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Time-History Analysis on Seismic Stability of Nuclear Island Bedrock with weak Interlayer

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ABSTRACT

This paper presents a three-dimensional numerical simulation method for the seismic response calculation of nuclear island foundation based on the nuclear power plant in Tai Shan. There are two weak interlayers in the bedrock. The numerical simulation aimed at the analysis and the evaluation of the stability of bedrock with the consideration of the interaction between the bedrock and nuclear island. Main features of nuclear numerical model are: (1) the mechanical interaction of nuclear island buildings, turbine room and bedrock have been taken into consideration, (2) the two weak interlayers may decrease the stability of the bedrock, which are the focused research in the models, (3) non-reflective free field boundary have been used in the boundary condition of model. The commercial numerical software FLAC3D has also been used in the simulation and analysis. A finite difference of numerical model for nuclear island bedrock was established and it have been used to analyze the bedrock's mechanical phenomenon and safety performance. Dynamic characteristics, distributions of mechanical parameters and failure characteristics of bedrock have been studied under the action of seismic wave.

Keywords: *Nuclear island bedrock, Weak interlayer, Seismic resistance stability, Time history analysis.*

I. INTRODUCTION

The stability of the foundation is very important for the safety of nuclear power structures. The siting of nuclear power is very strict in the majority of nuclear power plants. With the increasing demand of energy, the siting of nuclear power demanding is in harsh requirements, but the geological conditions can't usually fully meet the requirements, and the non-uniform of nuclear power foundation is caused by the geological rupture zones and faults [1]. So the foundation of the nuclear power containing weak interlayer is very common. the main feature of this kind of foundation is: (1) The mechanical parameters of rock and soil have spatial variability and uncertainty; (2) Under certain conditions that the mechanical properties of weak intercalated layers are relatively low and part of the weak interlayer clay and high content of clay mineral, it will show the characteristics of mud and softening. Therefore, the safety of the foundation should be analyzed by the seismic response of rock soil structure interaction. In terms of time-history analysis on seismic stability of nuclear power, many scholars have conducted a plenty of mature research results.

Zhang et al introduced the concept of the change of porosity and pore water pressure influence the bedrock damage, established a brittle dynamic damage and failure mechanism model, through the method of finite element analysis the damage mode of the concrete gravity dam [2]. Song et al based on the dynamic deformation of anti-slide safety coefficient method, comprehensive nonlinear seismic stability of dam body and dam foundation of fractured rock mass by three-dimensional dynamic analysis [3]. Li et al, in the first sedimentary bedrock for nuclear power as an example, through design and use of vibration experiment, obtain the kinetic parameters of Sedimentary Rock Island batholith and make a guidance for engineering [4]. Scavvzzo established a multi degree of freedom of the particle spring model, through the response spectrum method to analyze and study the stability of the bedrock under the common action of structure and bedrock [5]. Leonardo et al respectively by using the finite element method and response spectrum method of AP1000 type reaction cone and bedrock of Westinghouse's interaction model for calculation and analysis, the dynamic analysis of the internal structure of the reaction cone and make safety assessment[6]. Lei et al by finite element method and the joint development of the nuclear island bedrock stability analysis and evaluation, and the two methods of nuclear stability analysis compared the effectiveness evaluation of numerical method for the analysis of nuclear stability with further research [7]. Huang et al developed a simplified procedure based on finite element method (FEM) for analyzing the longitudinal performance of shield tunnels considering the longitudinal variation of geotechnical parameters [8]. Juang et al illustrated the benefit of performing reliability-based design and the procedure for conducting reliability-based robust design when the statistics of the random variables are incomplete [9].Gong et al proposed a new method for computing the reliability index, based upon the numerical integration of the cumulative distribution function (CDF) of the performance function [10-11]. Ching et al analyzed a cone penetration test sounding at the Wufeng District in Taichung City to illustrate the importance of treating statistical uncertainty in full and the limitations of the existing point-estimation and detrending approaches [12].

Thus it can be seen that the existing results mainly focused on the dynamic interaction between soil foundation and the upper nuclear facilities in the nuclear power plant. However, few of them studied the suitability of foundation for nuclear power plant. On the basis of existing research results, by the finite difference program FLAC3D, a foundation model with the characteristics of weak intercalation was established; Physical and mechanical parameters were obtained through field investigation and laboratory tests, using the time history dynamic analysis method simulated the seismic input and response, and the propagation and reflection law of seismic wave in weak interlayer were got. Meanwhile the load distribution characteristics and the uneven settlement of the soft interlayer on the ground rock are analyzed. And thus we can get the comprehensive evaluation and discussion of Taishan nuclear power plant safety and reliability of the foundation.

II. MODEL AND HYPOTHESIS

2.1. Regional geological and physical parameters

Taishan nuclear power plant is located in Guangdong Province of China. The nuclear power project boasts the world largest installed capacity of nuclear power units. The bedrock is in accordance with the standard of weathered granite in the plant design process, but from the end of the foundation excavation, there are two tectonic fracture zones in the foundation, and the granite are highly weathered in the local area, so it’s necessary to have a further analysis and evaluation based on the survey data.

According to the report of geological exploration of Taishan nuclear power, the foundation of the HQT zone is relatively single, as shown in figure 1. There are two fracture zones, F1and F2. The F1 fracture zone is located on the west side of HQT by the middle, strike continuity is better with a tendency of 160 ~ 165 degrees, and a dip angle of 63 ~ 68 degrees, the F1 foundation for tectonic fracture surface showed cross section of HQT in alignment. While the F2 structure rupture surface is located in the northwest side of the central HQT with a tendency of 350 ~ 355 degrees, and a dip angle of 50 ~ 55 degrees. The exposed area in the excavation area is about 35.1m.

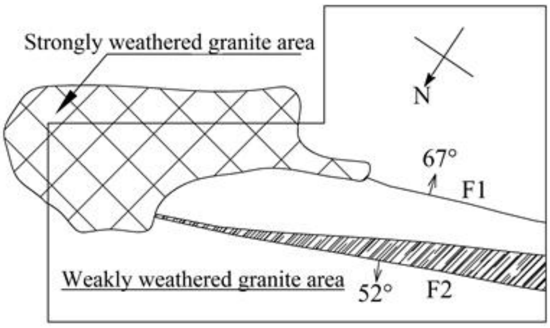


Figure 1. Geological map of HQT district

Comprehensive supplementary survey results and preliminary survey results, the values of the physical and mechanicalindexes of the main rock and soil layer in the HQT region are shown in Table 1 and table 2.

Table 1. Physical and mechanics parameters of rock layer

Rock mass property	Bulk density Kg/m^3	Poisson ratio	Elastic modulus /Gpa	Cohesion /MPa	internal friction angle φ/°
Weathered granite	2610	0.23	23.970	2.2	42
Moderately weathered granite	2550	0.26	20.870	1.05	37
Strongly weathered granite	1860	0.28	8.475	0.019	23
Fractured zone	1720	0.28	6.742	0.021	21

Table 2. Wave velocity of rock and soil layer

Rock mass property	Shear wave velocity (m/s)	Longitudinal wave velocity（m/s)	Dynamic shear modulus (MPa)	Dynamic elastic modulus (MPa)	Dynamic Poisson's ratio
Weathered granite	2210	4320	12796	33853	0.323
Moderately weathered Granite	1410	3566	5109	14381	0.407
Strongly weathered granite	650	2320	786	2291	0.457
Fractured zone	320	1750	612	1754	0.446

2.2. Computational model

As shown in Figure 4, the model we calculated is 1015m long in the north-to-south direction, 217.53m high in vertical direction, and the bottom elevation of the model is -200m. In accordance with the geological conditions, the calculation model was selected with a limit situation along the north-south direction of geological profile, where the nuclear island building is located in the strong weathering zone, The F1 and F2 zone is located in the lower of strong weathered, fracture zone throughout the entire foundation. Reaction cone size is 70m*60m; turbine engine room size is 70m*58m, as shown in figure 5. According to the design , the nuclear island foundation strongly weathered granite should be replacement for plain concrete after excavation. According to the actual geological geometry of soft interlayer orientation and size , The rupture zone F1 set dip angle to 44 degrees, and it’s width is 5.27m; the rupture zone F2 dip angle of 50 degrees, and it’s width is 1.53m.

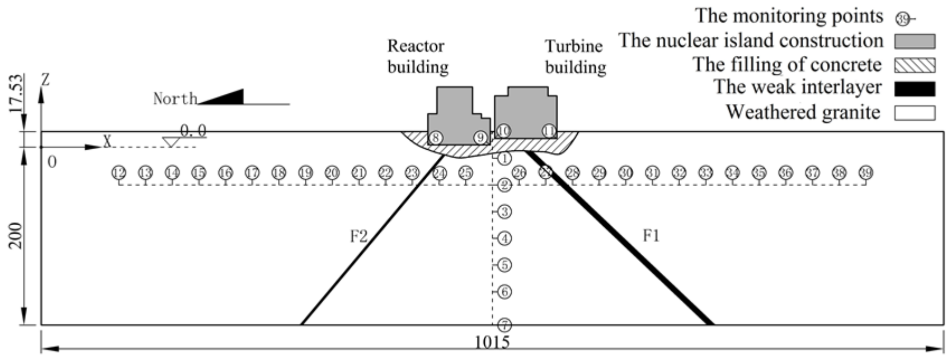


Figure 2. Interaction model of nuclear island foundation

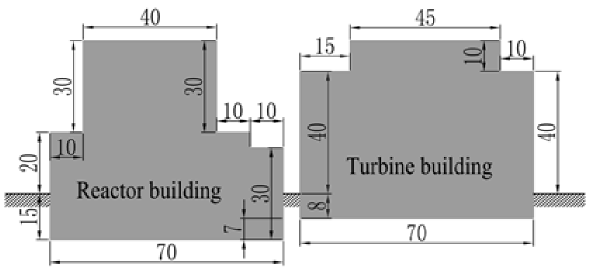
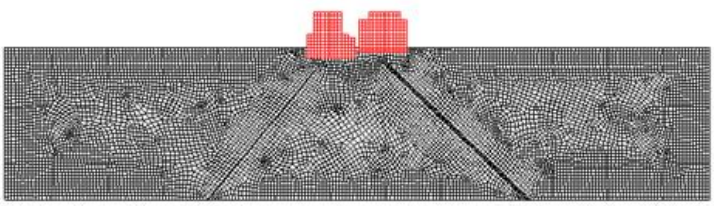
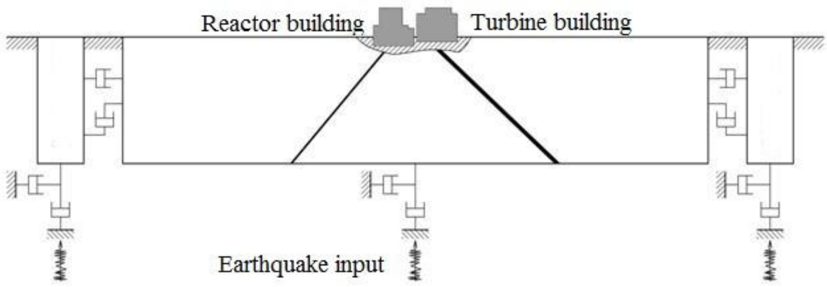


Figure 3. Simplified model of the nuclear island structures



(a) Gridding model



(b) Model boundary condition

Figure 4. The mesh and boundary conditions of simulation model

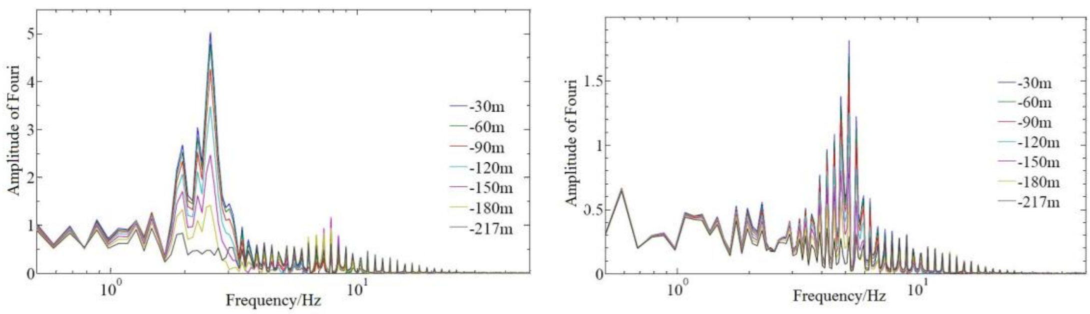
For dynamic numerical simulation, the accuracy of the numerical simulation is largely controlled by the size and wavelength of the element. The results show that the size effect exists in the numerical simulation [13]. In order to ensure numerical accuracy and find out wave propagation problems, the selected cell ratio should be less than the wavelength of 1/8~1/12. According to the actual characteristics of the project, the maximum unit size of the numerical model is 5m. The natural mechanical properties of intact rock can be obtained from table 1 and table 2. The average density of nuclear island building is $2.47g/cm^3$. According to the field survey, the damping coefficient of rock material is set to 3%. The side boundary condition of the model is the free field boundary and at the bottom of the model is viscous damping boundary. The free field boundary allows the seismic waves to travel freely around them without reflection. The bottom viscous boundary absorbs the reflected seismic wave to reduce the reflection of seismic wave. Finally, the number of cells in the model is 9008, and the number of nodes is 18556, as shown in figure6 (a).

3. The nuclear dynamic time history analysis of seismic performance of bedrock

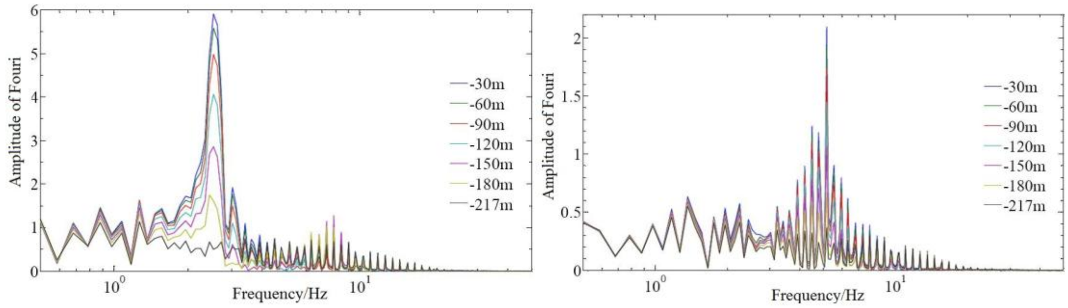
In order to study the law of seismic wave propagation and mechanical phenomena and characteristics in bedrock interior, a certain number of monitoring points are arranged in the numerical model. Thus the physical and mechanical parameters of bedrock are recorded in the process of earthquake occurrence.

3.1. Propagation of seismic waves at different depths

During the propagation of stress wave in the bedrock, the wave dynamic phenomena such as amplification, attenuation, reflection and diffraction of stress wave will occur. As shown in figure 5. When the frequency is in the range of 1.0~3.0Hz, the phenomenon of amplitude amplification occurs when the horizontal acceleration waves propagate to the surface. In the higher frequency range, there will be a certain attenuation phenomenon in the process of horizontal acceleration wave propagating to the surface. For vertical acceleration wave, amplitude amplification is more obvious in the frequency range of 1.0~6.0Hz; In other frequency range, there will be some attenuation or amplification of vertical acceleration wave. It can be seen that the amplification effect of low-frequency seismic wave in the foundation is obvious because the low frequency wave is closer to the natural frequency of the foundation model. The distribution curve of peak acceleration in vertical direction is shown in Figure 9, With the increase of propagation distance of acceleration wave in bedrock, the peak acceleration is also gradually increased.



(a) First condition, horizontal acceleration Fourier spectrum (b) Second condition, vertical acceleration Fourier spectrum



(c) Third condition, horizontal acceleration Fourier spectrum (d) Fourth condition, vertical acceleration Fourier spectrum

Figure 5. Fourier amplitude spectrum of acceleration wave

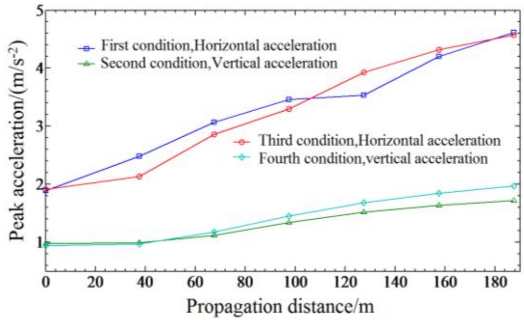
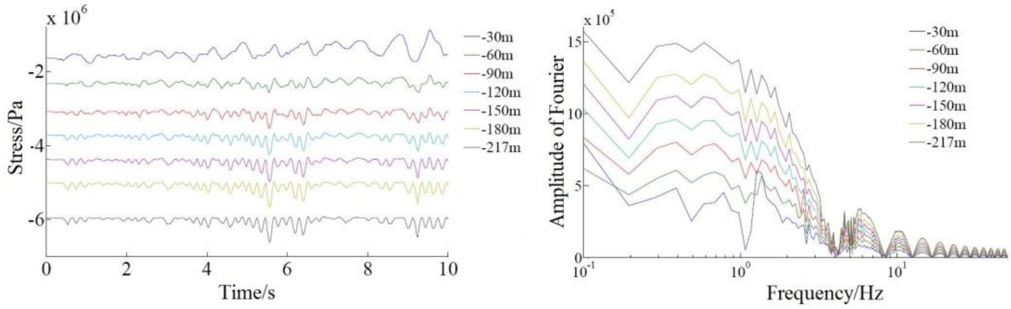
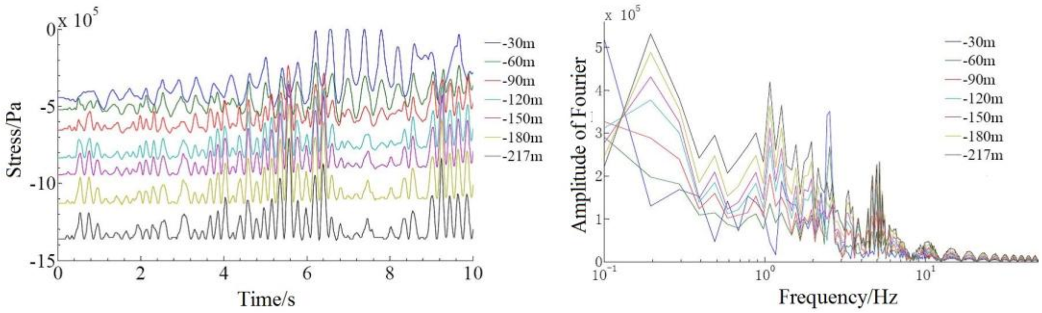


Figure 6. Vertical Distribution curve of acceleration peak

Under the action of earthquake load, the stress transformation curve and frequency spectrum in the bedrock are shown in figure 10~12. Under the action of horizontal seismic load, the fluctuation range of the stress wave in the shallow depth of bedrock is relatively larger than in the deeper depth in the bedrock. The maximum principal stress fluctuation frequency decreases with the increase of seismic wave propagation distance, the Fourier amplitude decreases with the increase of propagation distance. This shows that with the increase of seismic wave propagation distance, the stress of bedrock gradually decreases with the influence of seismic wave.

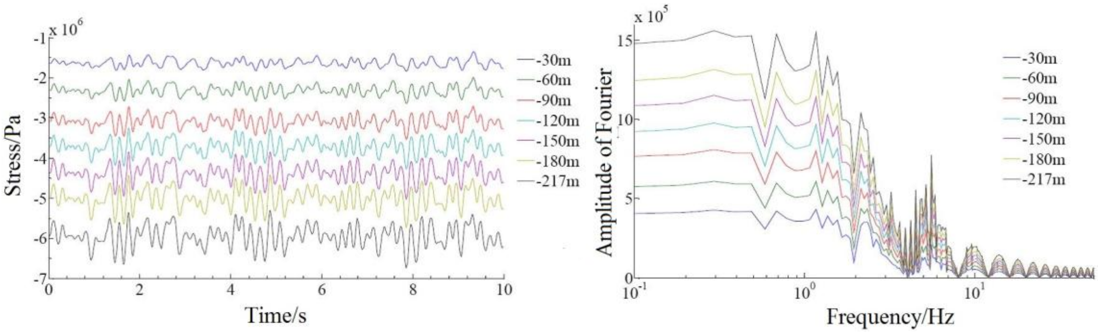


(a) Time history curve and Fourier amplitude spectrum of maximum principal stress in the ground

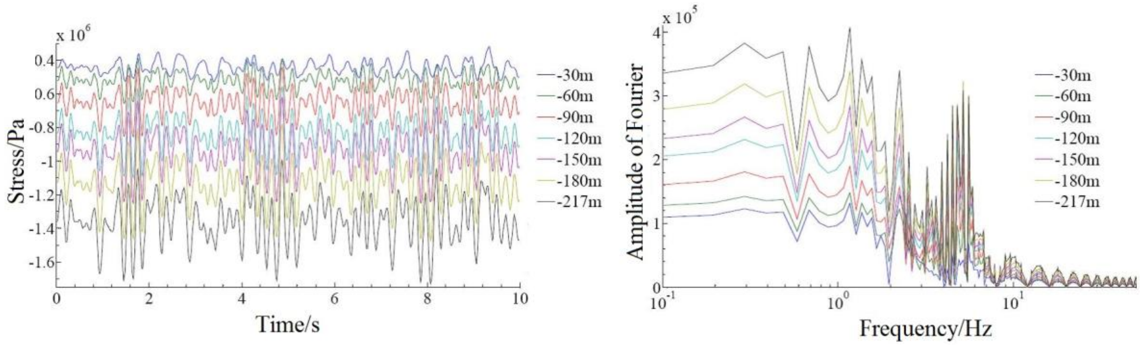


(b) Time history curve and Fourier amplitude spectrum of minimum principal stress in the ground

Figure 7. Time history curves and fourier amplitude spectrum of maximum principal stress or minimum principal stress in first condition

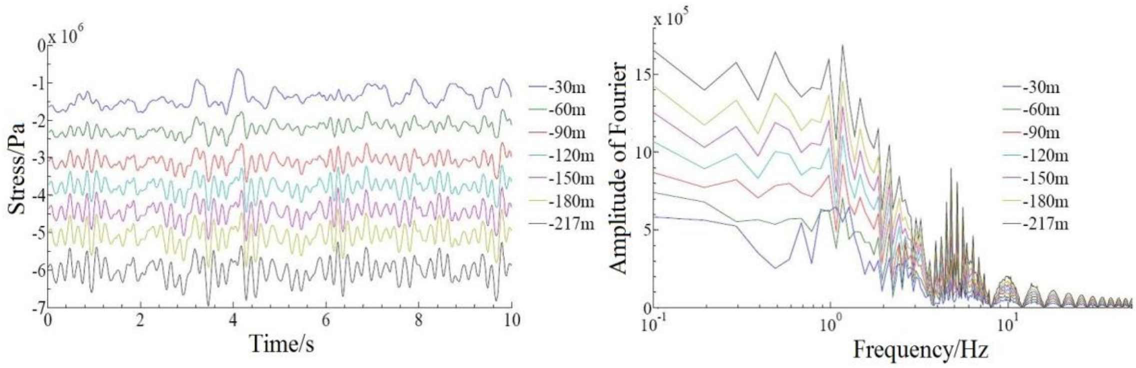


(a) Time history curve and Fourier amplitude spectrum of maximum principal stress in the ground

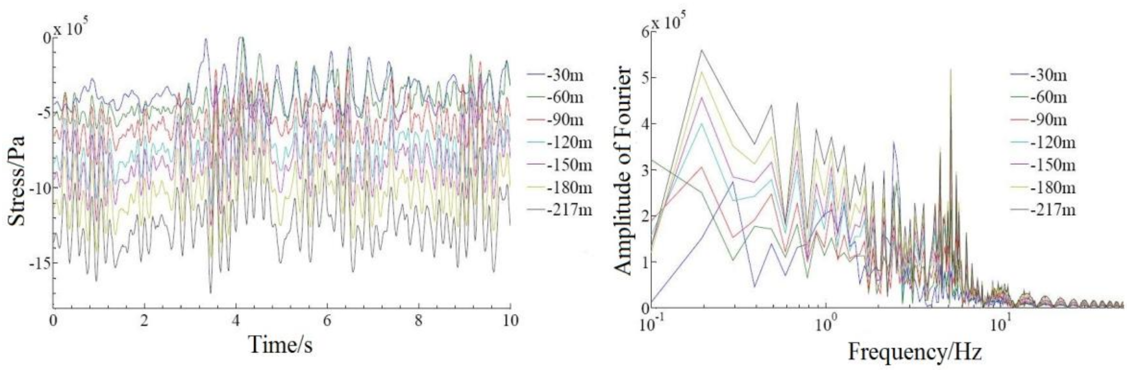


(b) Time history curve and Fourier amplitude spectrum of minimum principal stress in the ground

Figure 8. Time history curves and fourier amplitude spectrum of maximum principal stress or minimum principal stress in second condition



(a) Time history curve and Fourier amplitude spectrum of maximum principal stress in the ground



(b) Time history curve and Fourier amplitude spectrum of minimum principal stress in the ground

Figure 9. Time history curves and fourier amplitude spectrum of maximum principal stress or minimum principal stress in third condition

3.2. Distribution law of seismic wave in spatial horizontal direction

According to the simulation results, in the first condition, the horizontal acceleration time history curves of the particles at the same depth are basically the same regardless of different positions and its frequency and amplitude are all the same. But at the same height, the waveform, frequency and amplitude of the vertical acceleration have a great change at different positions. And the vertical acceleration amplitude is relatively small compared with the horizontal acceleration. At this time when the stress wave passes through the weak interlayer, there will happen several times of reflection and refraction and diffraction, and its spectral characteristics will become more complex and the weak interlayer has a great attenuation effect on low frequency wave. At the same time, the distribution law of the spectrum characteristics of the vertical acceleration of the particle in the space is that in the low frequency region 2~5Hz, the vertical acceleration of the bedrock in the vicinity of the two weak intercalated layers is less than that of the lower bedrock of the two weak interlayers. The horizontal acceleration wave is also affected by the reflected and refracted stress waves. However, the magnitude of the reflected and refracted stress waves is relatively small, and there is no obvious effect on the applied seismic load, as shown in figure 10.

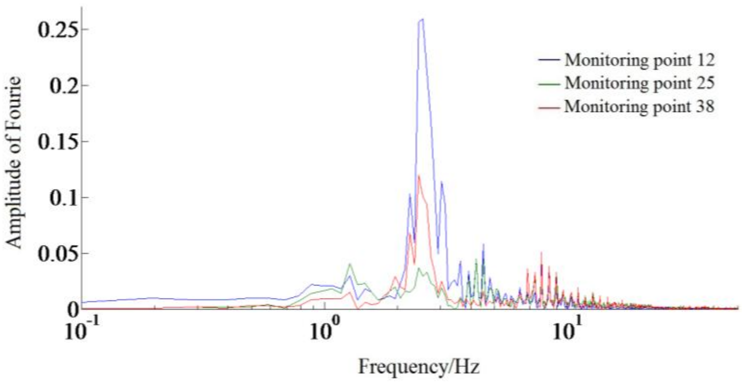
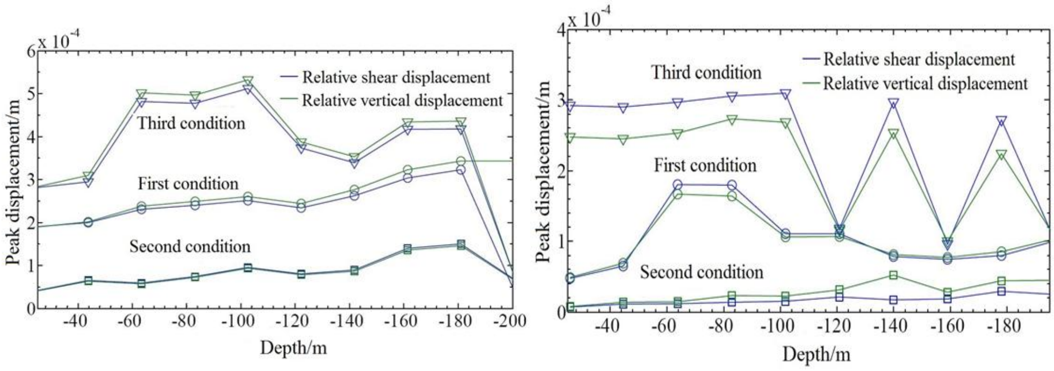


Figure 10. vertical acceleration spectral characteristics in first condition

3.3. Failure characteristics and deformation characteristics of weak intercalation

The peak distribution of F1 interlayer deformation at different depths is shown in Figure 15 (a), and the peak deformation of F1 interlayer increases with the increase of the depth in the first condition and the second condition. It is shown that with the decrease of depth or with the propagation of seismic wave, the effect of seismic wave will decrease gradually. In third condition, in the range of -40m to -120m, the peak displacement of interlayer F1 has a significant increase. Under the action of horizontal seismic wave and vertical seismic wave, the plastic deformation of the interlayer is larger. The peak distribution of F2 interlayer deformation at different depths is shown in Figure 15 (b). In the second condition, the peak deformation of F1 interlayer increases with the increase of depth. In the second condition, the peak displacement of the interlayer in the depth range from -40m to -100m was significantly increased. This is the main development area of F2 interlayer plastic zone In third condition, the F2 interlayer has a wide range of plastic deformation, at this time, the earthquake damage is most obvious. In the weak intercalated layer F1 and F2, the peak displacement is relatively small in the range near the bottom of the model, this is mainly due to the influence of the boundary properties of the model.

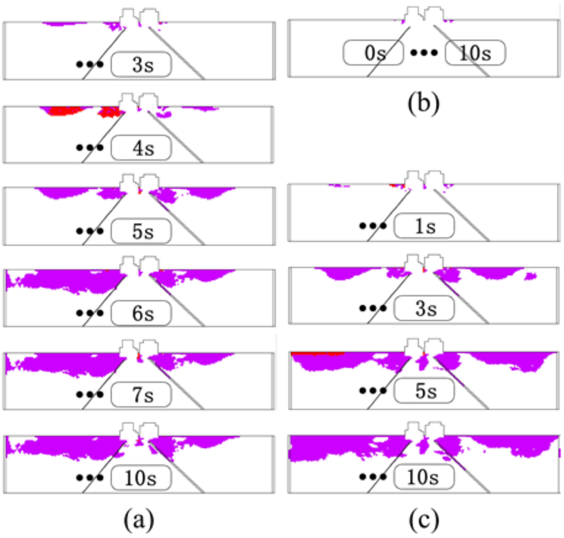


(a) Peak displacement curve of F1 interlayer (b) Peak displacement curve of F2 interlayer

Figure 11. the peak value distribution of relative displacement in weak interlayer

3.4. Time history analysis of failure characteristics of bedrock

Under the three conditions, the distribution and development of the plastic zone of bedrock is shown in figure 12. It can be seen from the distribution and development of the plastic zone, under the action of earthquake load in different working conditions that the plastic distribution changes in the development of nuclear island in bedrock is mainly divided into two types. One is due to the superposition of stress waves generated by the reflection of stress waves on the earth surface and the amplification effect of stress waves. along with the earthquake load, it develops to the depth of bedrock and it is mainly distributed far away from the nuclear island building area. The other is the shear load in the horizontal direction, the nuclear island under seismic load through foundation weathered granite area resistance force in the horizontal direction on both sides of the weak interlayer. plastic failure will be happening near the area.



(a)First condition，(b) Second condition，(c) Third condition

Figure 12. Distribution and expansion of plastic zones in the bedrock

III. CONCLUSIONS

This paper takes the Taishan nuclear power plant as the engineering background of established nuclear island foundation soil interaction model. The finite difference method is used to simulate and analyze the mechanical behavior of the structure under seismic loading. The main conclusions are as follows:

（1）In the propagation of seismic waves from the bedrock to the surface under the action of earthquake load, the frequency of seismic wave in the range of 1Hz~2Hz will increase with the increase of propagation distance. In the process of the propagation of seismic waves from bedrock to shallow, the amplitude and frequency of stress fluctuation in rock mass will decrease with the increase of propagation distance. And the nuclear island building dynamic role have a large inpact on the nearby nuclear island building foundation rock stress state.

1. On the same horizontal depth, the acceleration wave is basically the same as that of the input seismic wave in the same direction. In low frequency domain 2~5Hz, the vertical amplitude of the vertical acceleration of the bedrock in the vicinity of the two weak intercalated layers is less than the Fourier amplitude of the bedrock from the two weak interlayers.
2. The peak deformation of F1 interlayer increases with the increase of depth, it shows that with the decrease of depth, the force of seismic wave will decrease gradually. In the weak intercalated layer F1 and F2, the peak displacement is relatively small in the range near the bottom of the model. This is mainly due to the influence of the boundary properties of the model.
3. Under different conditions of seismic wave, the plastic failure of the bedrock itself occurs from the surface to the deep part of the rock mass. At the same time in the bedrock under the interaction of nuclear island, Near the nuclear island foundation concrete and rock layer landfill can cause local damage. Weak interlayer plays an important role in buffering seismic wave, and to some extent, it affects the development of plastic zone. The destructive effect of P-wave on bedrock is very limited. The destructive effect of longitudinal wave on the bedrock is very limited. Under the action of shear wave and longitudinal wave, the bedrock will be destroyed. However, there will not be a large instability of bedrock because of the high residual strength of bedrock. The nuclear island building foundation part will have serious damage, and it should be strengthening and repairing at this time.

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