Base-Isolation Technology Investigation for SMR Nuclear Island Building

Chen Jian and Ma Jia

Abstract The application of Lead-Rubber Bearing base-isolation technology was studied in this paper, including base-isolation method scheme, selection of seismic isolation devices, determination of isolation structure models, etc. Taking one SMR nuclear safety-related building for example, the influence on isolation effectiveness of buildings from various spaces and various hysteretic models for the isolation layer were investigated based on the dynamic analysis of isolation structures. The study shows that: (1) the application of isolation measures can significantly increase the structure's natural vibration period, reduce the dynamic response of the superstructure, and amplify the structure's horizontal displacement, but the story displacements are small; (2) the bilinear model for isolation bearing has a more actual isolation effectiveness, it should be pay more attention in design.

Keywords SMR · LRB · Isolation structures · Equivalent linear model · Bilinear model

1 Introduction

Base-isolation technology has been applied widely and accumulated mature experience after nearly forty years of development. It has also obtained favorable benefits both on economy and on society. However, there is fewer application of base-isolation technology in structural design of NPPs, especially in China; it is empty for the engineering application of base-isolation technology for nuclear safety-related building. Theoretically, the application of base-isolation technology can improve the reliability and safety of nuclear power building. Therefore, standard design can be realized without caring of the value of earthquake during the seismic design of primary structures and facilities. Consequently, the speed of design and construction can be accelerated and the cost can be reduced [1]. However,

C. Jian (✉) · M. Jia
China Nuclear Power Engineering CO., Ltd., Structure Analysis, Beijing, China
e-mail: Chenjian@cnpe.cc

considering of the particularity and complexity of nuclear structures and the incomplete of related criterions, the attitude toward the application of base-isolation technology for nuclear power buildings from leading countries including America, Japan, and France is still prudential. Accordingly, there is a great necessity to develop the investigation on base-isolation technology for nuclear power buildings. The self-designed SMR and Hualong One proposed the subject of base-isolation technology prospectively under which this paper is just set. Based on a certain site, taking one nuclear island building for example, the research was developed on base-isolation method scheme, selection of the seismic isolation device, determination of isolation structure model, etc. And then, dynamic analysis of isolation structures was carried out. The technical sustain on standard design and site adaption for new type of nuclear plant was provided through this investigation.

2 Base-Isolation Method Scheme

2.1 Description of Project

The description of ground motion at the site: The PGA of ultimate safety ground motion (SL2) is 0.50 g in horizontal direction and 0.33 g in vertical direction.

Necessity of base-isolation: the peak acceleration (SL2) exceeds 0.3 g which is the standardized design value. In order to meet the standard design of structures and nuclear-related facilities, base-isolation technology should be adopted so as to decrease the earthquake action.

The location of isolation layer: the isolation layer locates at the bottom of foundation.

2.2 Description of Isolation Devices

The seismic isolation device can be divided into two types, seismic isolation device and damping device. Seismic isolation device is used to provide large deformation and prolong the natural period, so as to decrease the earthquake action on superstructure. Damping device is used to provide vibratory decay damping force so as to restrict structural displacement. Based on the aim of seismic isolation, the following essential performance should be considered when choosing of isolators: enough vertical bearing capacity and vertical stiffness, smaller horizontal stiffness and proper damping decay characteristic, isolator durability, fire resistance, and other related characteristics [2–5]. Lead-Rubber Bearing (LRB) is adopted in this paper for base-isolation technology investigation of nuclear power building. Because of the heavier weight, larger stiffness, larger earthquake action, and more restrict displacement requirement of nuclear power structures compared with normal civil

structures, large diameter isolators are considered for using. The related parameters of LRB are as follows:

Effective diameter D: 1000 mm;
Total thickness of rubber layers tr: 162 mm;
Vertical bearing capacity P: 7850 kN;
Vertical stiffness Kv: 6929 kN/mm;
1st shape factor $S1$: 41.7; 2st shape factor $S2$: 6.17;
Horizontal equivalent stiffness 4539 kN/m;
Equivalent damping ratio $\xi = 21.6$ %;
Pre-yield stiffness $K1 = 29{,}240$ kN/m;
Post-yield stiffness $K2 = 2924$ kN/m;
Yield force $Qy = 261.7$ kN.

2.3 Arrangement of Isolators

Based on the estimation of bearing capacity, detailing requirement of installation and maintain space, three kinds of uniform arrangement of isolators are considered preliminarily: 2.5 m × 2.5 m, 3.0 m × 3.0 m, and 3.5 m × 3.5 m of spaces. Because of the uniform arrangement of isolators, the stiffness center of isolators is located at the center of base plate which is closed with the quality center of overlying structures. So the influent of torsion caused by eccentric can be decreased. Checking calculation of vertical bearing capacity of isolators is carried out to verify the preliminary feasibility of these three kinds of arrangement. Through checking calculation, the two spaces 2.5 m × 2.5 m and 3.0 m × 3.0 m can meet the preliminary design requirement.

3 Computational Models

3.1 Model of Superstructure

Compared with isolation layers, the stiffness of overlying structures is very large because of the thick concrete wall and thick concrete floor. So lumped mass stick model is adopted in this paper. Meanwhile because of the complexity of structure configuration, the stiffness center and quality center are not coincident, so torsion effect should also be taken into account, which is the considering of two horizontal linear displacements and one angular displacement of floor. Therefore, the model of superstructure adopts lumped mass stick model considered with prejudicial torsion effect (Fig. 1).

Fig. 1 Lumped mass stick model
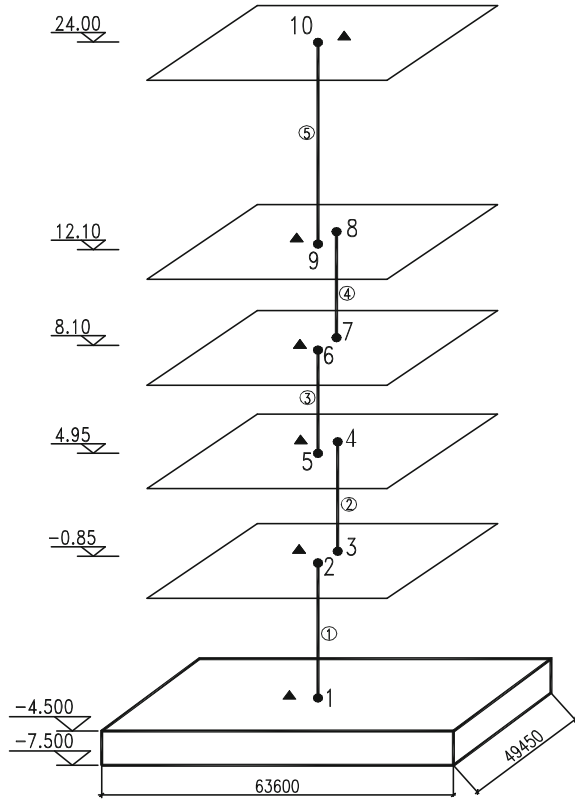
3.2 Model of Isolation Layer

In order to confirm the mechanical model of isolation layer, linear elastic model is adopted in vertical tension–compression hysteretic model, while nonlinear constitutive model and equivalent linear model are adopted in horizontal. Equivalent bilinear model is adopted to indicate nonlinear constitutive model approximately.

4 Time History Analysis

4.1 Finite Element Model of Building

ANSYS is adopted in this paper to establish the lumped mass stick computational model of the building. Every isolator is composed of three combine elements in *X*, *Y,* and *Z* direction. For equivalent linear model, Combin14 linear spring element is adopted to modify the *X, Y,* and *Z* direction of isolator. For bilinear model,

Combin40 element is adopted to modify the X and Y direction of isolator, while Combin14 element is adopted to modify the Z direction of isolator.

4.2 Modal Analysis

The first two steps of modal analysis results of isolation structure are listed in Table 1. As space is limited, first two vibration modes of the isolation structures in horizontal direction of equivalent linear model at the space of 3.0 m × 3.0 m are shown in Fig. 2. Based on the vibration modes, it can be seen that the mode shape of superstructure is nearly rigid body motion because its stiffness is much larger than that of the isolator layers, which is coincident with the result of academic analysis in isolation system. The data in Table 1 shows that the horizontal natural periods increase significantly after using isolation for both equivalent linear model and bilinear model. The natural period is 6–15 times larger than nonisolation structure. The larger the space of LRB isolators, the larger the period increased. From the basic principle of isolation structures, the aim of prolonging the structural natural period is achieved.

Table 1 First two vibration modes of the isolation structures

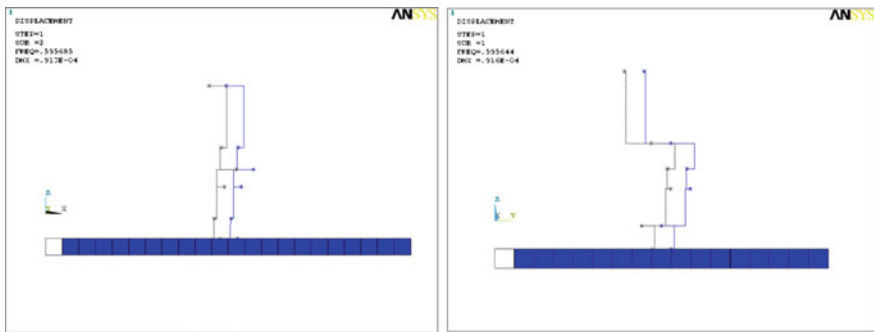| Mode shapes	Natural period of isolation structure (s) (equivalent linear model)		Natural period of isolation structure (s) (bilinear model)		Natural period of nonisolation structure (s)
	LRB space 2.5 m × 2.5 m	LRB space 3.0 m × 3.0 m	LRB space 2.5 m × 2.5 m	LRB space 3.0 × 3.0 m	
1	1.390	1.679	0.552	0.665	0.0899
2	1.389	1.679	0.551	0.665	0.0877

Fig. 2 First two vibration modes of the isolation structures in H direction

4.3 Ground Motion

Dynamic time history analysis is adopted in this isolation analysis. Three single groups (two in horizontal and one in vertical) of mutual orthogonal and statistic independently manual time histories are achieved by fitting from RG1.60 standard response spectra. The total duration of time history is 25 s. The stable period duration of ground motion is 8 s. The time step length of time history is 0.01 s. The total time step is 2500 steps. The PGA is 0.50 g in horizontal direction, and 0.33 g in vertical.

4.4 Dynamic Response of Isolation Structure

4.4.1 Acceleration Response Analysis

(1) Equivalent linear model

As space is limited, only list the result of structural response in *X*-direction below. Figures 3 and 4 show the comparison of accelerations in *X*-direction for space 3.0 m at bottom layer and top layer, respectively. As can be seen from the figures, the structural acceleration response decreases significantly for isolation structure. Figure 5 shows the comparison of peak values of accelerations at each floor of isolation structure under two kinds of isolator spaces and the same condition of nonisolation structure. Figure 6 shows the comparison of seismic reduction factors (seismic reduction factor = response with isolation/response without isolation). As can be seen from the figures: Peak values of accelerations response at each floor above isolation layers are nearly the same, which is coincident with the conclusion that the overlying structure is rigid body motion generally. The maximum seismic reduction factor is located at bottom layer, which is about 0.5. The higher the
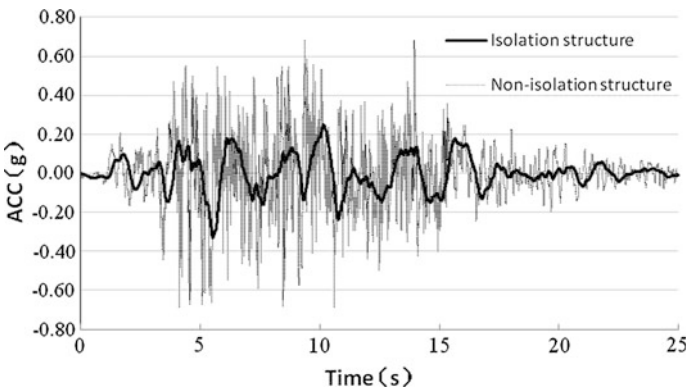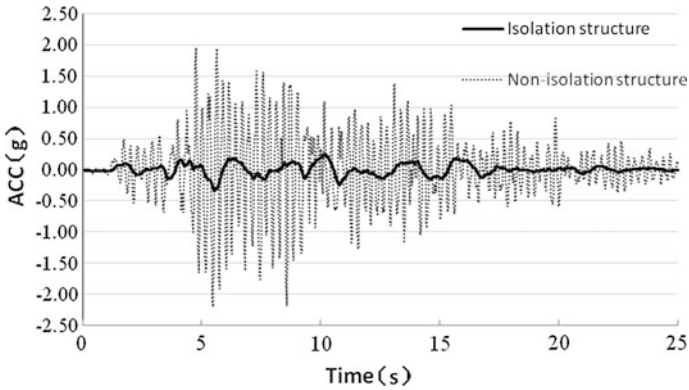

Fig. 3 Accelerations in *X*-direction at bottom layer

Fig. 4 Accelerations in *X*-direction at top layer

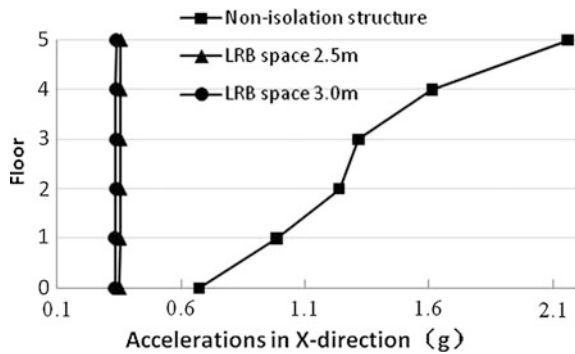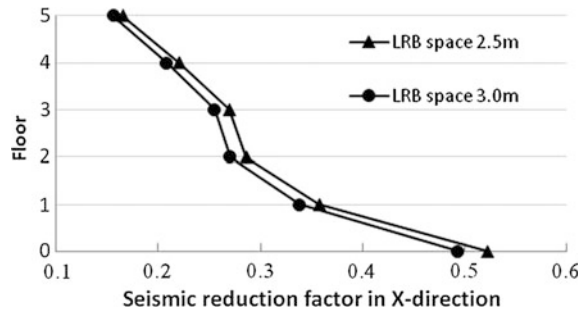**Fig. 5** Peak values of accelerations for different isolator spaces

Fig. 6 Seismic reduction factors for different isolator spaces

elevation is, the more significant the factor is. The seismic reduction factor is about 0.15 at top layer. As increasing of isolator space (from 2.5 to 3.0 m), stiffness of isolation layer, peak values of accelerations response and seismic reduction factor decrease. That means the effect of isolation is more significant.

(2) Bilinear model

Figures 7 and 8 show the comparison of accelerations in *X*-direction for space 3.0 m at bottom layer and top layer, respectively, in bilinear model. Figures 9 and 10 show the comparison of peak values of accelerations and seismic reduction factors at each floor under the same condition. The analysis result of bilinear model shows the same trend as equivalent linear model: Peak values of accelerations response at each floor are nearly the same. The maximum seismic reduction factor is located at bottom layer, which is about 0.5. The higher the elevation is, the more significant the factor is. The seismic reduction factor is about 0.15 at top layer. As, increasing of isolator space (from 2.5 to 3.0 m), peak values of accelerations response and seismic reduction factor decrease. That means the effect of isolation is more significant.
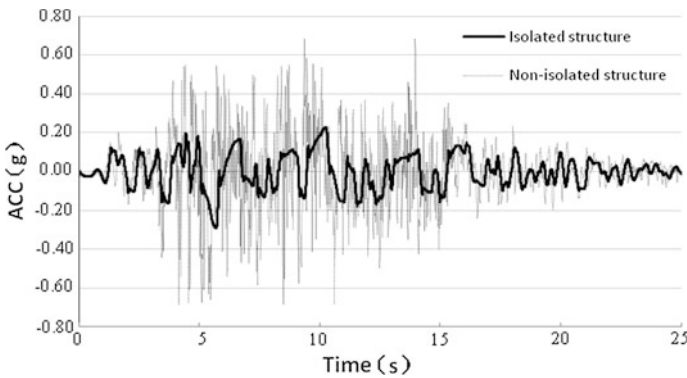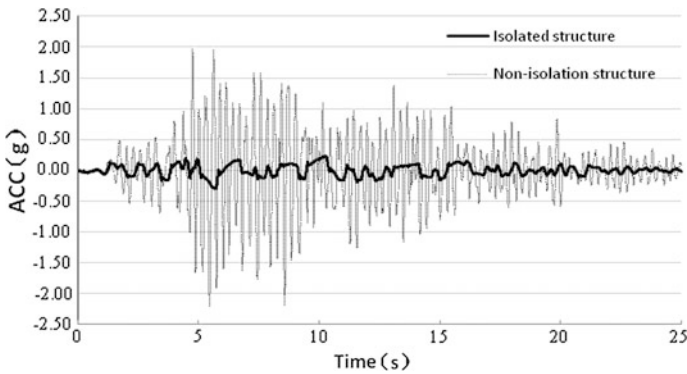

Fig. 7 Accelerations in *X*-direction at bottom layer

Fig. 8 Accelerations in *X*-direction at top layer

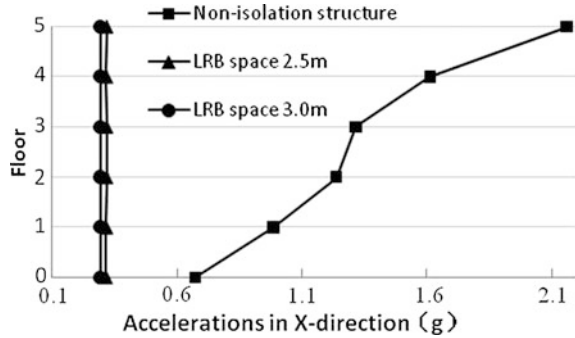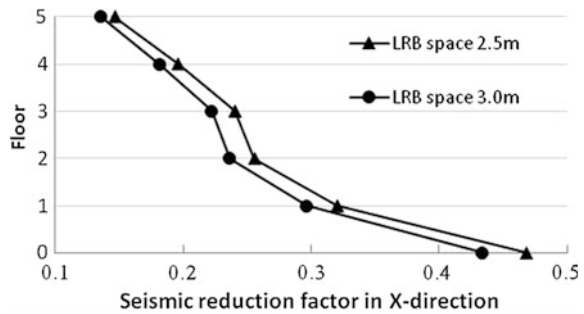**Fig. 9** Peak values of accelerations for different isolator spaces

Fig. 10 Seismic reduction factors for different isolator spaces

4.4.2 Displacement Response Analysis

(1) Equivalent linear model

Figures 11 and 12 show the comparison of displacements in *X*-direction and story displacements in equivalent linear model. Compared to nonisolation structure, the rigid body motion of overlying structure in isolation system is larger. The maximum displacement in *X*-direction is 187.6 mm, which is far larger than the maximum displacement of nonisolation structure at top layer of 45.9 mm. Although there are large displacements of isolation structure, but the story displacements of overlying structure are very small because of its rigid body motion (Fig. 12), which is of great benefit to structure. As increasing of isolator space (from 2.5 to 3.0 m), stiffness of isolation decreases and the displacements of overlying structure increases significantly (increased about 40–50 %). The analysis result of displacement shows the opposite trend as acceleration result. It can be concluded that, the structural period will be increased and achieve favorite isolation effect when decreasing the structural stiffness. But the disadvantage is the increasing of structural displacement, which can be weakened by installation damping devices. Consequently, it is necessary to choose proper stiffness and damping in order to achieve ideal effect of isolation.

Fig. 11 Peak values of horizontal displacement for different isolator spaces
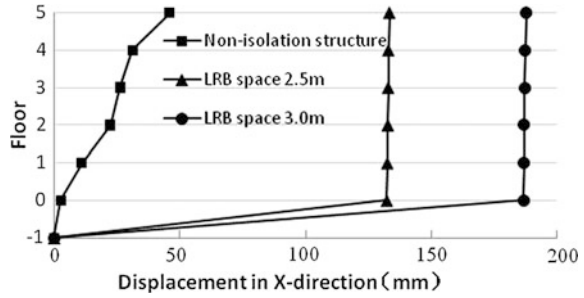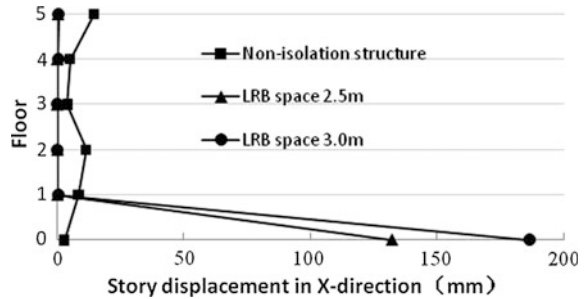

Fig. 12 Story displacements for different isolator spaces

(2) Bilinear model

Figures 13 and 14 show the comparison of displacements in *X*-direction and story displacements in equivalent bilinear model. The analysis result of bilinear model shows the same trend as equivalent linear model: The rigid body motion of overlying structure in isolation system is relatively large. The maximum displacement in *X*-direction is 221.6 mm, which is far larger than the maximum displacement of nonisolation structure at top layer of 45.9 mm. As the result of rigid body motion, the story displacement of overlying structure is quite small (Fig. 14). As increasing of isolator space (from 2.5 to 3.0 m), stiffness of isolation decrease, and the displacements of overlying structure increase significantly (increased about 50–80 %). It can be seen, the displacement of isolation structure is very sensible to the stiffness of isolation layer. Consequently, it is necessary to balance the effect of isolation and restriction of displacement during isolation designing.

4.4.3 Dynamic Response Comparison Between Equivalent Linear Model and Bilinear Model

Figures 15 and 16 show the comparison results of structural dynamic response between equivalent linear model and bilinear model.

It can be seen from the comparison: peak displacements of bilinear model increase 5–8 % than equivalent linear model at the LBR space of 2.5 m and

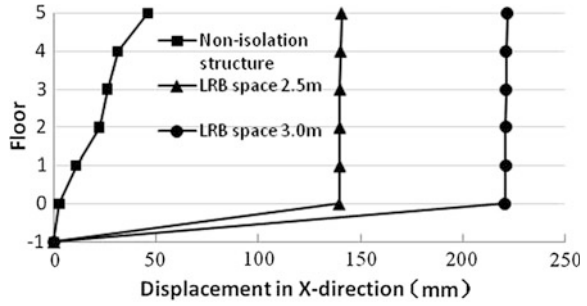**Fig. 13** Peak values of horizontal displacement for different isolator spaces

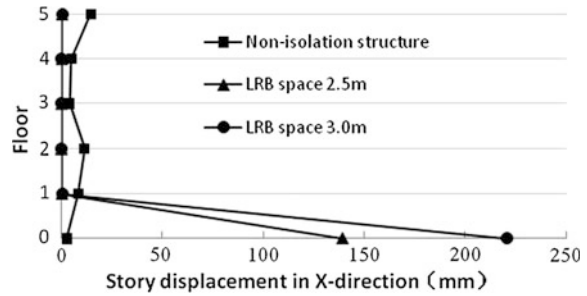**Fig. 14** Story displacements for different isolator spaces

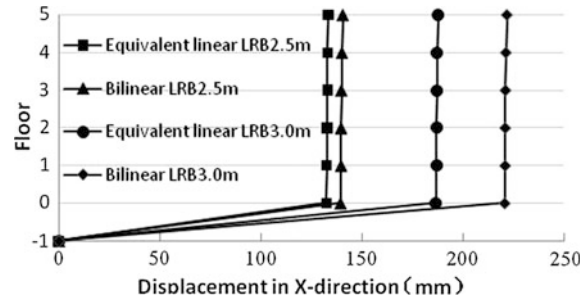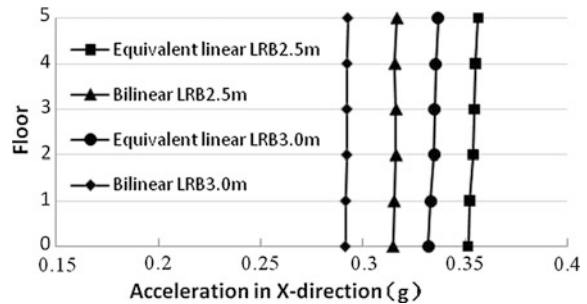**Fig. 15** Displacements in *X*-direction for different isolator spaces

Fig. 16 Accelerations in *X*-direction for different isolator spaces

increase 18 % at the space of 3.0 m. It can be concluded that, the influence of stiffness of isolation layer is obvious to the displacement of isolation structure. For acceleration response, peak values of bilinear model are smaller than equivalent linear model. Also, the reduction extent of both kinds of LRB space is nearly the same, which is about 10–16 %. Accordingly, the sensitivity on acceleration of LRB space is weaker than displacement.

5 Conclusions

Taking one SMR nuclear safety-related building for example, LRB base-isolation technology was studied in this paper, including base-isolation method scheme, determination of isolation structure model, dynamic response analysis of isolation structure, etc. Conclusions are listed as follows:

(1) After using of LRB base-isolation technology, the natural period of isolation building can be extended to 15 times larger than nonisolation structure. The horizontal acceleration responds can be decreased significantly, and the seismic reduction factor can reach up to 0.15–0.50. With wonderful seismic reduction effect, the horizontal displacements of isolation structure increase significantly. Because of the rigid body motion of overlying structure, the story displacements are quite small, which could be beneficial for structural design.

(2) The model of superstructure adopts lumped mass stick model considered with prejudicial torsion effect, which can meet the requirement of engineering design. For determination of isolation structure model, the result of bilinear model is more closed to actual stress condition, while equivalent linear model is good for its faster calculation speed and lower cost of computation. Consequently, it is suggested that equivalent linear model can be adopted at the phase of base-isolation method scheme, while bilinear model and other modified model can be adopted at the phase of final design because it is more coincident with actual hysteretic characteristic. The problem of large displacement can be settled by tectonic methods or by installing damping devices.

(3) Combined the earthquake characteristic of nuclear power structure, isolators of large diameter, and large space should be adopted preferably during base-isolation method scheme designing. Convenience for construction and maintenance should also be taken into account.

(4) The effect of isolator stiffness on structural displacement is more sensible than the effect of acceleration. Consequently, it is necessary to balance the relationship between the effect of isolation and restriction of displacement synthetically during engineering design.

References

1. XIE Lili, ZHAI Changhai. A prospective study on applicability of base isolation in nuclear power plants [J]. Journal of Earthquake and Engineering Vibration, 2012, 32 (1): 1–10.
2. ZHOU Fulin. Shock Attenuation Control for Engineering Structure [M]. Beijing: Seismological Press, 1997.
3. DANG Yu, DU Yongfeng. Base-isolation Structure Design and Construction Guide [M], Beijing: China Water and Power Press, 2007.
4. GB20668.3-2006 Rubber Isolation Bearings for Buildings [S].
5. CECS 126: 2001 Technical specification for seismic-isolation with laminated rubber bearing isolators[S].