Research on base isolation design of nuclear island plant of a new-type metal-cooled fast reactor

Guo Liu¹, Yibo Fan¹, Yanqiang Bai¹, Xiaohai Qi¹

¹China Nuclear Power Technology Research Institute Limited, Shenzhen, Guangdong, 518124, P.R.China

Abstract. This paper establishes a 3D finite element model of a new-type metal-cooled fast reactor (MCFR) nuclear island plant for applied research of base isolation technology, and the research includes the base isolation scheme for the split base layer structure, the selection from different types of isolation bearings, etc. According to the mechanical characteristics of different isolation bearings and rigidity distribution of the structure itself, the layout of isolation bearing scheme is carried out. Dynamic analysis of nuclear plant has been done based on ANSYS, and the optimal isolation scheme is determined by repeated trial calculation, isolation design schemes adjustment, acceleration and displacement of key nodes comparison. The results show that: applying base isolation design to the nuclear island plant, natural vibration period of the structure increases, acceleration response of the key nodes of the superstructure and displacement between the layers of the structure significantly decreases, seismic resistance of the nuclear island plant is improved significantly; isolation effect of the scheme with multiple types of isolation bearings is much better than that of the scheme with only rubber bearings.

1. Introduction

With the development of society and economy, nuclear power is regarded as a kind of clean energy which can effectively solve the problem of energy shortage and environmental deterioration. The metal-cooled fast reactor, which has been particularly valued internationally, is rated by the “nuclear system international BBS”as the first fourth-generation reactor to implement industrial demonstrations and commercial applications. If the metal-cooled fast reactor is damaged under earthquake, it will cause serious nuclear and metal pollution, so it is especially significant to reduce the effect of earthquakes on the metal-cooled fast reactor. Many cases prove that the base isolation technique can effectively reduce the seismic response of civil buildings [1-2], and many scholars have studied the application of isolation technology in nuclear power engineering [3-5]. If the base isolation technique can be successfully applied to the nuclear island plant of the metal-cooled fast reactor, the seismic performance of the metal cold fast reactor will be significantly improved. Therefore, it is necessary to study the basic isolation of metal cold fast reactor. To improve the seismic performance of the metal-cooled fast reactor. This paper discusses the isolation schemes of the foundation split-layer structure and the multiple isolation bearings, and conducts the time-history analysis of the isolation design of the nuclear island plant.
2. Design of the isolation scheme

2.1. Project profile
The nuclear island plant is seismic class I structure, and the Raft foundation is adopted. The plant is 55.5m long and 55.5m wide, 25.0m high above the ground and 36.5m deep below the ground. It is divided into 8 floors (5 floors underground and 3 floors above ground) along the height. Its profile is in the shape of "T", and the bottom surface of the structure has two elevations, -11.5m and -36.5m, respectively. The whole plant is a reinforced concrete shear wall structure. The isolation layers are arranged at -11.5m and -36.5m respectively.

2.2. Isolation bearings
In this paper, the isolation schemes of multiple isolation bearings are studied for split base layer structure. According to the structural requirements and performance characteristics of different isolation bearings, lead rubber bearings (LRB900, LRB1400), non-lead rubber bearings (LNR700) and slide bearings (ESB800) are selected. The mechanical performance parameters of the isolation bearings are mainly including vertical stiffness $K_v$, pre-yield stiffness $K_u$, post-yield stiffness $K_d$, yield shear force $Q_d$ and equivalent damping ratio $C$. Table 1 shows the main mechanical properties of several isolation bearings.

| Bearing type | $K_v$/N·m$^{-1}$ | $K_u$/N·m$^{-1}$ | $K_d$/N·m$^{-1}$ | $Q_d$/KN | C |
|--------------|-----------------|-----------------|-----------------|--------|---|
| LRB900       | 2.70×10$^9$    | 1.59×10$^7$    | 1.59×10$^6$    | 92.70  | 0.05 |
| LRB1400      | 5.64×10$^9$    | 3.46×10$^7$    | 3.46×10$^6$    | 257.60 | 0.05 |
| LNR700       | 2.18×10$^9$    | 1.24×10$^7$    | 1.24×10$^6$    | 8.00   | 0.05 |
| ESB800       | 1.42×10$^{10}$ | 1.99×10$^7$    | 0.01           | 401.92 | 0.05 |
| ESB900       | 3.20×10$^{10}$ | 1.99×10$^7$    | 0.01           | 508.68 | 0.05 |

2.3. Isolation scheme
After calculation and analysis of several isolation schemes, two isolation schemes are selected. One is the isolation scheme using LRB900, another is the isolation scheme using LRB900, LRB1400, LNR700 and ESB800. The detailed layout of isolation scheme is shown in figure 1 and figure 2. In the figures, the inner rectangle part is the isolation layer at elevation -36.5m, and the part between the outer rectangle and the inner rectangle is the isolation layer at elevation -11.5m.
FIGURE 1. Isolation bearing plane layout of scheme 1

FIGURE 2. Isolation bearing plane layout of scheme 2
3. Time history analysis

3.1. Finite element model
Software ANSYS is used to establish 3d finite element model of the nuclear power plant structure. SHELL181 elements are used for simulation of floor structure, wall structure and raft foundation. Spring elements are used to simulate isolation bearings, among which two horizontal springs (X and Y) are simulated by COMBIN40 elements, and vertical springs (Z) are simulated by COMBIN14 elements.

3.2. Eccentricity and flexural weight ratio
Calculated by ANSYS software, the coordinates of the mass center of the structure are X=28.08m, Y=27.67m, and the coordinates of the rigid center of the isolation layer are X=27.99m, Y=27.53m. The horizontal eccentricity ratio meet the requirement of less than 3% \[6\]. The flexor-weight ratio of the isolated system is 2.38%, which is within a reasonable range. Therefore, the layout of the isolation layer is reasonable.

3.3. Modal analysis
Table 2 lists the first three orders modal analysis results of the nuclear island plant structure without and with the isolation design. As can be seen from the data in the table, with the isolation design, the natural vibration period of the structure significantly increases, which can be extended to 4-5 times of the structure without the isolation design. The purpose of extending the natural vibration period of the structure with isolation design is achieved, which is conducive to the seismic resistance of the structure.

| Vibration mode       | Natural period without the isolation design | Natural period of scheme 1 | Natural period of scheme 2 | Modal descriptions               |
|----------------------|---------------------------------------------|-----------------------------|-----------------------------|----------------------------------|
| First vibration mode | 0.201                                       | 1.015                       | 0.911                       | The whole thing vibrates, translation in |
the X direction
The whole thing vibrates, translation in
the Y direction
The whole thing vibrates, the x-y
torsional vibration

3.4. Modal analysis
According to the RG1.60 spectrum proposed by the United States Atomic Energy Commission for the third generation PWR nuclear power plant [11], five sets of artificial seismic waves are fitted. Each set contains three seismic waves, which are in two horizontal directions (X and Y) and one vertical direction (Z). As shown in figure 4, the peak acceleration of ground motion is 0.3g in two horizontal directions (X and Y) and 0.3g in vertical direction (Z), with a duration of 20.48 seconds and the time step of 0.01 seconds.

![Time-history curve of acceleration of ground motion in the X direction](image1.png)

**FIGURE 4-1.** Time-history curve of acceleration of ground motion in the X direction

![Time-history curve of acceleration of ground motion in the Y direction](image2.png)

**FIGURE 4-2.** Time-history curve of acceleration of ground motion in the Y direction

![Time-history curve of acceleration of ground motion in the Z direction](image3.png)

**FIGURE 4-3.** Time-history curve of acceleration of ground motion in the Z direction
3.5. Response analysis

Different from civil buildings, the main purpose of isolation design of nuclear island plant is to reduce the impact of earthquake on the equipment inside the plant. Therefore, this paper focuses on the seismic isolation effect of acceleration and displacement at the important location of the structure (roof and the place where the equipment is placed).

3.5.1 Displacement response analysis

In table 3, the displacement of each node is the absolute displacement of the node minus the displacement of the top of the isolation layer.

In addition, the coefficient $\eta$ is defined in order to evaluate the isolation effect. The larger the coefficient value is, the more significant the isolation effect is.

$$\eta = \frac{|R_{\text{non-iso}} - R_{\text{iso}}|}{R_{\text{non-iso}}} \times 100\%$$

In the formula, $R_{\text{iso}}$—Response with the isolation design.

$R_{\text{non-iso}}$—Response without the isolation design.

| Node location and number | Scheme | D-X/ (mm) | D-Y/ (mm) | D-Z/ (mm) | a-X/ (m/s$^2$) | a-Y/ (m/s$^2$) | a-Z/ (m/s$^2$) |
|--------------------------|--------|-----------|-----------|-----------|--------------|--------------|--------------|
| Node 1 at the roof at elevation 25m | Without the isolation design | 32.52 | 17.58 | 7.28 | 29.93 | 25.15 | 9.17 |
| | Scheme 1 | 5.29 | 5.09 | 2.07 | 7.28 | 7.08 | 7.71 |
| | Scheme 2 | 4.46 | 3.44 | 1.51 | 6.09 | 6.19 | 5.34 |
| Node 2 at the reactor pit at elevation 0m | Without the isolation design | 9.55 | 5.12 | 1.49 | 10.41 | 9.41 | 2.06 |
| | Scheme 1 | 2.91 | 1.85 | 0.28 | 5.95 | 6.50 | 3.10 |
| | Scheme 2 | 1.69 | 1.16 | 0.29 | 4.99 | 5.28 | 0.88 |

As shown in table 3, the isolation design is effective to reduce the displacement response of the important position of the structure. The coefficient $\eta$ is around 70% - 80%, and is basically close at different heights of the structure. The isolation effect of scheme 2 is better than that of scheme 1, and the coefficient $\eta$ is increased by about 10%.

Figure 5 shows the horizontal displacement response comparison of the angular node of the structure without the isolation design and with the isolation design of scheme 2. The displacement amplitude of the superstructure with the isolation design is much larger than that of the structure without the isolation design. With the isolation design, the superstructure is almost rigid body translation so that the relative displacement between the floors of the plant is very small, which is conducive to the structural stress.
3.5.2 Acceleration response analysis

It can be seen from table 3 that the acceleration response at important location of the structure has a certain isolation effect with the isolation design. The coefficient $\eta$ at elevation 25m of the structure is about 70%-80%, and that at elevation 0m of the structure is about 30%-50%. However, the vertical acceleration isolation effect at elevation 0m of the structure is not so good. The acceleration isolation effect of scheme 2 is better than that of scheme 1. The lower the structural height is, the more the isolation effect of scheme 2 improve compared with that of scheme 1. And the important equipment placement layer of the nuclear island plant is located at elevation 0m of the structure, so scheme 2 is more conducive to the seismic resistance of the structure and equipment.

![Comparison of horizontal acceleration without and with the isolation design at the angular node A](image1)

**FIGURE 6.** Comparison of horizontal acceleration without and with the isolation design at the angular node A

Figure 6 shows the horizontal acceleration response comparison of the angular node A of the structure without and with the isolation design of scheme 2. As the structural height increases, horizontal acceleration response increases without the isolation design, while the horizontal acceleration response basically does not increase with the isolation design, and the acceleration response values at different heights of the structure are almost equivalent, which conforms to the conclusion of the rigid body translation of the whole structure. With the isolation design, the overall acceleration value of the structure is greatly reduced to achieve the goal of the isolation design.

3.5.3 Analysis of vertical compressive stress of the isolation bearings

In this paper, the vertical compressive stress of the isolation bearings under gravity load, live load and vertical seismic load is calculated. In case of uniform layout of isolation bearings in the isolation scheme 1, the distribution of pressure of the superstructure among the isolation bearings is extremely uneven. The maximum compressive stress of the isolation bearings reaches 23MPa, while the minimum is only 1.3mpa. The vertical compressive stress of rubber lead bearings should be controlled within 15MPa (according to relevant specification) under ultimate safe earthquake, and within 10MPa under safe operation earthquake. The experimental results show that when the compressive stress of lead rubber bearings is less than 5MPa, its hysteretic energy dissipation characteristics cannot be effectively played, therefore, it is necessary to adjust the number, type and plane layout of the isolation bearings in scheme 1 to ensure that the compressive stress is not too low.

According to the mechanical characteristics of the structure and referring to the calculation results of scheme 1, scheme 2 is adjusted as shown in figure 2. The maximum compressive stress of the elastic slide bearings is 25.3Mpa (the maximum allowable compressive stress is 30Mpa) and the minimum compressive stress is 11.5mpa. The maximum compressive stress of non-lead rubber bearings is 12.4mpa and the minimum compressive stress is 2.5mpa. The maximum compressive stress of lead rubber bearings is 12.3MPa, and the minimum compressive stress is 6.9MPa. The vertical compressive stress of all types of bearings meet the limit requirements, so scheme 2 is a reasonable one. In particular, it is pointed out that the bearings with lower stress are not in the main force transfer area of the superstructure and raft foundation, and the purpose of arranging these bearings is to make the bearing arrangement in the isolation layer regular, and make the stiffness distribution of the isolation layer uniform.
4. Conclusion
In this paper, a 3D finite element model of a nuclear island plant in a metal-cooled fast reactor is established. By dynamic time-history analysis, the application of the isolation scheme with multiple isolation bearings in the nuclear island plant structure with split base layer is studied. The research conclusions are as follows:

1) for a complex structure like the nuclear island plant (with large seismic force and irregular torsion), it is necessary to use a mixture of lead rubber bearings, non-lead rubber bearings and elastic sliding plate bearings to achieve an ideal isolation effect. 

2) the local vertical stiffness of the structure should be coordinated with the stiffness of the isolation bearings, that is, the structure with relatively large local vertical stiffness should adopt the isolation bearings with relatively large vertical stiffness, so as to make the vibration frequency of each part of the structure be the same with the isolation design.

3) for the equipment which is sensitive to vertical seismic effect, another vertical isolation can be done for the equipment.

Acknowledgments
This paper is supported by the research and development of nuclear power plant safety management platform based on Building Information Model (BIM) technology of Shenzhen Science and Technology Commission (Grant No. AN2017001).

References
[1] Fulin Zhou. (1997) Seismic control of engineering structures. Earthquake Press, Beijing.
[2] Lili Xie, Changhai Zhai. (2012) Feasibility study on application of isolation technology in nuclear power engineering. J. Seismic engineering and engineering vibration, 32: 1-10.
[3] Tajirian F.F., Kelly J.M., Aiken I.D. (1990) Seismic isolation for advanced nuclear power stations. J. Earthquake Spectra, 6: 371-401.
[4] Tao Wang, Fei Wang. (2014) Experimental study on vibration table of isolation structure of nuclear power plant. J. Engineering mechanics, 31: 62-68.
[5] Zhongcheng Li , Tao Zhang , Songqi Li. (2016) Base isolation technology scheme of nuclear power plant emergency command centre. J. Nuclear science and engineering, 36: 218-222.
[6] Frano R.L, Forasassi G. (2010) Isolation systems influence in the seismic loading propagation analysis applied to an innovative near term reactor. J. Nuclear Engineering and Design, 240: 3539-3549.