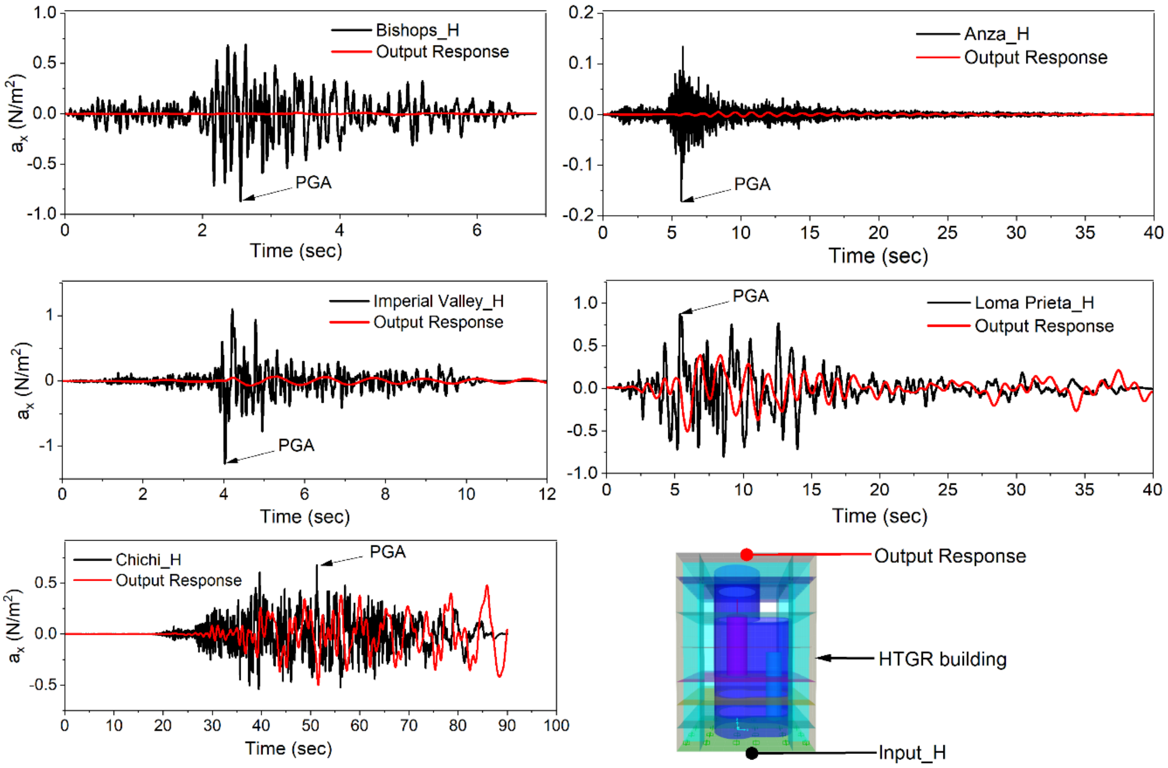


Figure 5. Horizontal acceleration time-history of 3D isolated HTGR building.

Bishops, Anza, and Imperial Valley are high frequency earthquakes, with predominant frequencies between 1 Hz and 10 Hz, thus, exhibiting significant response reduction in the horizontal direction. On the other hand, Loma Prieta and Chi-chi earthquakes, characterized by high energy concentrated in the 0.1 Hz to 1 Hz range, resulted in modal frequencies coinciding with the ground motion, leading to higher response. However, in all five cases, the response at the output was less compared to the Peak Ground Acceleration (PGA) in the horizontal direction, showing the efficacy of the 3D-IS.

The reduction of vertical input ground motions relies on the frequency bandgap concept of 1D-PIS. The output response of the HTGR building (at the top-midpoint) in the vertical direction was evaluated and compared with the input ground motions as shown in figure 6 (a) and (b), both in the time-domain and frequency-domain, respectively. In the time-domain results, it is evident that the response is reduced at the top for all five cases, except that the reduction is less pronounced in the case of Loma Prieta and Chi-chi earthquakes due to their low predominant frequency range falling outside the frequency bandgap. The frequency domain response results clearly illustrate the reduction in response for frequencies within the bandgap. The yellow shaded region highlights the frequency bandgap area. Therefore, it is apparent that for the response to be attenuated with 1D-PIS, the frequency of the incoming waves must strictly fall within the bandgap region. Therefore, this analysis convincingly demonstrates the effectiveness of the proposed 3D-IS in isolating the HTGR building both horizontally and vertically.

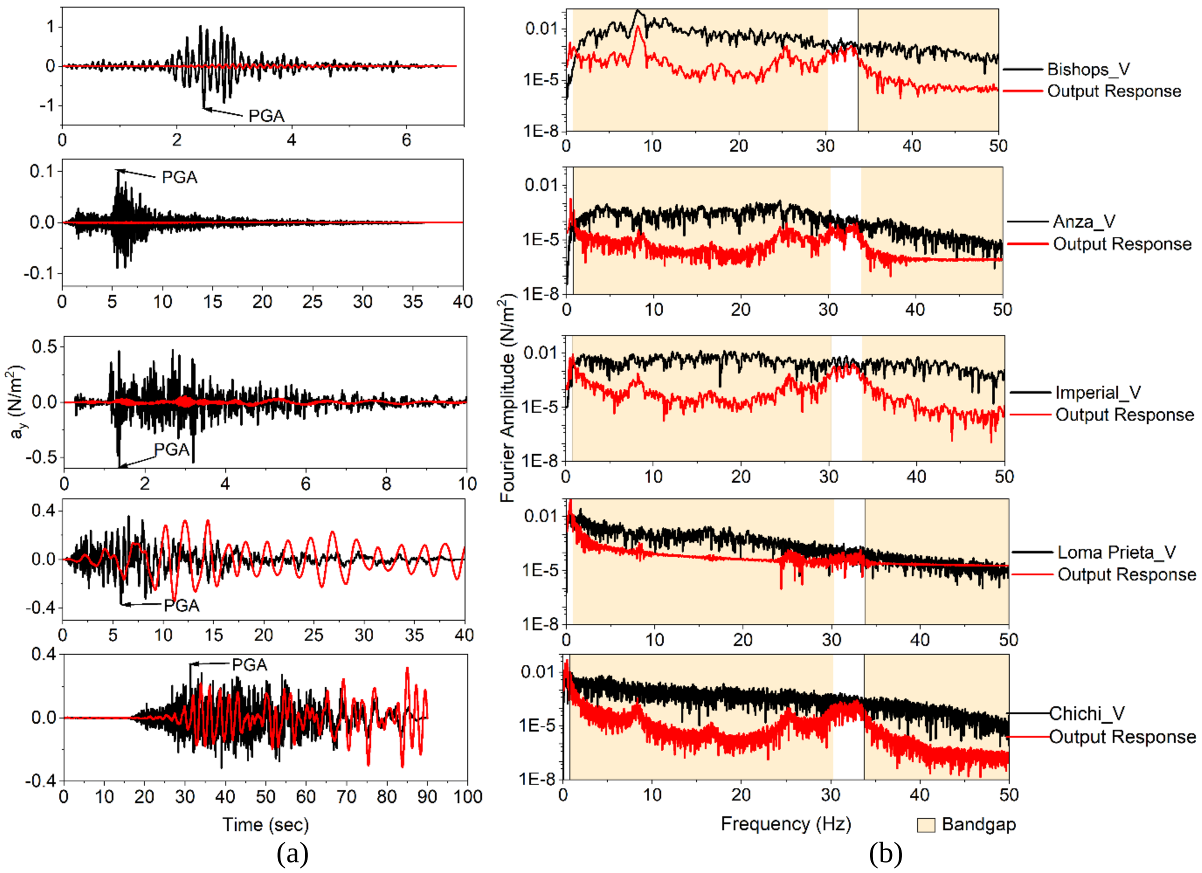


Figure 6. (a) Vertical acceleration history of 3D isolated HTGR building (a) time domain (b) frequency domain

SUMMARY AND CONCLUSION

The standardization of advanced nuclear reactors requires complete protection of structures from varying seismic hazards. This necessitates the implementation of base isolation technology to address both horizontal and vertical seismic loadings. Unlike traditional methods, base isolation employs rubber or sliding bearings to isolate structures without significantly altering their load-bearing design thereby standardizing the structural design. However, elastomeric or sliding bearings provide isolation only in the horizontal direction without addressing seismic safety in the vertical direction, which may especially be critical for varying seismic hazards at near fault sites. This paper therefore explores the application of a three-dimensional isolation system (3D-IS) to enhance the safety of structures. The 3D-IS proposed in this study is simple, passive, component independent and easy-to-construct. A high-temperature gas reactor (HTGR) building used an example case study. The vertical orientation of the HTGR is considered as it is likely to be more critical with respect to rocking induced axial (vertical) accelerations.

The 3D-IS combines a metamaterial-based periodic isolation system (1D-PIS) for vertical seismic waves with elastomeric rubber bearings (ERB) for horizontal isolation. The design and numerical modeling of the 1D-PIS and ERB are discussed, considering load-bearing capacity and frequency bandgap requirements. The load-bearing capacity of the 1D-PIS was effectively enhanced by incorporating intermediate steel shims into the soft rubber layer of its unit cells. The discrete stick modeling approach demonstrated that it can accurately replicate the wave-filtering capabilities of the 1D-PIS. The effectiveness of the proposed 3D-IS is evaluated through steady-state dynamic analysis, modal analysis, and fast non-linear time history analysis. Time history analysis using various ground motions demonstrates the efficacy of the 3D-IS in reducing seismic response in both horizontal and vertical directions. The modal analysis reveals predominant shear deformations with some rocking motions. The paper concludes by acknowledging the challenges of rocking motions in 3D isolators and suggests exploring alternative configurations for further mitigation. The horizontal orientation of HTGR or other SMRs with smaller aspect ratio may be better suited for such applications. Nevertheless, the proposed 3D-IS presents a promising solution for enhancing the seismic resilience of HTGR buildings through a combination of 1D-PIS and ERB.

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