

Time-domain finite element analysis of base isolation systems for nuclear power plants

*Jian Cheng, Sheng Yan, Wentao Hao**

Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing, China

*Corresponding Author. Email: haowentao@tsinghua.edu.cn

Abstract. Existing studies on base isolation for nuclear power plants have primarily focused on component-level mechanical performance tests of seismic isolation bearings and conceptual designs for individual structures. Systematic investigations of complete nuclear island systems and quantitative relationships between the stiffness of seismic isolation bearings and the effectiveness of nuclear island isolation remain limited. In this study, an advanced Small Modular Reactor (SMR) is selected as the research subject, and a simplified finite element model is developed to represent the mass distribution of the reactor building and its major equipment. Artificial ground motions synthesized from code-based response spectra are employed, and an implicit dynamic time-history analysis is conducted to systematically investigate the effects of the horizontal and vertical stiffness of isolation bearings on the acceleration responses of critical nuclear equipment, nozzle displacements, and building stresses. The results show that, following the implementation of base isolation, the peak acceleration is reduced to an average of 49% of that without isolation. A reduction in horizontal stiffness effectively attenuates horizontal responses. Lower vertical stiffness not only directly suppresses vertical vibration but also indirectly reduces horizontal acceleration by limiting foundation rotation, revealing the underlying mechanical mechanism of vertical–horizontal coupling. Nozzle displacements increase significantly with decreasing horizontal stiffness, whereas they exhibit little variation with changes in vertical stiffness. In addition, an equipment cost estimation method centered on the acceleration under the governing load case is proposed to quantify the reduction in equipment costs resulting from base isolation. The time-domain analysis framework established in this study, together with the identified parameter-dependent response characteristics, provides a methodological basis and data support for the standardization of seismic isolation design for nuclear islands.

Keywords: nuclear power plant, base isolation, laminated rubber bearing, implicit dynamic time-history analysis, acceleration attenuation

1. Introduction

Earthquakes are the most critical external natural hazards threatening the safety of nuclear power plants. Following the Fukushima Daiichi nuclear accident in Japan in 2011, the international community has imposed increasingly stringent requirements on the ability of nuclear facilities to withstand earthquakes beyond their

design-basis levels. Ensuring absolute safety while simultaneously maintaining economic viability and flexibility in site selection has therefore become a major challenge in nuclear power structural engineering.

At present, engineering approaches to earthquake protection can be broadly classified into four categories: seismic resistance, vibration reduction, seismic avoidance, and seismic isolation. Base isolation involves installing an isolation layer with horizontal flexibility and vertical rigidity between a building foundation and the supporting ground. By lengthening the natural period of the structure, the isolation system shifts the structure away from the predominant periods at which seismic energy is concentrated, while seismic isolation and damping mechanisms dissipate seismic energy and reduce its transmission to the structure. With base isolation, the large horizontal seismic forces are interrupted by the isolation layer, substantially reducing the peak response of the upper nuclear island structure under seismic excitation [1]. This can not only significantly reduce the amount of structural materials required, thereby lowering construction costs by more than 30%, but also minimize post-earthquake repair costs, as post-earthquake restoration generally requires only inspection or replacement of the isolation bearings [2]. More importantly, base isolation effectively "decouples" the foundation from the superstructure, potentially enabling a high degree of standardization in the design of future nuclear power plants. For different sites, only the parameters of the isolation layer would need to be adjusted, eliminating the need to repeat seismic qualification of the costly main nuclear island structures and their sophisticated internal equipment [3]. More than 20% of China's territory is currently located in seismic zones, and approximately 33% of destructive earthquakes worldwide occur in China. The application of seismic isolation systems could therefore alleviate seismic constraints on site selection and make the construction of nuclear power plants in high-seismic-intensity regions more feasible.

Base isolation for nuclear power plants cannot be regarded as a straightforward application of isolation technology developed for civil buildings. The internal structural configuration of a nuclear island differs substantially from that of a conventional civil building, and the acceleration levels that can be tolerated vary among different locations and components. Moreover, the use of base isolation can significantly amplify piping nozzle displacements. The connecting pipes between the reactor building and external auxiliary buildings must therefore accommodate larger relative displacements, resulting in a substantially increased risk of pipe rupture [4].

In terms of isolation devices, the bearings applicable to nuclear islands can be broadly classified into four categories: laminated rubber bearings, friction-sliding bearings, vertical spring bearings, and composite bearings. Among these, laminated rubber bearings have become the preferred option for seismic isolation in nuclear power plants because of their stable performance and strong self-centering capability. A laminated rubber bearing consists of multiple layers of thin rubber sheets and interleaved steel plates bonded together through vulcanization. The steel plates constrain the lateral deformation of the rubber, allowing the bearing to sustain vertical loads while maintaining extremely low horizontal shear stiffness [5].

Internationally, representative research on seismic isolation for nuclear power plants originated in the United States. For the PRISM and SAFR series of modular sodium-cooled fast reactors, the United States was among the first to complete the design and feasibility demonstration of laminated-rubber-bearing base isolation systems, with the objective of increasing the site-level ultimate safe shutdown earthquake level to 0.4g. The Korea Atomic Energy Research Institute developed three-dimensional composite bearings integrating horizontal and vertical isolation functions for the STAR-LM transportable liquid-metal reactor and demonstrated the technical feasibility of multidirectional seismic isolation. In China, research on three-dimensional isolation bearings has also been initiated for nuclear islands associated with low-temperature heating reactors, including preliminary performance testing and numerical simulations [6]. However, existing studies have largely focused on component-level mechanical performance testing and conceptual designs for

individual structures. Systematic coupled analyses of complete nuclear island systems have yet to be conducted. Quantitative conclusions regarding the effectiveness of base isolation for entire nuclear island systems remain limited, and the intrinsic relationship between the key parameters of seismic isolation bearings and isolation effectiveness has not yet been clearly established. These limitations have hindered the engineering implementation and practical deployment of seismic isolation technology in nuclear power plants.

2. Finite element analysis and simulation method

2.1. Reactor model

A simplified finite element model was developed based on an advanced Small Modular Reactor (SMR). The reactor adopts a symmetric dual-reactor configuration with two pressure vessels arranged in an integrated and compact layout. This configuration offers several advantages, including enhanced safety, a compact structure, simplified systems, and ease of operation. In particular, it exhibits typical characteristics of inherent safety and passive safety, making it promising for widespread application in multiple fields. Accordingly, this reactor was selected as the computational subject to investigate the effectiveness of applying base isolation technology to nuclear power plants, with the aim of further relaxing site-selection constraints and reducing seismic design costs.

In addition to the Reactor Vessel (RV), the major nuclear island process systems of the reactor, in terms of mass, include the Steam Generator (SG), Essential Cooling Water System (ECW), and Chemical and Volume Control System (CVC). To simplify the model and improve computational efficiency, the mass and center-of-gravity coordinates of each system were calculated according to its spatial arrangement. These parameters were incorporated as the principal factors in the model. Specifically, each system was represented in a simplified manner by a lumped mass point defined according to its mass and center of gravity, and was connected to the foundation of the reactor building through coupling constraints. In addition, the reactor building was modeled using a concrete structure with a coating layer. Table 1 lists the masses and center-of-gravity coordinates of the relevant systems, while Figure 1 presents the simplified finite element model. The x -, y -, and z -directions are defined as shown in Figure 1.

Table 1. Masses and center-of-gravity coordinates of the systems

No.	Major System (or Equipment) Name (One Side)	Mass (t)	Center-of-Gravity Coordinates (m)
1	Reactor Vessel (RV)	100	0.000, 0.000, 2.875
2	Steam Generator (SG)	60	5.200, 3.500, 2.875
3	Essential Cooling Water System (ECW)	40	-2.670, 8.210, 6.680
4	Chemical and Volume Control System (CVC)	60	1.040, 7.380, 2.575

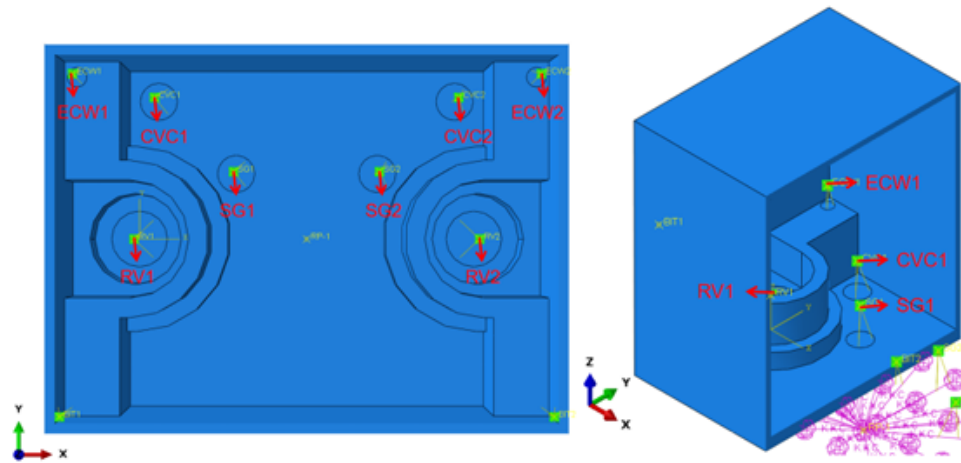


Figure 1. Simplified finite element model

The constitutive parameters of the concrete material were selected in accordance with the requirements of relevant nuclear safety codes and standards. The elastic modulus was set to 34.5 GPa, the Poisson's ratio to 0.2, and the density to 2,400 kg/m³. The reactor building has a wall thickness of 0.5 m and external dimensions of 19 m × 25.6 m. After completion of the model, the mass distribution of the overall structure could be characterized based on the stress distribution at its base, as shown in Figure 2.

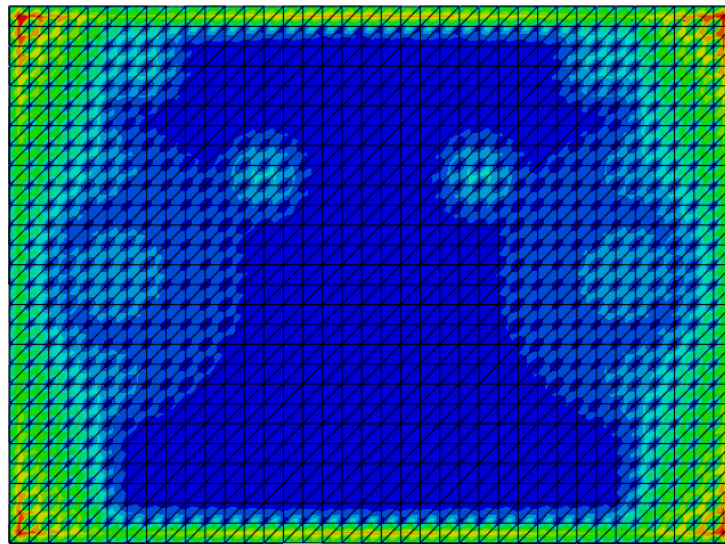


Figure 2. Stress distribution at the base

Solid elements were used for the analysis of the model. A finer mesh can provide more accurate computational results; however, reducing the element size also increases the computational time and resources required for dynamic analysis. After comparative analysis, the final mesh configuration shown in Figure 3 was adopted. The analysis was performed using the Abaqus implicit dynamic analysis procedure, with a total analysis duration of 20 s divided into 2,000 computational increments. Stress, displacement, and acceleration field variables were output during the analysis.

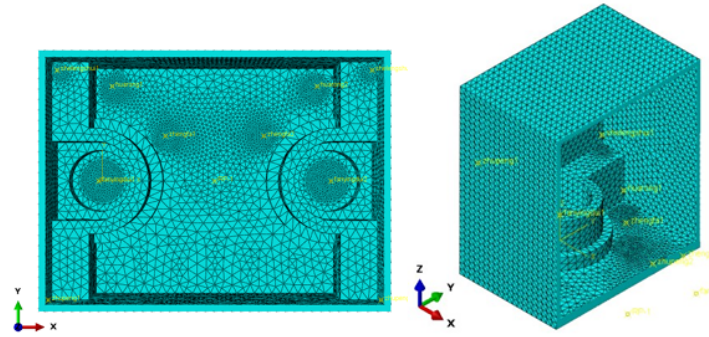


Figure 3. Finite element model mesh

2.2. Seismic response spectrum

To extend the applicability of nuclear power plants to higher seismic-intensity levels, this study adopts the standard response spectrum corresponding to an extremely high seismic intensity of Intensity Level 9 (seismic influence coefficient curve) as the input condition for the numerical analysis. The structural response under this seismic excitation is then evaluated. According to the relevant seismic design code, the design-basis earthquake corresponding to Intensity Level 9 has a Peak Ground Acceleration (PGA) of 0.9g, with a characteristic period of 0.35 s. The Kaul formula was used to convert the response spectrum into a power spectral density, and the acceleration time-history data were subsequently generated using the trigonometric series method. The resulting seismic-wave time-history curve (artificial response spectrum) is shown in Figure 4.

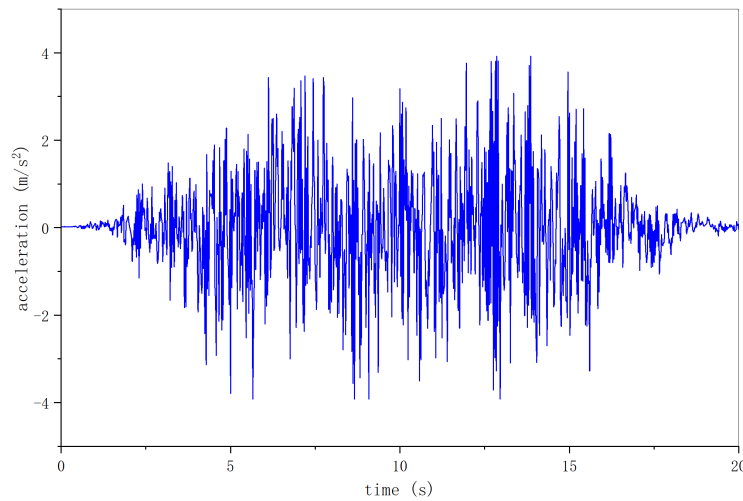


Figure 4. Seismic-wave time-history curve

To verify the consistency between the seismic-wave time-history curve (artificial response spectrum) and the standard response spectrum specified in the code, the time-history curve was transformed into the frequency domain and compared with the standard spectrum. The two spectra show good agreement, as illustrated in Figure 5.

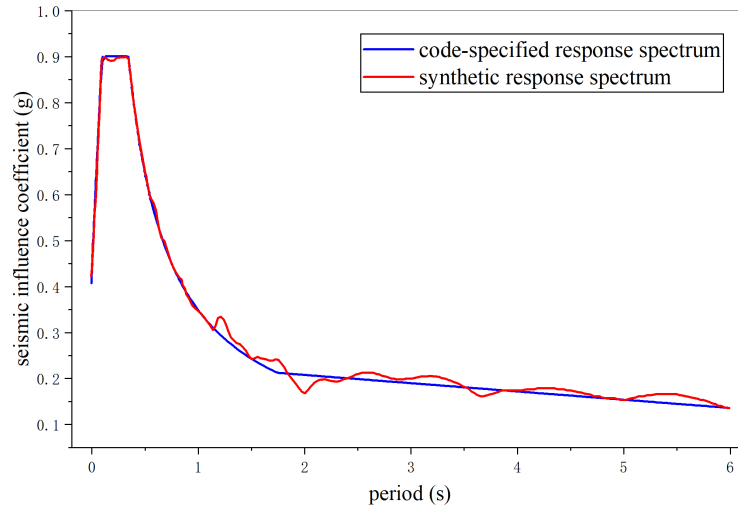


Figure 5. Comparison between the artificial and code-specified response spectra

According to the requirements of the seismic design code, the acceleration time histories in the three directions—horizontal direction 1 (x), horizontal direction 2 (y), and vertical direction (z)—are taken as 1.0, 0.85, and 0.65 times, respectively, the acceleration time history of the seismic wave. The definitions of the x -, y -, and z -directions are shown in Figure 1.

2.3. Seismic isolation bearings

Spring elements were employed to simulate the mechanical behavior of the seismic isolation bearings. In Abaqus, spring elements were established between the upper structure of the isolation layer and the foundation to represent the horizontal and vertical mechanical characteristics of the bearings. The horizontal stiffnesses are denoted by K_x and K_y , while the vertical stiffness is denoted by K_z . This approach simplifies the seismic isolation bearings as linear elastic connection elements, enabling their fundamental stiffness characteristics to be effectively represented while substantially reducing computational complexity.

Based on the characteristics of the seismic excitation, the target of seismic isolation control for the nuclear island is to increase its natural period to 2.5–4 s. Based on the natural-period equation for a single-degree-of-freedom system, calculations indicate that the corresponding total horizontal stiffness of the seismic isolation bearings is approximately 4.0×10^4 kN/m to 1.0×10^5 kN/m. Considering the weight of the nuclear island, the load-bearing capacity of the isolation bearings, and the length-to-width ratio of the reactor building, a total of 28 isolation bearings, arranged in a 7×4 configuration and uniformly distributed, were selected. Accordingly, the stiffness of each isolation bearing falls within the range of approximately 1,428–3,571 kN/m. The above range was further extended and representative values were selected for the parametric analysis. Accordingly, the horizontal stiffnesses of the isolation bearings considered in this study were 1,000, 2,200, and 4,000 kN/m. Based on the parameters of representative commercially available seismic isolation bearings, the vertical stiffness was set to 3.9×10^6 kN/m.

3. Results and discussion

Finite element analyses were conducted to investigate the effects of different horizontal and vertical isolation-bearing stiffnesses on the overall seismic isolation performance. Considering the actual design requirements of

nuclear power plants, the overall effectiveness of base isolation is evaluated in terms of the acceleration responses of individual pieces of equipment, piping nozzle displacements, stresses in the reactor building, and the potential changes in construction costs.

3.1. Effect of horizontal stiffness of isolation bearings on seismic isolation performance

3.1.1. Acceleration

The acceleration attenuation coefficient is defined as the ratio of the acceleration before and after the implementation of base isolation, i.e.,

$$\alpha = a_{iso}/a_0 \quad (1)$$

where a_0 and a_{iso} denote the maximum acceleration at the point of interest without and with seismic isolation bearings, respectively.

The effect of the isolation bearings on the key equipment is characterized using the acceleration attenuation coefficient. By varying the horizontal stiffness of the isolation bearings, the acceleration attenuation coefficients of the key equipment were obtained, as presented in Table 2 and Figure 6.

Table 2. Acceleration attenuation coefficients

Stiffness kN/m	Attenuation coefficient- <i>x</i>				Attenuation coefficient- <i>y</i>				Attenuation coefficient- <i>z</i>			
	RV	SG	ECW	CVC	RV	SG	ECW	CVC	RV	SG	ECW	CVC
1,000	0.391	0.564	0.171	0.225	0.359	0.452	0.386	0.255	0.523	0.595	0.788	0.669
2,200	0.633	0.688	0.223	0.342	0.387	0.489	0.415	0.3	0.532	0.578	0.608	0.654
4,000	0.675	0.929	0.262	0.353	0.51	0.497	0.438	0.341	0.536	0.564	0.64	0.636

It can be observed that the installation of seismic isolation bearings reduces the acceleration of the individual pieces of equipment to 0.2–0.93 times that under the non-isolated condition, demonstrating a significant base isolation effect. Both the horizontal stiffness of the isolation bearings and the spatial location of the equipment have a substantial influence on the resulting acceleration.

Overall, for the same equipment location, decreasing the horizontal stiffness leads to a corresponding reduction in the maximum acceleration in both horizontal directions. In contrast, changes in horizontal stiffness have a relatively limited effect on the maximum vertical acceleration (*z*-direction). The differences in the acceleration attenuation coefficients of the reactor vessel, steam generator, essential cooling water system, and chemical and volume control system are 3%, 8%, 29%, and 7%, respectively. The ECW exhibits the most pronounced difference. This is primarily because it is located at a relatively high elevation and far from the center of the floor slab. When the horizontal stiffness of the isolation bearings is low, the earthquake induces a larger inclination angle of the floor slab, and the resulting slab rotation causes a greater variation in its vertical acceleration.

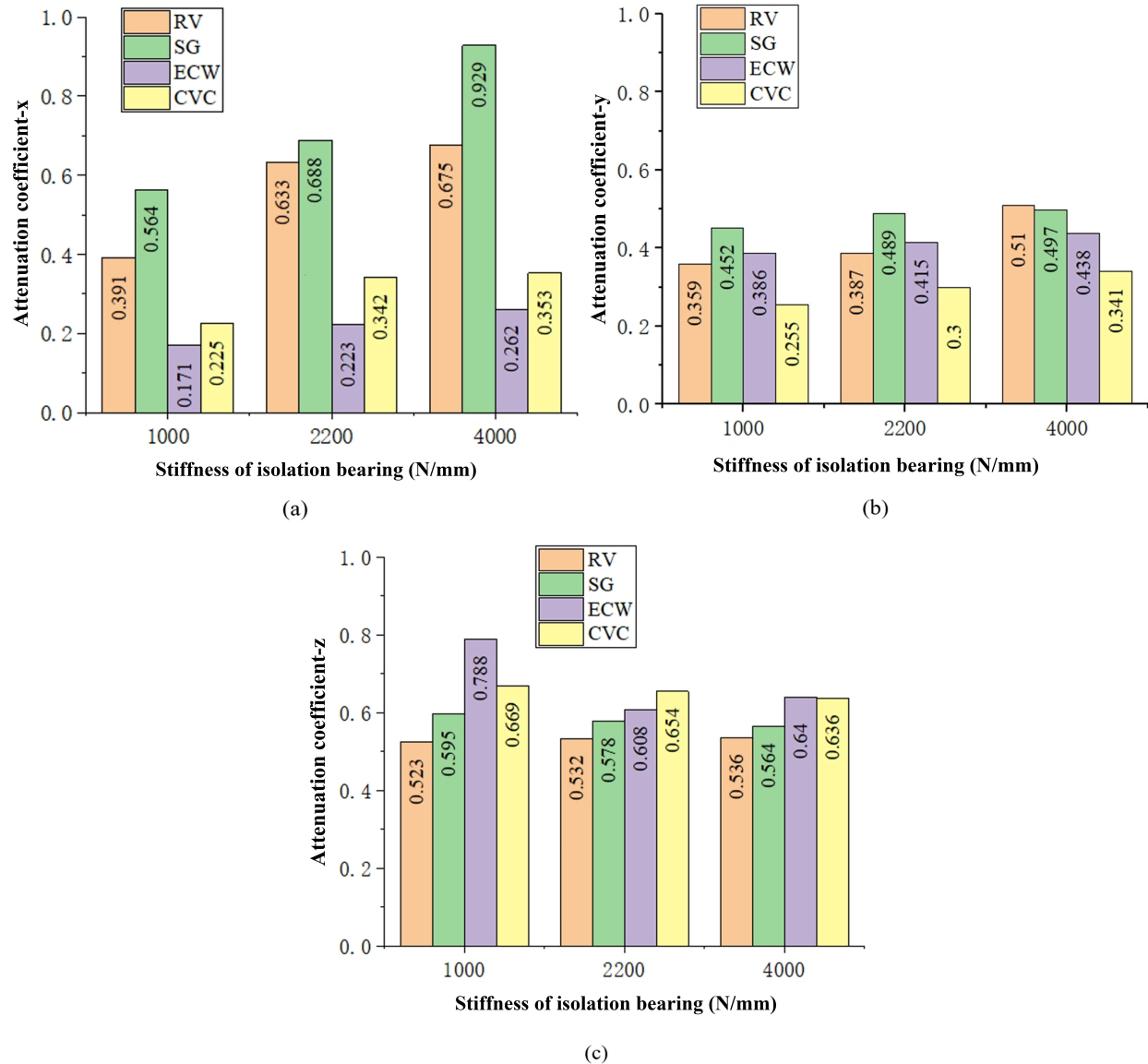


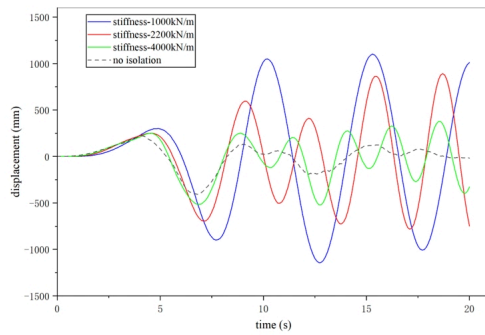
Figure 6. Acceleration attenuation coefficients at the points of interest for different horizontal stiffnesses of the isolation bearings: (a) attenuation coefficient in the x-direction; (b) attenuation coefficient in the y-direction; (c) attenuation coefficient in the z-direction

3.1.2. Piping nozzle displacement

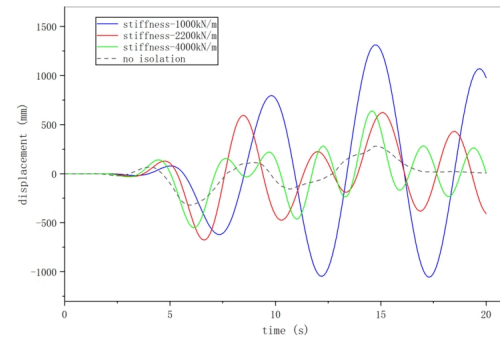
The penetration point where the piping passes through the reactor building was selected as the displacement point of interest. This point connects the reactor building with other buildings and contains a piping penetration. Under seismic excitation, the presence of isolation bearings significantly increases the displacement at this location, thereby increasing the risk of pipe rupture.

During the analysis, the displacements of this point in the x -, y -, and z -directions under the seismic time-history excitation were extracted and combined to obtain the resultant displacement, as shown in Figure 7. The results indicate that, compared with the non-isolated condition, the displacement at this location increases by 230%, 109%, and 39% for isolation bearings with different horizontal stiffnesses, respectively. Thus, the

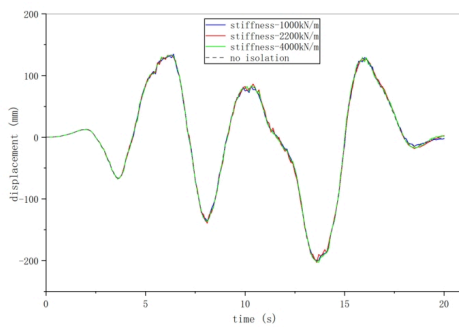
implementation of base isolation imposes more stringent requirements on piping displacement accommodation.



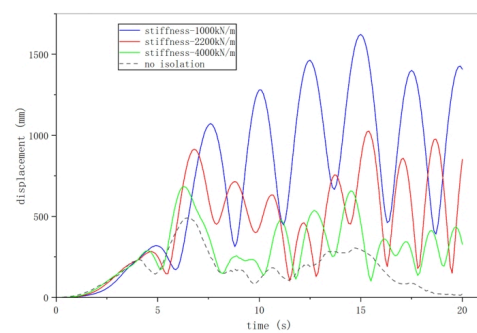
(a) displacement of the piping interface in the x-direction



(b) displacement of the piping interface in the y-direction



(c) displacement of the piping interface in the z-direction



(d) resultant displacement of the piping interface

Figure 7. Comparison of piping interface displacements for different horizontal stiffnesses

3.1.3. Stress in the reactor building

The reactor building itself also represents an important component of the construction cost of the nuclear island. The analysis results are shown in Figure 8. The results indicate that the stress in the reactor building decreases by approximately half when seismic isolation is implemented. Although the locations of the maximum stress are similar to those under the non-isolated condition, the corresponding stress values are substantially reduced. Meanwhile, as the stiffness of the seismic isolation bearings decreases, the maximum stress in the reactor building decreases accordingly.

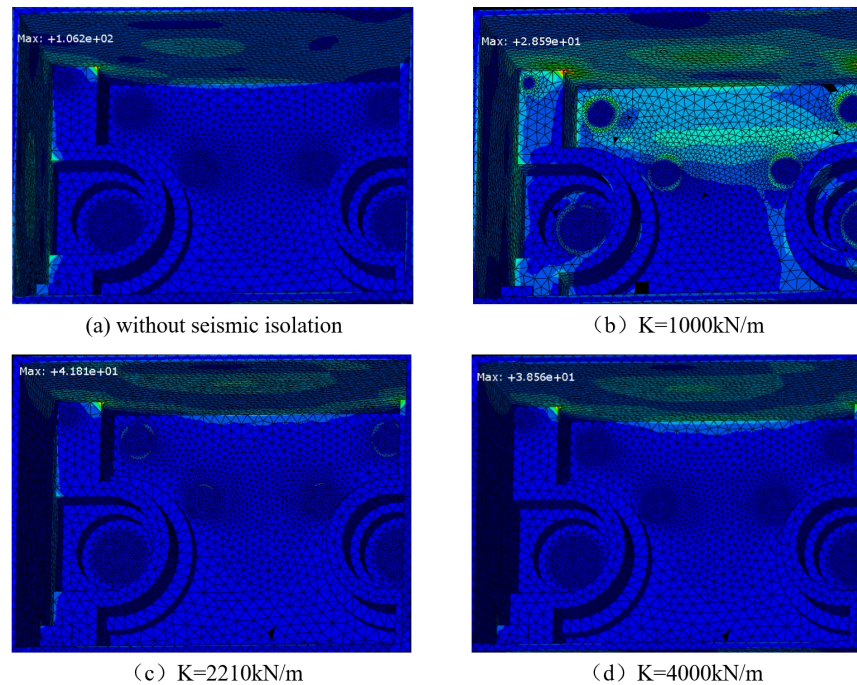


Figure 8. Stress distribution in the reactor building

3.2. Effect of vertical stiffness of isolation bearings on seismic isolation performance

In addition to horizontal stiffness, the effect of variations in the vertical stiffness of the seismic isolation bearings on isolation performance was also investigated. For comparison, an isolation scheme with a horizontal stiffness of 2,200 kN/m was selected, and its vertical stiffness was varied for the parametric analysis. Preliminary calculations indicated that the isolation performance was relatively insensitive to vertical stiffness. Therefore, to fully examine its effects, a wider range of vertical stiffness values was considered, with 3.9×10^4 kN/m selected as the comparison value.

3.2.1. Acceleration

For the seismic isolation bearings with different vertical stiffnesses, the calculated results are presented in Table 3 and Figure 9. The attenuation coefficients of the various pieces of equipment range from 0.14 to 0.69, indicating a significant base isolation effect. Both the vertical stiffness of the isolation bearings and the spatial location of the equipment have a substantial influence on the acceleration response.

Table 3. Acceleration attenuation coefficients

Stiffness kN/m	Attenuation coefficient- <i>x</i>				Attenuation coefficient- <i>y</i>				Attenuation coefficient- <i>z</i>			
	RV	SG	ECW	CVC	RV	SG	ECW	CVC	RV	SG	ECW	CVC
3.9E4	0.332	0.138	0.206	0.292	0.35	0.238	0.369	0.279	0.368	0.396	0.562	0.588
3.9E6	0.633	0.688	0.223	0.342	0.387	0.489	0.415	0.3	0.532	0.578	0.608	0.654

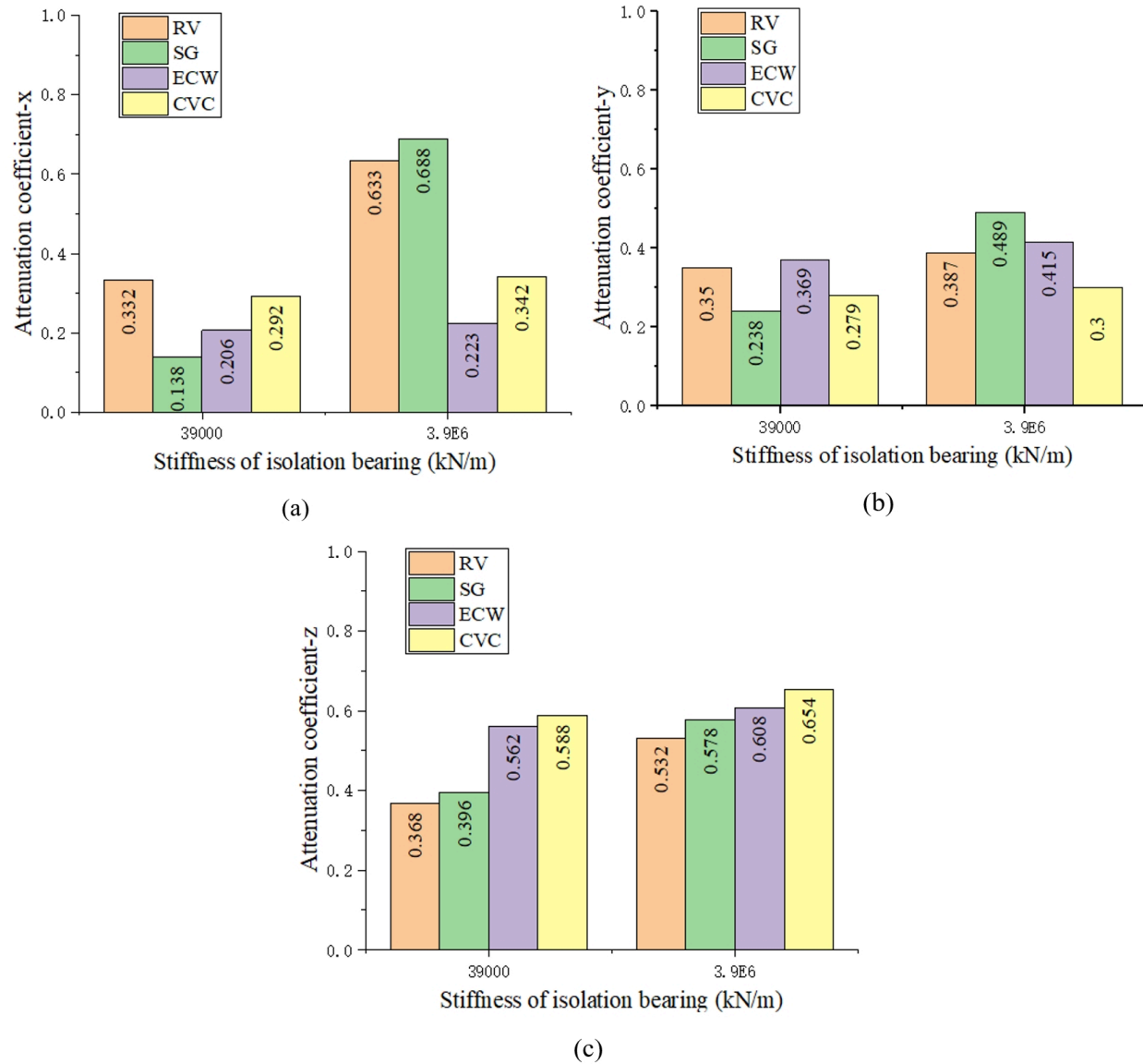


Figure 9. Acceleration attenuation coefficients at the points of interest for different vertical stiffnesses of the isolation bearings: (a) attenuation coefficient in the x -direction; (b) attenuation coefficient in the y -direction; (c) attenuation coefficient in the z -direction

Overall, for the same equipment location, increasing the vertical stiffness leads to an increase in the attenuation coefficients in the vertical direction as well as in both horizontal directions. This indicates that variations in vertical stiffness affect not only the attenuation coefficient of vertical acceleration but also those of horizontal acceleration.

3.2.2. Piping nozzle displacement

The penetration point where the piping passes through the reactor building was likewise selected as the displacement point of interest. During the analysis, the displacements of this point in the x -, y -, and z -directions under the seismic time-history excitation were extracted and combined to obtain the resultant displacement. The results are shown in Figure 10.

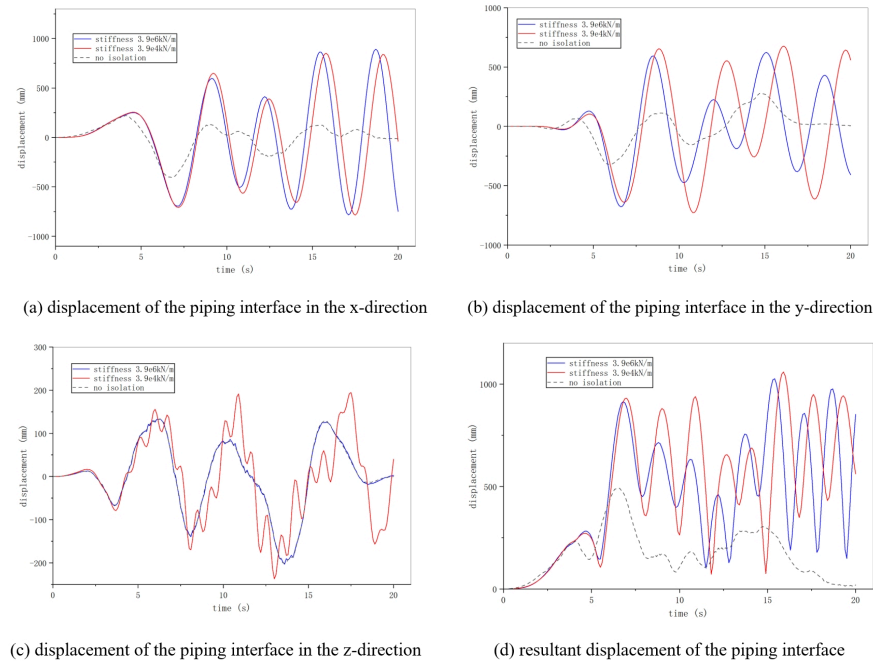


Figure 10. Comparison of piping interface displacements for different vertical stiffnesses

The results show no significant change in the displacement of the piping interface following variations in vertical stiffness. This is because vertical stiffness primarily affects vertical displacement, whereas vertical displacement is relatively small compared with horizontal displacement and therefore has little influence on the resultant displacement. Thus, although a reduction in vertical stiffness can have a significant effect on the acceleration attenuation coefficient, it does not result in a significant change in piping nozzle displacement.

3.2.3. Stress in the reactor building

The stress analysis results for the reactor building under different vertical stiffnesses are shown in Figure 11. The stiffness of the seismic isolation bearings has a significant effect on the stress state of the reactor building and can substantially alter the peak stress, thereby indirectly affecting the construction cost of the reactor building.

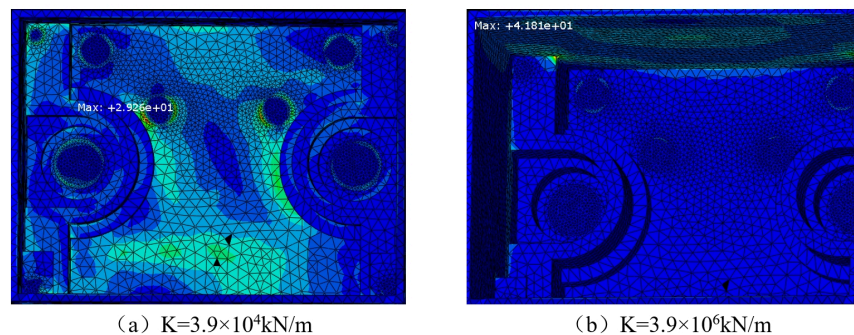


Figure 11. Stress distribution in the reactor building

3.3. Construction cost analysis after the implementation of base isolation

As indicated by the above computational results, the introduction of base isolation reduces the acceleration at the points of interest and the stresses in the reactor building to a certain extent, which is conducive to reducing

the overall construction cost. However, base isolation also has a certain effect on piping nozzle displacements, which can be addressed by adopting flexible piping connections.

3.3.1. Cost estimation method

The seismic design of nuclear power plant equipment strictly follows the requirements of ASME Boiler and Pressure Vessel Code, Section III (ASME BPVC Section III), which requires stress evaluations under multiple load combinations, including design, normal, upset, emergency, and faulted conditions. The allowable stress limits for materials differ among these conditions: the limit under the design condition is the basic allowable stress, whereas the allowable stress under an earthquake-induced faulted condition may be increased accordingly. The minimum wall thickness or section modulus of the equipment is determined by the load combination that most closely approaches the applicable allowable stress limit, namely, the governing load case. Suppose that the peak acceleration of a given piece of equipment under the original design-basis earthquake is a_0 , and that it is reduced to a_{iso} after the implementation of base isolation, with an acceleration attenuation factor of $\alpha = a_{iso}/a_0$. To quantify the reduction in equipment cost resulting from base isolation, this study proposes an estimation method based on analysis of the governing-condition threshold.

The loads acting on the equipment can be decomposed into non-seismic loads, including pressure P , self-weight W , and thermal expansion, and seismic inertial loads. The combined stress induced by non-seismic loads is denoted as σ_0 and can be regarded as constant under given operating parameters. The seismic inertial force is proportional to acceleration, and the maximum stress induced by seismic loading, σ_e , can therefore be expressed linearly as:

$$\sigma_e = ka \quad (2)$$

where k is a coefficient related to the structural stiffness, mass distribution, and support conditions of the equipment, which can be determined using finite element analysis or a simplified mechanical model. The allowable stress under the design condition is S , while the allowable stress under the earthquake-induced faulted condition is increased to λS , where λS ($\lambda \approx 1.33$). In the original design, with acceleration a_0 , the faulted condition is generally the governing condition:

$$\sigma_0 + ka_0 \approx \lambda S \quad (3)$$

After the implementation of base isolation, the acceleration is reduced to $a_{iso} = \alpha \cdot a_0$. The stress ratios under the two conditions are recalculated as follows:

$$R_E = \frac{\sigma_0 + ka_{iso}}{\lambda S}, R_D = \frac{\sigma_0}{S} \quad (4)$$

Let $R_E = R_D$. The critical acceleration is then obtained as:

$$a_{cr} = \frac{(\lambda-1)\sigma_0}{k} \quad (5)$$

When $a_{iso} \geq a_{cr}$, the faulted condition remains governing; otherwise, the governing condition shifts to the design condition.

The amount of equipment material, V , is approximately related to the required section modulus, Z , as $V \propto Z^{\frac{1}{n}}$, where n is the section-shape index (with $n = 1$ for thin-walled cylindrical structures and $n = 2$ for solid supports). Because the seismic bending moment is $M_E \propto a$, the required Z under faulted-condition control is therefore $\propto a$. Accordingly, the ratio of material quantities can be obtained as:

$$\frac{V_1}{V_0} = \begin{cases} \alpha^{\frac{1}{n}}, & \text{(Accident Scenario Control)} \\ 1, & \text{(Design Condition Control)} \end{cases} \quad (6)$$

The total equipment cost, C , can be decomposed into material costs, C_m , manufacturing costs, C_f , both of which are approximately proportional to $\propto V$, and other qualification and certification costs. The overall cost reduction ratio can therefore be conservatively estimated as:

$$R \approx 1 - \alpha^{\frac{1}{n}} \quad (7)$$

Here, n takes a value of 1 for thin-walled vessels and approximately 2 for solid supports.

3.3.2. Cost estimation results

Based on the equations presented above, the overall cost reduction ratios for each piece of equipment under different seismic isolation bearing parameters can be obtained. Here, α is taken as the maximum value among the three directions (x , y , and z). The upper bound is calculated with $n = 1$, while the lower bound is calculated with $n = 2$. The results are presented in Table 4. With the application of base isolation technology, the average construction cost of the equipment can be reduced by approximately 30%.

Table 4. Equipment cost reduction ratios under different isolation-bearing parameters

Horizontal Stiffness	Vertical Stiffness	Percentage reduction in costs							
		RV	RV	SG	SG	ECW	ECW	CVC	CVC
kN/m	kN/m	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound
1,000	3.90E+06	0.48	0.28	0.41	0.23	0.21	0.11	0.33	0.18
2,200	3.90E+06	0.37	0.20	0.31	0.17	0.39	0.22	0.35	0.19
4,000	3.90E+06	0.33	0.18	0.07	0.04	0.36	0.20	0.36	0.20
2,200	3.90E+04	0.63	0.39	0.60	0.37	0.44	0.25	0.41	0.23

4. Conclusions

The conclusions of this study are as follows:

1. A time-domain finite element analysis method for evaluating the base isolation performance of nuclear islands was established based on a realistic nuclear island model. A simplified model of an advanced small modular reactor was developed according to its mass distribution. A seismic-wave time-history curve was generated using a time-domain-to-frequency-domain transformation approach, laminated rubber isolation bearings were simulated using spring elements, and the finite element calculations were performed using a dynamic analysis procedure.

2. The installation of seismic isolation bearings substantially reduces the peak acceleration of equipment within the nuclear island, thereby significantly reducing construction costs. Multiple cases involving the non-isolated condition and different horizontal stiffnesses of the isolation bearings were analyzed. The results show that the average acceleration attenuation coefficient under the isolated conditions is 0.49, corresponding to an average 51% reduction in peak acceleration, demonstrating a significant isolation effect. Within the range of parameters investigated, a lower horizontal stiffness results in a smaller attenuation coefficient and, consequently, better seismic isolation performance.

3. The vertical stiffness of the seismic isolation bearings is also important, and bearings with vertical isolation capability should therefore be selected. A comparison between cases with and without vertical isolation shows that the maximum acceleration is substantially attenuated when vertical isolation is incorporated, further demonstrating the importance of vertical stiffness. Variations in vertical stiffness do not

readily produce significant changes in piping nozzle displacement. The results further indicate that, as the vertical stiffness decreases, the overall acceleration attenuation performance improves.

4. The application of seismic isolation increases interface displacement, and piping displacement compensation must therefore be considered in practical design. Following the implementation of base isolation, larger interface displacements occur at the piping penetration through the reactor building. The displacement effects must therefore be carefully evaluated when base isolation is adopted, and devices such as flexible piping connections can be used to accommodate the resulting displacement.

5. The application of seismic isolation technology can substantially reduce the cost of major equipment and offers significant economic benefits. According to the cost estimation equations, the average cost reduction across the equipment considered is approximately 30%, which can effectively improve the economic efficiency of the equipment. Meanwhile, seismic isolation enables a standardized nuclear island design to be adopted across different plant sites, with only the parameters of the isolation foundation requiring adjustment, thereby providing further opportunities for cost reduction.

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