Research on Floor Response Spectrum of Shielded Building Structure under Seismic Loading

Chen Yang*, Xiong Cheng, Ma Tengfei, Zeng Wenlin and Wang Juan

Xinyu University, Xinyu, Jiangxi, 338000, China
*Corresponding author’s e-mail: 517737775@qq.com

Abstract. As a clean energy source, nuclear power has broad prospects for development. It is of great significance to study the seismic response of nuclear power plants. PLAXIS software is used to establish the whole finite element model of AP1000 nuclear power plant shielding plant structure. Considering the foundation embedding and soil-structure interaction, the seismic response analysis of nuclear power plants on different inclined soft rock sites was carried out under seismic loading. By analyzing and comparing the calculated results of the floor response spectrum amplification factor, the peak frequency of the floor response spectrum at the important position is smaller than the peak frequency of the design response spectrum, the inclination of the inclined site will affect the peak frequency and cause the amplification effect.

1. Introduction
As a clean and environmentally friendly energy source, nuclear energy has broad prospects for development [1]. Due to the special structure of the nuclear power plant and the danger of nuclear materials, safety issues must be placed first in the seismic design. The seismic problem of nuclear power plants should start from the site selection which follow the principles that, and trying to choose the area without earthquake history, and avoiding the active earthquake area. Secondly, seismic design needs to be improved. Soil-structure interaction (SSI), as an important link in seismic design, must be paid attention to. In addition, the stiffness of nuclear power superstructure is very large [2-3], so the influence of SSI must be considered when the flexibility of non-bedrock foundation is relatively large. According to the American ASCE 4-86 code when the average shear wave velocity of the local soil is less than 1100 m/s, the influence of SSI needs to be considered in the dynamic response research analysis. China is actively promoting the localization of AP1000 nuclear power units, and many nuclear power plants to be built at present take AP1000 nuclear power units as target structures [4]. Considering the interaction between the environment and nuclear power plants, the range of site options is very limited. If ground-based constraints are needed, the choice of nuclear power plants will become increasingly difficult. With the scarcity of good hard rock sites, it is imperative to study the seismic response of AP1000 nuclear power unit under soft rock sites.

At present, the existing research and analysis work mostly take the uncertainty of soft rock foundation parameters as the research direction [5-7], and the influence of soft rock foundation with different surface inclination angle on the seismic response of nuclear power structure is seldom studied. Therefore, this paper takes AP1000 shielded power plant structure as the research object, considers the soil-structure interaction, and discusses the influence of soft rock foundation with different surface inclination angle on the floor response spectrum of shielded power plant structure in important locations, which has certain reference significance for the construction of nuclear power plant in soft...
rock field.

2. Finite element model

2.1. AP1000 shielded building model

The AP1000 nuclear island structure is divided into three parts: SCV (steel containment vessel), CIS (containment internal structures), and ASB (annex and containment structure). The shielded building structure is an independent, cylindrical, axisymmetric shell with elliptic tops on both ends, with a radius of 19.8 m. The internal structure includes large reinforced concrete support system, internal steam pipeline, large nuclear power equipment, channels and other structures. The structural diagram and the top view of the internal shear wall structure are shown in figure 1(a) and 1(b). The buried depth of the shielded building is 12.02 m (all the following heights are relative heights obtained from the base plane of the foundation), and the total height is 85.2 m. The elevation of vessel support is located at 30.48 m, the operation deck is located at 41.2 m, the control room is located at 49 m, the top floor of the fuel building is located at 56.4 m, and the polar crane is located at 68.2 m. It should be pointed out that the above five important positions are the selected positions of floor response spectrum. It should be pointed out that the above five important positions are the selected positions of floor response spectrum.

![Internal shear wall construction diagram](image1.png)  ![Top view of internal shear wall](image2.png)

Figure 1. Internal shear wall structure

According to the design document provided by Westinghouse, the cylindrical shell with an ellipsoid at the top is simplified into a cylindrical concrete shell with a circular plane at the top. Considering the complicated arrangement and distribution of the shielded building, the steel plates on the outer side of the main structure and the internal structural steel bars are not separately modeled, but are evenly distributed into the concrete structure model. The concrete material has a density of 2,500, a modulus of elasticity of 34.5, and a Poisson's ratio of 0.2. The finite element model of AP1000 shield building is shown in figure 2.

![Finite element model of AP1000 shield building](image3.png)

Figure 2. Finite element model of AP1000 shield building

2.2. Soft rock foundation-structure model

The soft rock foundation adopted in this paper is composed of two layers of hard rock at the bottom
and soft rock at the top, both of which are homogeneous soil layers. The total height of the model is 50m (the average height of the left and right sides of the foundation), and the bottom of the model is the seismic input surface. The molar coulomb constitutive model was adopted. The specific related physical and mechanical parameters were shown in table 1. In order to get the effect of soft rock foundation with different inclination angles on floor response spectrum under soil-structure interaction, in this paper, a total of four different working conditions were considered, the thickness of soft rock was 30m, the thickness of hard rock was 20m, and the surface inclination angle was 0°, 1°, 2° and 3°, respectively. Soil-structure interaction model with 1° surface inclination is shown in figure 3.

Table 1. Physical parameters of soft rock foundation

| Soil name | density/(kg/m³) | Elastic Modulus/(Pa) | Poisson's ratio | Longitudinal wave velocity/(m/s) | Shear wave velocity/(m/s) |
|-----------|-----------------|----------------------|----------------|---------------------------------|--------------------------|
| Soft rock | 2200            | 2.78×10⁹             | 0.25           | 1220                            | 700                      |
| Hard rock | 2300            | 8.1×10⁹              | 0.20           | 1959                            | 1200                     |

3. Seismic time history analysis

3.1. Ground motion input method
In the process of ground motion input, in order to better simulate the projection process of seismic waves at the boundary without generating seismic wave reflection, dynamic boundary can be applied in the dynamic calculation process [8-9]. The dynamic boundary includes viscous boundary and free field boundary. In this numerical analysis, viscous boundary is applied on the bottom seismic input surface and free field boundary is applied on the side. As shown in figure 4, the free boundary is simulated by coupling the damper with the free field, while the viscous boundary is simulated by Lysmer's viscous damping.

3.2. The selection of input ground motion
In this paper, the time history of ground motion based on RG1.60 response spectrum synthesis is adopted as the horizontal input ground motion at the bottom of the soil-structure interaction model. The input ground motion intensity is taken from the ground motion value of the standard design which makes the structure in an elastic working state, and the peak acceleration amplitude is 1.50 m/s². The total duration of RG1.60 spectrum artificial ground motion is 20.48 s, and the acceleration time history
curve and response spectrum are shown in figure 5.

Figure 5. Acceleration time history and response spectrum of input seismic wave

4. Analysis and discussion of calculation results

Based on the calculation of Plaxis software, the acceleration-time history curves at the five important positions mentioned above are extracted separately and converted into floor response spectra by Fourier transform. In order to make a better quantitative evaluation, the floor response spectrum amplification factor is defined as the ratio of floor response spectrum to the response spectrum of input ground motion. The variation of the floor response spectrum amplification factor at five important positions under different inclination angles is shown in figure 6. As can be seen from the figure, the peak frequency of the response spectrum amplification factor under inclination soft rock field is larger than that under the horizontal field (the horizontal field is 1.72Hz and the inclined field is 1.88Hz). The variation of the response spectrum amplification factor at different positions under four conditions is roughly similar. It should be pointed out that there is a significant double-peak effect under the 3° inclined field, and the response spectrum amplification factor around the 5.32 Hz in the vessel support and the operating deck has a significant increase.

Figure 6. Response spectrum amplification factor of different inclined angles at important position
Table 2. Acceleration peak value of floor response spectrum in important position

| Surface inclination angle | Vessel Support | Operating Deck | Control Room | Fuel Building | Polar Crane |
|--------------------------|----------------|----------------|--------------|--------------|------------|
| 0                        | 0.333          | 0.500          | 0.775        | 0.875        | 1.056      |
| 1                        | 0.266          | 0.450          | 0.748        | 0.883        | 1.063      |
| 2                        | 0.368          | 0.563          | 0.920        | 1.054        | 1.271      |
| 3                        | 0.345          | 0.498          | 0.805        | 0.894        | 1.080      |

Peak acceleration value of floor response spectrum at 5 positions is shown in table 2. By comparison, the peak value of floor response spectrum generally presents a rule of $2^\circ > 3^\circ > 0^\circ > 1^\circ$, which indicates that the inclined field has a magnifying effect on the dynamic response of the shielded building structure. In order to see the difference of response spectrum peaks in five important positions at different inclination angles, the relative height of important positions was taken as the X-axis and the peak acceleration of response spectrum as the Y-axis, the peak value comparison of response spectrum amplification factor can be seen in figure 7. As can be seen, the peak changes under different inclination angles are basically the same, and both increase with the increase of relative height. The peak value of response spectrum at the fuel building and polar crane under surface inclination angle of $1^\circ$ is larger than the value at the horizontal site, but the gap is not large, and the overall variation of $0^\circ > 1^\circ$ is still present. The peak value of the floor response spectrum under the horizontal field and $3^\circ$ inclined field are relatively similar. Overall, the $2^\circ$ inclination field peak value is significantly larger than the other three cases, and the gap increases with height.

![Figure 7. Peak value comparison of response spectrum amplification factor](image)

5. Conclusion
The peak frequency of the five important positions obtained in this paper is about 16% lower than the peak frequency of the designed response spectrum. The main reason for this phenomenon is the insufficient stiffness caused by the simplification of some structures.

The peak frequency of floor response spectrum at important positions in inclined site is larger than that in horizontal site. The reason for this phenomenon is that the presence of inclination angle causes the predominant frequency change of seismic wave.

Comparing the peak values of the floor response spectra of important locations under different inclined sites, it can be concluded that the peak value generally shows a rule of $2^\circ > 3^\circ > 0^\circ > 1^\circ$, which indicates that the inclined field has a magnifying effect on the dynamic response of the shielded building structure.

References
[1] Ou Y O, Wang D S. (2007) International nuclear power application and its prospect forecast and our country nuclear electricity development. J. Journal of North China Electric Power University., (05): 1-10.
[2] Cao G A, Li F. (1993) The Dynamic Responses of the Soil-Auxiliary Buildings Interaction System. J. Civil Engineering Journal., 14(04): 374-380.

[3] Yin X Q, Yuan W Z, Wang G X. (2017) Seismic Response Analysis for Nuclear Power Plant Considering Structure Foundation Structure Interaction Effect. J. Nuclear Safely, 16(03): 68-74.

[4] Wang Y R, Zheng Z. (2017) Analysis on the Domestic Manufacture of AP 1000 Nuclear Reactor. J. ELECTRIC POWER., 50(01): 43-48+55.

[5] Li Z X, Li Z C, Rang W Q. (2006) Seismic response simplified analysis method considering soil-structure interaction of inner containment in nuclear power plant. J. Seismic Engineering and Engineering Vibration., 26(02): 143-148.

[6] Dai Z J, Li X J, Hou C L. (2013) An Analysis of the Sensitivity of Parameters of Ground Soil for the Ground Motion Response of Nuclear Power Plant Structures. J. Journal of Basic Science and Engineering., 21(03): 479-488.

[7] He Q M, Li X J, Zhang J W, et al. (2014) Seismic response analysis of high temperature gas cool reactor nuclear power plant. J. Earthquake Defense Technology., 9(03): 454-461.

[8] Du X L, Zhao M, Wang J T. (2006) Stress-type time-domain artificial boundary condition for finite-element simulation of near-field wave motion and its engineering application. J. Journal of Mechanics., 38(1): 49-56.

[9] Du X L, Zhao M. (2006) Analysis method for seismic response of arch dams in time domain based on viscous-spring artificial boundary condition. J. Shuili Xuebao., 37(09): 1063-1069.