Research Article

Research on Seismic Response of Base-Isolated Nuclear Island Building considering FSI Effect of PCS Water Tank

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Base isolation can be used to reduce seismic response of structure and protect the structure from damage subjected to earthquake. To study the isolation effect of new PWR nuclear power plant with a base isolation system, considering FSI (fluid-structure interaction) effect by the simplified model, two 3D numerical models (one nonisolated model and one isolated model) were established. After natural frequency analysis, one artificial ground motion was chosen to analyze isolation effect qualitatively. Based on the results, the accelerations and relative displacements of nuclear island building under ten natural ground motions were statistically analyzed to evaluate the isolation effect quantitatively. The results show that the base isolation system can reduce the natural frequencies of nuclear island building. Horizontal accelerations can be reduced effectively, but the isolation effect is not obvious in vertical direction. The acceleration reduction ratio of the top is about 70%–90%, and the acceleration reduction ratio of the lower part is about 20%–60%. Horizontal displacement of the isolated model is far larger than that of the nonisolated model, and horizontal displacement will become larger considering FSI effect. These conclusions could provide some references for studies on the isolation system of nuclear island building.

1. Introduction

The seismic safety of the nuclear power plant has always been an important issue of nuclear safety. Since the twenty-first century, the constructions of nuclear power plants are developed rapidly, especially in China. Compared with the traditional nuclear power plants, passive idea is introduced into new PWR (pressurized water reactor) nuclear power plants. As one important component of PCS (the passive containment cooling system), the cooling water tank which has high position and large mass is at the top of shield building [1]. So, the FSI effect should be considered in seismic response analysis. The PCS of nuclear island building is shown in Figure 1.

To improve the seismic safety of structures, base isolation has been widely used in industrial plants, high-buildings, and bridges. However, for nuclear power projects, there are also some limitations in the direct application of base isolation technology. Currently, in the commercial plants, only two nuclear power plants (Cruas in France and Koeberg in South Africa) which have been built and two nuclear power plants which are being built adopted base isolation technology [2, 3]. To promote the application of base isolation technology in a nuclear power plant, some corresponding research has been carried out in France, Japan, America, and China.

In the field of FSI effect of nuclear power plant, Liu [4] adopted the CEL (Coupled Eulerian Lagrange) method to analyze the FSI of the PCS water tank and studied the effect of seismic performance of shield building based on ABAQUS. The research shows that the method recommended by specifications is not entirely applicable for the seismic requirement of shield building. Zhao et al. [5–7] used the ALE (Arbitrary Lagrange Eulerian) method to simulate the FSI effect and studied the influence of water tank and the air intake systematically. The research shows that water levels and the locations of air intake could change the dynamic characteristics of shield building. Xu et al. [8] used SPH
Figure 1: PCS of nuclear island building.

(smoothed particle hydrodynamics) and the FEM (finite element method) coupling method to simulate the FSI effect between cooling water and shield building of AP1000. The research shows that the water tank can decrease the natural frequencies and responses of shield building. Considering the whole shield building and auxiliary building, Zhao et al. [9, 10] did some research on the natural frequencies and dynamic responses of nuclear island building with various water levels and different elevations of air intake. Song et al. [11, 12] established finite element models with water, shield building, and auxiliary building, and investigated FSI effect of nuclear island building. In addition, one simplified method was proposed and proved to be reasonable to simulate FSI effect. Wang et al. [13] designed seven cases of water levels to investigate dynamic responses of shield building and proposed the optimal water level ratio.

In the field of base isolation of nuclear power plant, Xie and Zhai [14] pointed out that base isolation is a mature technology that can benefit the nuclear power plant in resisting the potential severe earthquake and facilitating the standardization of design and construction, as well as reducing the initial and life-cycle cost. Wang et al. [15] studied the seismic responses of nuclear containment with and without isolations through shaking table tests and numerical simulations. The research shows that the horizontal seismic responses of structure can be effectively reduced using the isolation system, and the vertical seismic responses of structure will be amplified. Chen et al. [16] numerically investigated the dynamic responses of AP1000 nuclear island building with and without isolators under a typical safe shutdown earthquake. The research shows that base isolation can obviously reduce the acceleration responses of floors and proposes some isolation suggestions. Medel-Vera and Ji [17] summarized the isolation research of nuclear power structures. The conclusion shows that base isolation has a good effect on horizontal directions, but not in vertical direction. Zhu et al. [18] took one nuclear power plant as an example and analyzed the seismic responses of structure with base isolation technology by ANSYS. The research shows that the floor response spectra, acceleration responses, and seismic action of reactor building in the horizontal direction can be effectively reduced after the application of base isolation. However, this effect is not obvious in the vertical direction. Zhuang et al. [19] established a finite element model of AP1000 nuclear island building by ANSYS program and studied the three-dimensional seismic vibration responses of structure under safe shutdown earthquake and beyond-design basis earthquake. The research shows that the base isolation system can effectively ensure the safety of a nuclear island structure under the beyond-design basis earthquake. Wang et al. [20] proposed a base isolation design for AP1000 nuclear shield building on considering the performance requirements of the seismic isolation systems and devices of shield building. The research shows that the base isolation technology is an effective approach to maintain the structural integrity which subjected to both DBE (design basis earthquake) and BDBE (beyond-design basis earthquake) shaking.

The previous studies show that horizontal seismic responses of nuclear power plant will be reduced effectively using the base isolation system. However, the auxiliary building and FSI effect of cooling water were not considered systematically for new PWR nuclear power plant. In this paper, two 3D numerical models (one nonisolated model and one isolated model) were established and analyzed based on FEM software ABAQUS. Firstly, natural frequencies of two models were obtained. Secondly, one artificial ground motion was chosen to analyze isolation effect qualitatively. Finally, the accelerations and relative displacements of nuclear island building under ten natural ground motions were statistically analyzed to evaluate the isolation effect quantitatively.

2. Description of Isolation System

For the concept design of isolation bearings, the relevant experts and scholars have done some research and given the suggestions [21, 22]. In addition to bearing the load of nuclear island building, the resonance of cooling water in the water tank should be avoided. In the author’s previous research [11], 1st sloshing frequency of cooling water is about 0.13 Hz. So, the isolation bearings are chosen to ensure that 1st frequency of isolation structure is greater than 0.4 Hz. Considering the foundation size, total mass, dynamic characteristics of nuclear island building, and so on, lead-rubber bearing GZY1000 is selected as the isolation bearing for the dynamic analysis of the nuclear island building after a series of trial calculations [23]. As shown in Figure 2, the main components of lead rubber bearing are connecting plate, lead core, rubber protective layer, steel plate, and rubber layer. The main mechanical parameters of GZY1000 are shown in Table 1.
To ensure that the nuclear island building will not be damaged due to excessive torsion, the center of mass and the center of stiffness of the isolated structure need to coincide approximately. According to the shape of foundation, 361 isolation bearings are arranged at the bottom of foundation. The total mass of nuclear island building is about $2.2 \times 10^5$ t, and the average vertical load of one isolation bearing is 6094 kN. The vertical ultimate load of GZY1000 is 7853 kN, and the safety margin is about 30%. So, the selection of isolation bearing is reasonable preliminary. The arrangement of isolation bearings is shown in Figure 3.

3. Introduction of Numerical Models

3.1. Simplified Method of FSI Effect. In the author’s previous research, one simplified method was proposed to simulate the FSI effect between cooling water and shield building. It has been proved that the simplified method has a good result in simulating the seismic response of the whole nuclear island building considering FSI effect. In this paper, this simplified method is used for analysis. The schematic diagram of the simplified model is shown in Figure 4, and the details of the simplified model have been reported in reference [11]. In Figure 4, $m_0$ is the impulsive mass and $m_1$ is 1st mode convective mass. $m_1$ is divided into two parts: horizontal components and vertical components. The horizontal components are connected to tank walls by spring-dampers and the vertical components are added to the bottom of water tank discretely. $m_0$ is added to the bottom and walls of the tank discretely.

In terms of the influence of water level on the seismic responses of nuclear island building, some researchers have done related studies and given the optimal water level [10, 13]. Synthetically considering the previous research results and design documents of new PWR nuclear power plant, the water level of the water tank in this paper is the standard design level. The water level ratio is about 0.81 which is close to the optimal scheme.

3.2. Numerical Models. In this paper, air intake and the steel containment vessel are not considered. To analyze the base isolation effect, two models are established in ABAQUS:

(a) Model one: nonisolated structure
(b) Model two: isolated structure

The bottom plate of nuclear island building is modeled by solid element while the shield building and auxiliary building are modeled by shell element. For the base isolation system, the Cartesian connector element is used to simulate the isolation bearing. In ABAQUS, the Cartesian connector element can provide a connection between two nodes that allows independent behavior in three local Cartesian directions.

The numerical models are shown in Figure 5, and X-direction, Y-direction, and Z-direction represent S-N, E-W, and vertical direction separately. The geometry sizes of previous papers [10, 11] are referenced, and the main material parameters are shown in Table 2.

4. Natural Frequencies

Natural frequencies are important dynamic characteristics for structures, especially for isolated structures. For the isolated structure, horizontal stiffness of the isolation layer is far less than the stiffness of superstructure. Therefore, the superstructure can be regarded as a rigid body and fundamental frequency can be calculated by a single degree-of-freedom system [24, 25]. The fundamental frequency of a single degree-of-freedom system is given by

| Vertical stiffness $K_v$ (kN/m) | Horizontal prefield stiffness $K_u$ (kN/m) | Horizontal postfield stiffness $K_d$ (kN/m) | Vertical ultimate load $F_z$ (kN) | Yield force $Q_d$ (kN) |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|-----------------|
| 6374                            | 12295                           | 1892                           | 7853                            | 261.7           |

**Figure 2:** Schematic diagram of GZY isolation bearing.

**Table 1:** Main mechanical parameters of GZY1000.
Figure 3: The arrangement of isolation bearings.

Figure 4: The schematic diagram of simplified model: (a) FSI model and (b) simplified model.

Figure 5: Numerical models: (a) model one: nonisolated structure and (b) model two: isolated structure.

Table 2: Material parameters of nuclear island building.

| Material parameters      | Concrete | Steel     | Water       |
|-------------------------|----------|-----------|-------------|
| Density (kg/m³)         | 2400     | 7800      |             |
| Young’s modulus (Pa)    | $3.00 \times 10^{10}$ | $2.00 \times 10^{11}$ | Simplified model |
| Poisson’s ratio         | 0.17     | 0.30      |             |
where $f_H$ is the fundamental frequency of the isolation system, $K_H$ is the total horizontal prefield stiffness, $n$ is the number of isolation bearings, $K_u$ is the horizontal prefield stiffness of one isolation bearing, and $m$ is the total mass of nuclear island building. Based on the above parameters, the fundamental frequency is 0.716 Hz.

Using ABAQUS, modal analysis of two models is studied. The first two natural frequencies are listed in Table 3. The 1st mode is the translation of structure in Y-direction, and 2nd mode is the translation of structure in X-direction. The first two frequencies of model two are 0.727 Hz and 0.769 Hz separately, and the relative error of fundamental frequency between theoretical formula and numerical analysis is 1.5%. It illustrates that the theoretical assumption of a single degree-of-freedom system and the numerical method of modal analysis are both reasonable. The first two natural frequencies are far larger than the 1st sloshing frequency of cooling water (0.13 Hz), and the resonance of cooling water in the water tank will not occur in dynamic analysis. Combining vertical ultimate load of isolation bearing, it is considered that the selection of the base isolation system is reasonable.

5. Seismic Responses of Numerical Models under Artificial Ground Motion

5.1. Input Ground Motion. To analyze the seismic responses of nuclear island building, the artificial ground motions fitted by code response spectrum are chosen as inputs. The peak ground accelerations (PGAs) of safe shutdown earthquake (SSE) in three directions are 0.3 g, and the input ratio of three direction is 1:11 [26, 27]. The acceleration time histories and the corresponding spectral acceleration with the damping ratio of 0.5% are shown in Figure 6.

5.2. Acceleration Responses. To analyze the dynamic response characteristics of two models, ten reference points are chosen. P1–P6 are at the east of shield building, P7–P9 are at the north of shield building, and P10 is at the top of auxiliary building. The locations of reference points are shown in Figure 7, and the heights of reference points are listed in Table 4.

Due to the space limitation, the acceleration responses of three reference points (P1, P7, and P10) in three directions are shown in Figure 8. It shows that the change law of acceleration time history curves of these reference points is similar using base isolation technology under artificial ground motion. Base isolation has a good effect on reducing the acceleration responses of nuclear island building in horizontal directions. However, in vertical direction, isolation effect is not obvious and the peak accelerations of two models do not change too much. The reduction of peak acceleration of auxiliary building (P10) is less than that of shield building (P1 and P7).

To study the distribution of accelerations along the height of structure and reflect the isolation effect clearly, the accelerations of six reference points at the east of shield building (P1–P6) were analyzed. Figure 9 shows the three direction accelerations along the height of structure under artificial ground motion.

In horizontal directions, the peak accelerations of model one increase with the increase of structure height, but the peak accelerations of model two along the structure height have little changes. The base isolation system can effectively reduce horizontal acceleration responses. Moreover, the higher the height is, the more obvious the isolation effect is.

In vertical direction, the peak accelerations of two models both increase with the increase of structure height. On the top of shield building, the base isolation system has certain isolation effect. However, at the middle and lower part of shield building, the isolation effect is not obvious.

The law of peak accelerations along structure height of two models is different in horizontal directions. The main reason is that the horizontal stiffness of isolation bearings is far less than that of nuclear island building, and the structure can be regarded as a rigid body approximately. So, the accelerations of model two change little along the structure height in horizontal directions.

5.3. Floor Response Spectra. To study the spectrum characteristics of nuclear island building, the floor response spectra with 5% damping ratio of reference points at water tank (P1), shield building (P7), and auxiliary building (P10) are drawn in Figure 10.

In horizontal directions, the amplitudes of floor response spectra and zero periodic accelerations of model two are both significantly reduced compared with model one. After the isolation system is adopted, the corresponding periods of amplitudes move to long period range obviously.

In vertical direction, the amplitudes of floor response spectra and zero periodic accelerations of two models do not change too much. And the corresponding periods of amplitudes of model two are similar to that of model one. From the perspective of the spectrum, this base isolation system has good isolation effect on horizontal directions but no obvious isolation effect on vertical direction.

5.4. Relative Displacement Responses. To study the displacements of nuclear island building relative to the ground, the relative displacements of six reference points at the east of shield building (P1–P6) were analyzed. Figure 11 shows
the three direction relative displacements along the height of structure under artificial ground motion.

In horizontal directions, the peak displacements of model one increase with the increase of structure height. The maximum horizontal displacement is 0.027 m in X-direction and 0.030 m in Y-direction. For model two, the peak displacement curves along structure height are approximate straight lines. The displacement differences between the top and bottom are 0.007 m in X-direction and 0.014 m in Y-direction. In addition,

Figure 6: Artificial ground motion: (a) acceleration time history in X-direction, (b) acceleration time history in Y-direction, (c) acceleration time history in Z-direction, and (d) response spectra.

Figure 7: The location of reference points.
the displacement of structure is similar to integral translation and the displacement is mainly concentrated in the base isolation layer. The relative displacements of structure are slightly larger in Y-direction than that in X-direction. The main reason is that the stiffness of nuclear island building is less in Y-direction than that in X-direction. Compared with previous studies [16, 20], the horizontal displacements calculated in this paper are slightly larger. The main reason is that FSI effect is considered in the models in this paper, but the previous isolation studies do not consider FSI effect. It shows that horizontal displacements will become larger considering FSI effect, and FSI effect should be considered in isolation analysis of nuclear island building.

In vertical direction, the peak displacements of two models increase with the increase of structure height. The maximum displacement difference between two models is 0.003 m, and the isolation effect is not obvious.

The horizontal displacements of model two are far larger than that of model one. The reason is also that the horizontal stiffness of isolation bearings is far less than that of nuclear island building. After the isolation system is adopted, some energy of earthquake is consumed by large deformation of the isolation layer.

6. Seismic Responses of Numerical Models under Natural Ground Motions

6.1. Input Ground Motion. According to the above analysis, the base isolation system can obviously reduce the acceleration responses and amplify the integral displacement in horizontal directions. In order to study the effect of base isolation quantitatively, statistical analysis of seismic responses is necessary. Taking the horizontal code response spectrum as the control factor, considering PGA and
duration time, ten natural ground motions (NG1 to NG10) from the PEER (Pacific Earthquake Engineering Research Center) ground motion database are chosen as inputs in this part. The parameters of ground motions are shown in Table 5.

The PGA in three directions is 0.3 g, and the input ratio of three directions is 1:1:1. The horizontal acceleration response spectra of the ten natural ground motions and code response spectrum with the damping ratio of 0.5% are compared in Figure 12. It can be seen that the spectrum curves are close to code spectrum curves in horizontal directions.

6.2. Acceleration Responses. To study the distribution of acceleration under ten natural ground motions, the accelerations of six reference points at the east of shield building (P1–P6) were analyzed. Figures 13 and 14 show the three direction accelerations along the height of structure.

In horizontal directions, the law of peak accelerations along structure height of two models is similar to that under artificial ground motion. For model two, the peak accelerations along structure height have little changes. The base isolation system can effectively reduce horizontal acceleration responses. Moreover, the higher the height is, the more obvious the isolation effect is.

In vertical direction, the acceleration responses of model two are slightly larger than that of model one for some ground motions (NG3, NG4, NG5, NG6, and NG10), and the acceleration responses of model two are slightly smaller than that of model one on the top of shield building for some ground motions (NG1, NG7, and NG9). Combined with the calculation results under artificial ground motion, the base isolation system has little effect on the vertical acceleration.

To study the isolation effect quantitatively, the acceleration reduction ratio is analyzed and the formula is defined as follows:

\[
\text{Acceleration reduction ratio} = \frac{\text{peak acceleration of model 1} - \text{peak acceleration of model 2}}{\text{peak acceleration of model 1}}
\]

Due to the space limitation, the acceleration reduction ratio of three reference points (P1, P4, and P6) in the horizontal directions is calculated and shown in Figure 15.

It can be seen that the acceleration reduction ratio of the top (P1) is about 70%–90%, the acceleration reduction ratio of the middle part (P4) is about 55%–75%, and the acceleration reduction ratio of the lower part (P6) is about 20%–60%. The acceleration reduction ratio decreases gradually with the decrease of structure height.

Under different ground motions, the horizontal damping effect of base isolation has certain differences. The reason is that the spectrum characteristics of ground motions are not consistent. The damping effect is not only related to the isolation bearing but also related to the
Figure 10: Floor response spectra of two models under artificial ground motion: (a) P1 in model 1, (b) P1 in model 2, (c) P7 in model 1, (d) P7 in model 2, (e) P10 in model 1, and (f) P10 in model 2.
Figure 11: Comparison of peak relative displacement along the height of structure: (a) X-direction, (b) Y-direction, and (c) Z-direction.

Table 5: Parameters of ten natural ground motions.

| Number | Earthquake event     | Station                  | Year | Magnitude |
|--------|----------------------|--------------------------|------|-----------|
| NG1    | Imperial Valley-02   | El Centro Array #9       | 1940 | 6.95      |
| NG2    | Imperial Valley-06   | El Centro Array #3       | 1979 | 6.53      |
| NG3    | Imperial Valley-06   | El Centro Array #5       | 1979 | 6.53      |
| NG4    | Imperial Valley-06   | Brawley Airport          | 1979 | 6.53      |
| NG5    | Imperial Valley-06   | Delta                    | 1979 | 6.53      |
| NG6    | Landers              | Amboy                    | 1992 | 7.28      |
| NG7    | Landers              | Big Tujunga, Angeles Nat F | 1992 | 7.28      |
| NG8    | Managua, Nicaragua-01| Managua, ESSO            | 1972 | 6.24      |
| NG9    | Kern County          | Taft Lincoln School      | 1952 | 7.36      |
| NG10   | Tabas, Iran          | Tabas                    | 1978 | 7.35      |

Figure 12: Acceleration response spectra with the damping ratio of 0.5%: (a) X-direction and (b) Y-direction.
Figure 13: Comparison of peak acceleration along the height of structure under NG1-NG5. Note. M1 and M2 are the mean of model one and model two. (a) X-direction, (b) Y-direction, and (c) Z-direction.

Figure 14: Comparison of peak acceleration along the height of structure under NG6-NG10: (a) X-direction, (b) Y-direction, and (c) Z-direction.
Figure 15: Acceleration reduction ratio in the horizontal directions: (a) acceleration reduction ratio of P1; (b) acceleration reduction ratio of P4; and (c) acceleration reduction ratio of P6.
Figure 16: Comparison of peak relative displacement along the height of structure under NG1-NG5: (a) $X$-direction, (b) $Y$-direction, and (c) $Z$-direction.

Figure 17: Comparison of peak relative displacement along the height of structure under NG6-NG10: (a) $X$-direction, (b) $Y$-direction, and (c) $Z$-direction.
structure frequency and the spectrum characteristics of ground motions.

6.3. Relative Displacement Responses. The relative displacements of six reference points at the east of shield building (P1–P6) under ten natural ground motions were analyzed. Figures 16 and 17 show the three direction relative displacements along the height of structure.

In horizontal directions, the peak displacements of model one increase with the increase of structure height and the maximum horizontal displacement at the top of model one is 0.033 m. The peak displacements of model two change little with the increase of structure height, and the horizontal displacements of whole structure are about 0.049 m–0.136 m. The peak displacement at the top of structure increases by 3–5 times when the base isolation system is used.

In vertical direction, the maximum displacement difference between two models is 0.004 m which is similar to that under artificial ground motion. Base isolation has little effect on the vertical displacement of the structure.

Similar to the acceleration responses, the horizontal displacement responses of model two are not only related to the isolation bearing but also related to the structure frequency and the spectrum characteristics of ground motions. The horizontal displacements of nuclear island building increase obviously when the base isolation system is used, and it is necessary to take measures to prevent structural damage caused by excessive displacement.

7. Conclusions

The nuclear island building of new PWR nuclear power plant was chosen as object. FSI effect was considered by the simplified method. Two 3D numerical models (one non-isolated model and one isolated model) were established and analyzed based on FEM software ABAQUS. One artificial ground motion and ten natural ground motions were chosen as inputs, and the isolation effect was evaluated. The following conclusions are obtained. These calculation results can be useful for analysis and application of base isolation of nuclear power plant.

(1) The base isolation system can reduce the natural frequencies of nuclear island building. The fundamental frequency of the isolated model is far larger than the 1st sloshing frequency of cooling water, and the resonance of cooling water in the water tank will not occur in dynamic analysis.

(2) Horizontal accelerations can be reduced effectively by the base isolation system. The acceleration reduction ratio of the top is about 70%–90%, and the acceleration reduction ratio of the lower part is about 20%–60%. The damping effect is not only related to the isolation bearing but also related to the structure frequency and the spectrum characteristics of ground motions.

(3) Horizontal displacements of the isolated model are far larger than that of the nonisolated model, and the peak displacement at the top of structure increases by 3–5 times when the base isolation system is used.

(4) Horizontal displacements will become larger considering FSI effect, and FSI effect should be considered in isolation analysis.

(5) The isolation effect of the base isolation system is not obvious in vertical direction.

Data Availability

The data used to support the findings of this study are included within this paper.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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